Human Behaviour in Design'05

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Preprints of the
International Workshop on
Human Behaviour in Design'05
Grand Hyatt Hotel, Melbourne, Australia
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edited by
John S Gero
Udo Lindemann

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PREFACE

Engineering design has become an increasing research focus as we try to understand design in order to improve it. This is the domain of the field of design science. Research in design science can be carried out using two primary paradigms. One, design computing, uses hypotheses about design processes, constructs computational models of them and carries out empirical studies on those computational models. The other, design cognition, uses concepts from cognitive science and carries out empirical studies using human designers. Much of the current research in design science focuses on positing and developing computational models of designing. There is surprisingly little research in the area of design cognition: studying humans designing. This workshop aims at addressing this latter area.

Studying human designers can be carried out in many ways ranging from experiments in laboratories with individual designers, experiments in laboratories with design teams, to in-situ studies of individuals and teams. The experiments can be concerned with elaborating aspects of the acts of designing or of changing the design environment. The latter is generally concerned with the introduction of various forms of computational and communication technologies. Many of these are represented in the papers in this volume.

This workshop is organised as part of the Design Society's Special Interest Group on Human Behaviour in Design. It aims to provide a forum for both the presentation and discussion of cutting-edge and ongoing research into human behaviour in designing. It follows on from an earlier workshop at DESIGN 2004 in Dubrovnik.

This volume presents the preprints of the *International Workshop on Human Behaviour in Designing'05*. The workshop is held as part of the *International Conference on Engineering Design, ICED'05,* held in Melbourne, Australia. The papers address questions of designing spanning disciplines and spanning the globe. The papers were selected from the submissions by two referees.

The support of the Key Centre of Design Computing and Cognition of the University of Sydney in organizing this workshop is gratefully acknowledged. Mercèdes Paulini worked hard to produce a coherently formatted volume.

John S Gero
Sydney
July 2005

SESSION ONE

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COMPARING COLLABORATIVE DESIGN BEHAVIOR IN REMOTE SKETCHING AND 3D VIRTUAL WORLDS

MARY LOU MAHER, ZAFER BILDA
University of Sydney, Australia

and

DAVID MARCHANT
Woods Bagot, Australia

Abstract. The aim of this study is to compare two architects' collaborative design behaviour while using a shared whiteboard application in one design session and a 3D virtual world in a second design session. Our preliminary analysis shows that designers spend more time discussing design ideas while sketching and more time creating the design model and inspecting spatial relationships while in a 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. Whilst 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 work 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. Only by gathering information about the rich and complex picture of collaborative design can we understand the characteristics and needs of the practitioners involved as well as those factors which contribute to their professional effectiveness.

2. Team collaboration in high bandwidth environments

The comparison presented in this paper is part of a larger study funded by the CRC for Construction Innovation in Australia[1]. In studying the impact of high bandwidth environments on design collaboration, an experimental study with 3 design settings was developed:

1. A collaborative design process in which designers work face to face with their current design and communication tools.
2. A collaborative design process in which designers use a shared drawing system with synchronous voice and video conference.
3. A collaborative design process in which a 3D virtual world is used in addition synchronous voice and video conference.

The reason for including the first setting is to understand the nature of the collaboration process as it takes place using traditional methods and without digital systems for designing and communicating. The study has been carried out over three months using an open ended exploratory approach into gathering data on existing design practice.

This paper presents an analysis of the data collected from the 2nd and 3rd settings, comparing two architects' collaborative design processes while using a shared whiteboard application and while using a 3D virtual world on a desktop computer. The two collaborative environments were selected as representative of current low-bandwidth technology (Net Meeting) and a prototype of high-bandwidth technology (extended Active Worlds). The paper begins with a summary of relevant methodologies and studies, and then the experiment design and data collection methods are described. Finally, protocol analysis of the design sessions and the results are presented.

3. Background

There are many studies that reveal the nature of design thinking and the characteristics of early conceptual design as distinct from detailed or embodiment design. The results of those studies can assist in our understanding of how the processes of design can be supported and how new technologies can be introduced into the workplace (Munkvold 2003).

Protocol analysis has been accepted as a prevailing research technique allowing elucidation of design processes in designing (Cross et al. 1996).

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[1] <http://www.construction-innovation.info>

And whilst the earlier studies dealt mainly with protocols' verbal aspects (Akin 1986), later studies acknowledge the importance of design drawing (Akin 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).

The protocol analysis technique has been adopted to understand the creative nature of collaborative design (Cross 1997), the design behavior of teams in terms of coherent idea production (Goldschmidt 1996; Van der Lugt 2003), process-oriented designing (Gero and McNeill 1998); and reflection-in-action (Valkenburg and Dorst 1998). Another stream of studies were concerned with the impact of use of different communication channels on design process (Vera et al. 1998; Gabriel and Maher 2002).

The ROCOCO project studying protocols of collaborative design presents one of the early approaches to detailed analysis of drawings together with analysis of verbalizations (Scrivener et al. 1992 cited in Mazijoglou et al. 1996). Consequently recent design protocol studies employed analysis of physical actions such as drawing, moving hands (referring to hand gestures in sketching) and also seeing/looking which provided a comprehensive picture of constructing external representations during designing (Suwa et al. 1998; 2000; Kavakli and Gero 2002).

Protocol studies in the engineering design domain focused on the work environment context and the social interaction discourse (Buciarelli 1994) as well as design behavior and communication (Badke-Schaub 2003; Glock 2003). These studies emphasized the analysis of conversation patterns, in order to gather information about the team dynamics, individual motivations, social interpretations etc. Protocol studies of this kind have been done relatively less in architectural design practice because of the difficulties in collecting protocols.

The internet and the expansion of international design practices have initiated our interest in studying "collaboration at a distance" both within the same profession and across professions. We believe that design work would be conceived as a social process, rather than design being influenced by social factors (Suchman and Trigg 1991; Bucciarelli 1994). Consequently the architectural design process could be conceived as a process of communication and interaction between designers and different domains instead of a process where the architect is a self-sufficient individual mind.

4. Method

In this study we worked with two architects from Woods Bagot, who were selected on the basis of observations carried out in the workplace/baseline study. In these observations, the collaborative roles of the participants were determined, and their face to face interactions were recorded. We name the designers as Alex and Casey, the same names as their avatar names in the virtual world environment, rather than using their real names.

A series of pilot studies have been conducted for testing the experiment set up and maintaining participants' acquaintance with the technologies. Before the experiment sessions, the participants were given a training session on the use of software and related tools. Then in the experiment sessions they were asked to work on a hypothetical design brief that they are exposed to for the first time.

4.1. EXPERIMENT SET-UP

We record the designers' activities and verbal exchanges in each session with a surveillance DVR (digital video recording) system. The DVR system was set to show four different views on one monitor. Two cameras were used to monitor the two participants' behaviors and the other two views are video streams directly from the two designers' computer display screens. Two separate microphones for each participant were fed into the DVR system through a sound mixer. Figure 1 shows the equipment set-up where two participants are located in the same room with a panel in between them. We placed the designers in one room to simulate high bandwidth audio, using the LAN for video and shared applications.

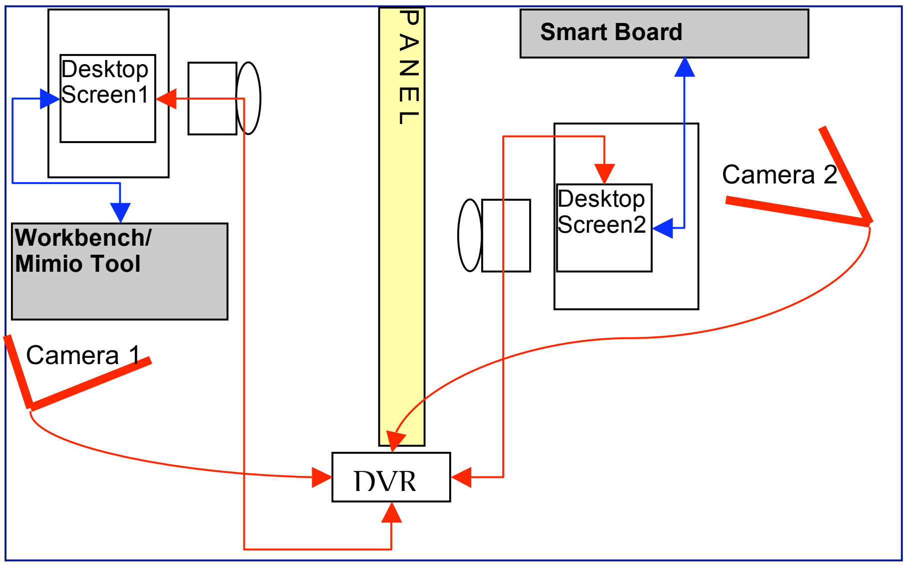

Figure 1. Diagram of equipment set up

In the experimental set-up, two cameras and two computers are connected to the DVR. "Desktop screen 1" was projected on a horizontal workbench (with glass top) and a Mimio Tool[2], and "desktop screen 2" was connected to the Smart Board with flat panel plasma display[3]. In the first setting, the plasma display and the horizontal workbench were used so the designers had a large drawing surface. In the second setting, the cameras and video streams were connected to a typical desktop computer configuration with a vertical screen, keyboard and mouse.

Figure 2(a) shows the set-up and Figure 2(b) shows the first experiment setting. The location of the cameras was an important issue, since we aimed at monitoring participants' movements, verbalizations, gestures and the drawing actions. Cameras 1 and 2 capture the gestures, general actions such as walking, looking at, moving to the side etc. while the direct connections to the computers/screens capture the drawing process in detail.

(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 first setting of the experiment, the architects used Microsoft Net Meeting, one participant via a Smart Board, Figure 2(b), the other participant via the Mimio on a projection table, Figure 2(a). Net Meeting includes a shared whiteboard application and web-cam application. The architects were able to see each other via the web-cam and also were able to talk to each other because they were located in the same room.

In the second setting of the experiment, the architects used an extended 3D virtual world application in Active Worlds, Figure 3. The 3D world includes a multi-user 3D building environment, video contact, a shared whiteboard, and an object viewer/insert feature. The participants can talk to each other because they are in the same room.

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2 http://www.mimio.com

3 http://www.smarttech.com

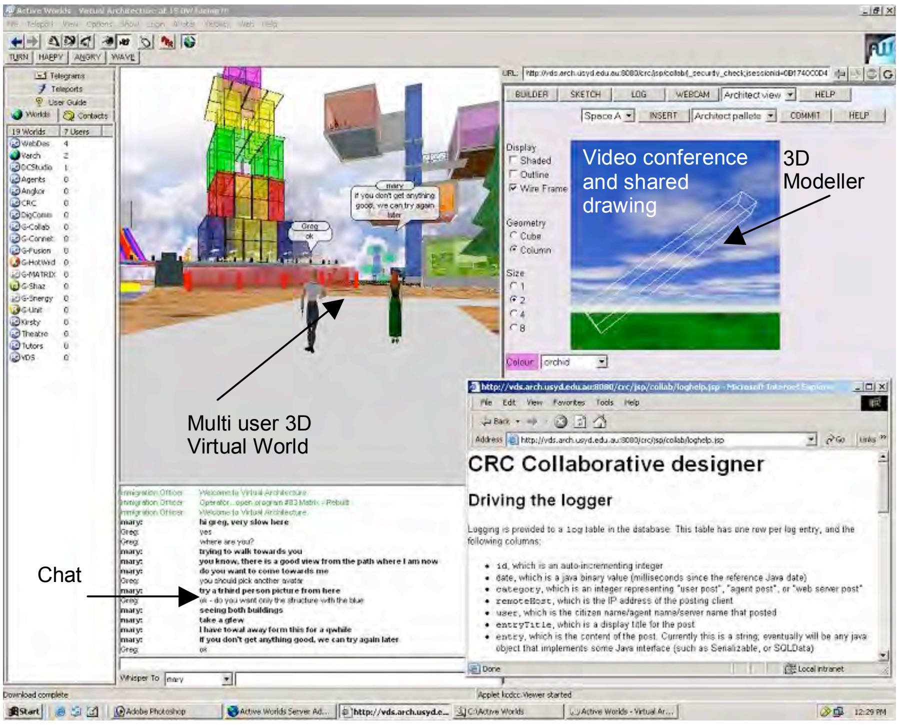

Figure 3. Extended virtual world

4.2. EXPERIMENT DESIGN

The experiment followed a 6 step procedure.

1. The designers were presented a short description of how they could use Smart Board or Mimio Tool. These are both pen and digital ink interfaces to a standard windows environment. The Smart Board is attached to a vertical plasma display and the Mimio is placed on a horizontal projection display.

2. The designers were given a 15 minute training session on the use of Net meeting. 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 software application provided for collaboration.

3. The designers were given a design brief (see Appendix) and shown a collage of the photos of the site they are required to build on. The design brief involves designing an art/craft gallery on a site in Sydney. They were given time to read through the design brief and inspect the site layout and photos. The site layout was set in the share whiteboard application as a background image on several pages so that participants can sketch on them.

4. The designers commenced designing using Net meeting. The duration of the session was half an hour. Five minutes before the end of the session they were reminded that this was the amount of time remaining.

5. After a 5 minute break, the designers were given a 15 minute training session on the use 3D world. 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 commenced designing collaboratively on the same design task/design brief, this time using the extended virtual world. The duration of the session was half an hour. Five minutes before the end of the session they were reminded that this was the amount of time remaining.

Table 1 shows the summary of methods, tools and activity of participants:

TABLE 1. Experiment sessions

	1st Phase	**2nd Phase**
Participants	Alex and Casey	Alex and Casey
Interface	Smart Board and Mimio on a glass table	Desktop Screen
Software	Net Meeting	Active Worlds
Application	Shared White Board	Construction Space
Webcam	√	√
Training tutorial	√	√
Design Brief	Architect Version	Architect Version

Figure 4 shows the shots from the recorded activities of the architects collaborating during Net meeting (Figure 4a) and 3D world session (Figure 4b).

(a)

(b)

Figure 4. Architects collaborating during (a) Net meeting session (b) 3D world session

4.3. PROTOCOL CODING

The software used for the analysis of the experiment sessions is called INTERACT[4], with the interface as shown in Figure 5 for coding the recorded videos. More information on the reasons for choosing this software and how it improved our coding process can be found in Candy et al (2004).

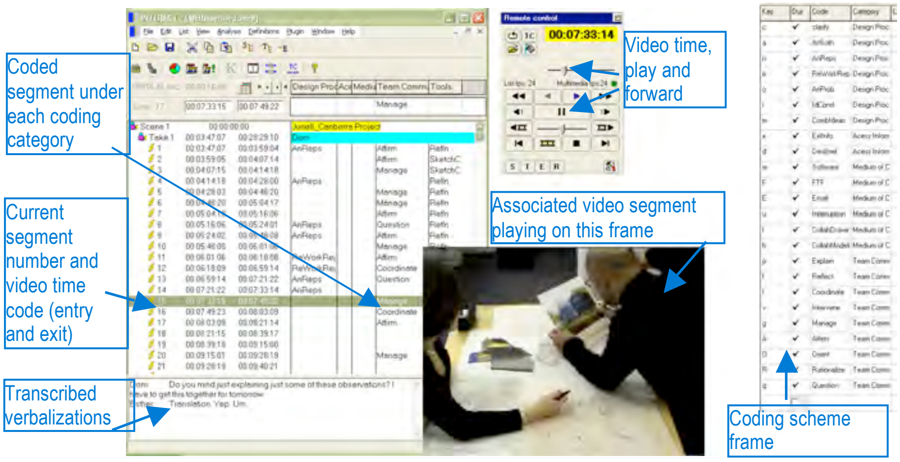

Figure 5. INTERACT Coding interface

4.3.1. Segmentation

The continuous stream of video and audio date needs to be segmented for coding and analysis. A single filmed session is called a Scene in INTERACT. There are "Takes" in a Scene which we refer to as design episodes. We utilized one take for coding one actor's activity, and second take for second actor's activity separately in a scene. "Events" are smaller activity definitions building up the "Takes" which are also the smallest segment definitions in the current study. In the study done by Dwarakanath and Blessing, an event was defined as a time interval which begins when new portion of information is mentioned or discussed, and ends when another new portion of information is raised (Dwarakanath and Blessing 1996). 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. For example, in Segment

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[4] www.mangold.de

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."

Then this conversation could be put into one segment despite the change in speaker. Table 2 shows the segmentation of a protocol excerpt from the study.

TABLE 2. Segmentation in terms of event definitions

Segment 11	Casey: You were feeding, the lobbies there but not facing the void. You saw the void from around this way. Alex: Yeah but this is again Site Specific it is related to the <inaudible>
Segment 12	Alex: That is ok. I mean again within that model... Just keep that. I guess the point is
Segment 13	Alex: I think even in this model you can still to have a lift opening up this way or a lift going this way. But what he was suggesting was maybe if we pulled the lifts out
Segment 14	Alex: but I think you could actually put the lifts here.
Segment 15	Casey: You know this... what I am saying... do that, you face this way and you come out and you turn a corner and that is hanging off the edge of the void there is a void there so this is like you come out, like when you are waiting for the lift you come out and you are off the edge.
Segment 16	Alex: I like that with glass under that... you walk past the sort of lobby as you come in Casey: and as you go up this thing jumps out.... Alex: yeah so you could put that line there...

4.3.2. Coding Scheme

The purpose of the coding scheme is to provide categories for the collected data that will highlight the similarities and differences in collaborative designing using the two different design environments. These differences provide the basis for understanding the impact of introducing a new design environment. We have developed 3 coding categories: communication content, design process, and operations on external representation. The communication content category partitions each session according to the content of their conversation, focusing on the differences in the amount of conversation devoted to discussing design development when compared to other topics. The design process category characterizes the different kinds of designing tasks that dominate in the two different design environments. The operations on external representation category looks specifically at how the designers interacted with their external representation of the design to see if using 2D entities or 3D objects was significant.

Communication Content:

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 3.

TABLE 3. Communication Content

Software features	Software/ application features or how to use that feature
Design Process	Conversations on concept development, design exploration, analysis-synthesis-evaluation.
Awareness	Awareness of presence or actions of the other
Context free	Conversations not related to the task
Tech Prob	Talking about a technical problem

Communication on software features involves the 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 etc.

Communication on design process involves statements about design issues, environmental or structural issues, design ideas, design solutions, judgments about design solutions, functional issues or design constraints, client requirements, comments on design brief, in other words any conversation about the design process.

Communication on awareness refers to conversations on participants' presence and actions in a digital environment, for example:

"I see where you are, I'll come down and join you and here I'm".

"aaaha you re working on the NE corner…."

"Did you manage to put walls?

Yes there are a couple of panels at the southwest corner".

Context free communication refers to the conversations that are not related to the design, the software, or awareness of others, for example "shall we have a beer after this?".

Communication on technical problems is coded separately from software features because they are problems that may be resolved in future experiments. The technical problems include software crashes, computer hardware or server failures, internet disconnection.

Design Process:

The design process category characterizes the kinds of design tasks the designers are engaged in for each segment. Assigning a design process category takes into consideration the words spoken during each segment as well as the actions observed in the videos. The codes in the design process category are an adaptation of the coding scheme developed by Gero and McNeill (1998). The codes in this category are shown in Table 4.

TABLE 4. Designing Process

Propose	Propose a new idea/concept/ design solution
Clarify	Clarify meaning or a design solution, 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 (for eg. how to get this done? In terms of areas we have nothing to scale)

Operations on external representations:

The external representations category looks specifically at the actions the designers perform while using the software. 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. Table 5 shows the codes in the external representations category.

TABLE 5. External Representation

Create	Create a design element
Group	Group elements
Move	Orientate/Rotate/ Move element
Erase	Erase or delete a design element
Inspect	Attending to, referring to the representation

The actions required to construct external representations differ in each media. Thus the definitions of the codes in this category need to be explained for Net meeting and 3D worlds, as shown in Table 6.

TABLE 6. External Representation Actions

Code	**Net Meeting**	**3D World**
Create	Drawing a new entity.	Inserting a design object (wall, column, beam, slab, box) into the environment.
Group	Creating entities next to each other, which form a group.	Duplicate an object next to the previous in one segment duration.
Move	Move action is not frequently used in a shared white board, because designers tend to use it like a sketch paper.	Designers move around the objects after they are created. This is to align them, change their arrangements or to carry them for using in another location.
Erase	Select a drawn entity and delete it	Select a created object and delete it.
Inspect	--Looking at the representation and refer to its parts/aspect --Using hand gestures over the representation --Attending to a visual feature of the representation --Zooming in and out --Scanning	--Looking at the model and refer to a design object. --Using hand gestures over the representation --Attending to a visual feature in the environment --Changing the view point in the environment

5. Interpretations

5.1. OBSERVATIONS

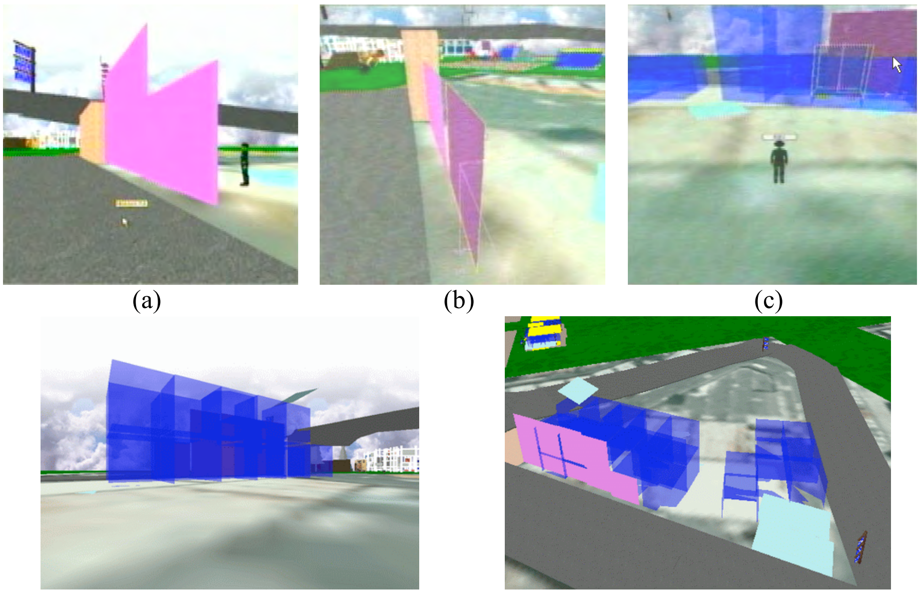
In the different design environments there was a noticeable difference in the designers' focus. The sketching environment encouraged the designers to stay at a high level of abstraction and the 3D virtual world encouraged the designers to focus on the relationships between the objects in the design solution.

In the Net Meeting session, the architects produced sketches on the aerial view of the site layout. In page 1, Figure 6(a), the participants focused on organization of the layout and the relationships between the larger elements in the environment. Then, in page 2, Figure 6(b), the participants focused on the elements of the building, where they deal with form and structure in parallel to functions and the organization of the building elements (such as the location of loading dock suggesting two levels on the south side, the plaza and open gathering space suggesting a curved façade). In page 3, Figure 6(c), they mainly worked on the form of the building, evaluating the form and how successfully they satisfied the design brief requirements. In pages 4 and 5 they produced section drawings where they worked out the form of the design and considered 3D aspects of the building.

(a) (b) (c)

Figure 6. Net meeting drawings (a) page 01 (b) page 02 (c) page 03

In the 3D World session the two architects constructed the design they previously worked on in the Net Meeting session. They started with placing the (pink) walls next to each other, Figure 7(a), and then moving them around, aligning them. Alex managed to put the walls on top of each other, and get the look of a second floor, Figure 7(b). Then they started using the space elements (blue transparent boxes) to represent the space, the building should cover, Figures 7(c) and 7(d). The construction of the blue spaces was relatively quick and towards the end of the design they managed to get a sense of the building on the site, Figure 7(d).



(a) (b) (c)

(d) (e)

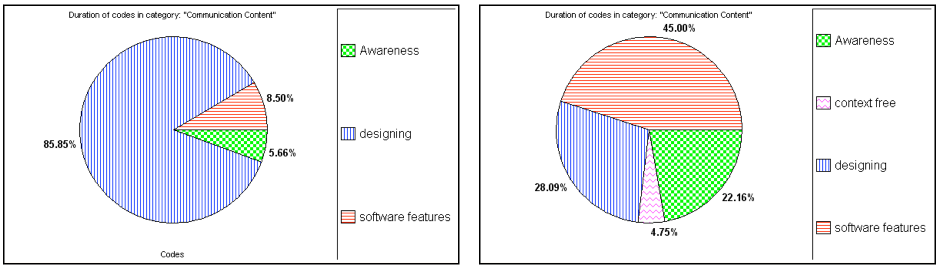
Figure 7. Progress of the design in 3D World

5.2. PROTOCOL ANALYSIS

In the protocol analysis, we consider each of the three categories of codes separately.

5.2.1. Communication Content

Figure 8 shows the percentages of the percentage of time in each of the communication content codes. Most of the communication in Net Meeting session was on “designing” (85 %) followed by relatively little percentages of “software features” (8.5 %) and “awareness” (5.7%), Figure 8(a). In the 3D world session nearly half of the communication was on software features, Figure 8(b). The remaining communication was primarily about awareness and designing (22% and 28%). The significant amount of time on the 3D virtual world on the features of the software may be due to the unusual experience of being in a 3D virtual world while creating and editing a building model. It is significant that the designers in the 3D world session focused on expressing issues related to their awareness of each other. This is relevant because the location of the avatar determines what each designer can see, so the ability to collaborate depends on knowing where the other avatar is and what the avatar is facing.



(a) (b)

Figure 8. Percentage of time on communication content (a) Net Meeting (b) 3DWorld

5.2.2. Design Exploration

Figure 9 shows the percentages of time on design exploration codes in Net Meeting versus 3D World sessions. The designers spent significantly more time in proposing and analyzing solutions during the Net meeting session, Figure 9. However in 3D world session participants spent most time on setting up goals and then on analyzing external representations, Figure 9. This is consistent with our observations that the designers were focused more on high level issues in Net Meeting and were more focused on building the 3D models in the 3D world.

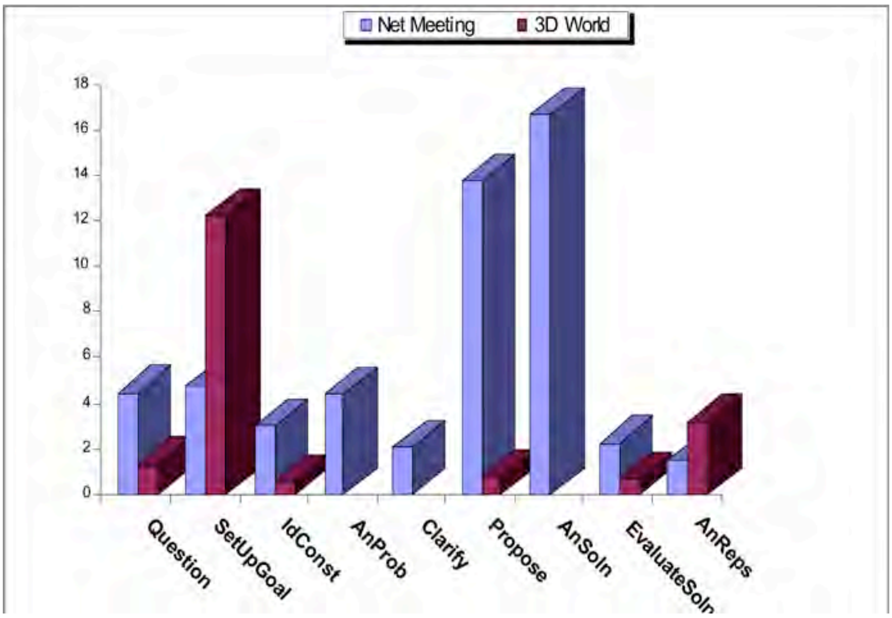


Figure 9. Percentages of time for design process actions (a) Net Meeting (b) 3D World

Figure 10 shows design process actions over time for each individual in Net meeting and 3D World sessions where "1" refers to Alex and "2" refers to Casey. In the Net meeting chart (Figure 10a) one can observe the cluster at the beginning of the session which is formed by analyzing a problem (AnProb), questioning (Question), and setting up goals (SetUpGoals) actions. Then proposal of ideas/ solutions (Propose) start to occur (Blue bars). Meanwhile analyzing solutions (AnSoln) are triggered by proposal actions (the pink arrows point to this relationship). Evaluation of solutions/ ideas (EvaluateSoln) occurs only after the first half of the session; in smaller time intervals in between analysis of solutions (orange ellipse markers point out to this relationship). However in the 3D world session there is hardly any pattern in occurrence of certain actions, Figure 10(b). Fewer segments are coded as "designing" in the 3D world than in Net Meeting, as explained in the section on communication content. This may account for the lack of patterns in their behaviour.

5.2.3. External Representations

Figure 11 shows the percentage of time related to operations on the external representation in Net meeting and 3D world sessions. "Inspect" was a dominant behavior in the Net meeting session that covers more than half of the total design session (60%) followed by "Create" (35%). Grouping elements consists of only 4.5% of the total actions time. In the 3D world session inspection is observed in nearly half of the total duration of the session (45%), and this is followed by moving and grouping elements (26% and 21%). Time spent in creating elements is significantly small (6%) in 3D world session compared to Net Meeting (35%). Thus the ratio of the actions in constructing an external representation seems to be quite different when participants are engaged in a different media.

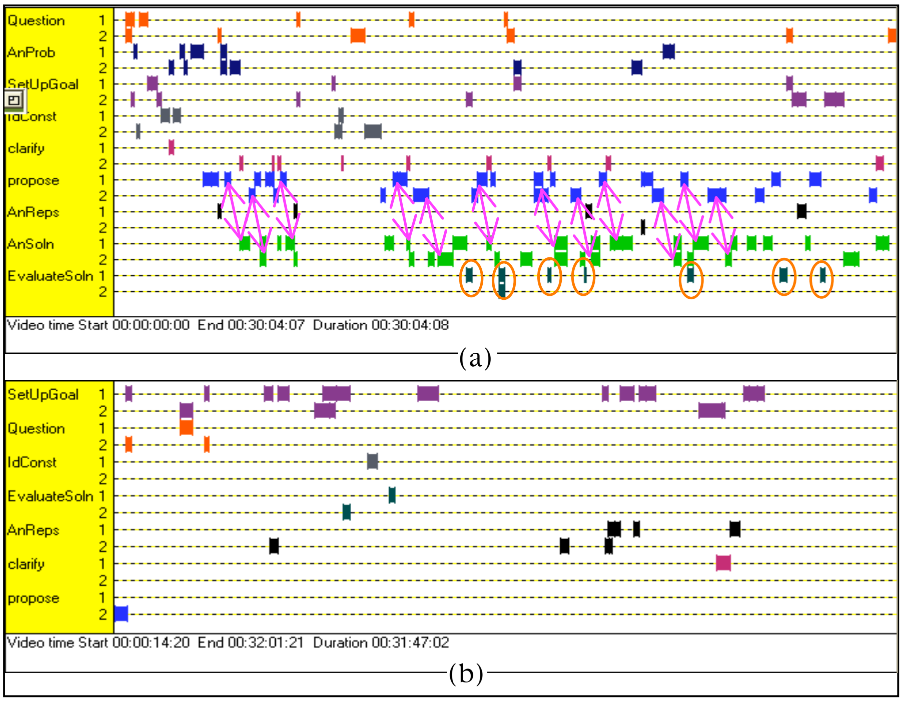


Figure 10. Individual design process actions over time (a) Net Meeting (b) 3DWorld

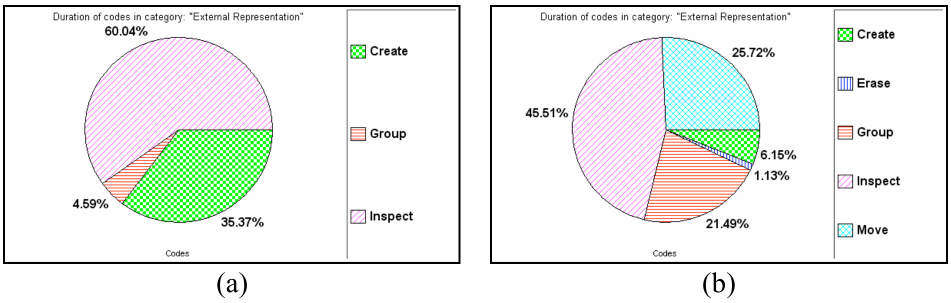


Figure 11. Percentage of segment on operations on external representations (a) Net Meeting (b) 3DWorld

Figure 12 shows actions for operations on external representation over time for each individual in Net meeting and 3D World sessions where “1” refers to Alex and “2” refers to Casey. Looking at the occurrence of actions for each individual in the Net meeting session, Figure 12(a), we see Inspect-Create and Create-Inspect patterns (see the pink arrows), as a frequently observed combination. Create and Inspect actions are observed to trigger each other rather occurring in parallel.

Looking at the occurrence of actions in 3D World, we again observe the Inspect-Create pattern (see pink arrows). Then, Create is usually followed by Move forming the Create-Move pattern (see orange arrows), and then Move is followed by Group action, forming a Move-Group pattern (see purple arrows). This chain of actions i.e. Inspect-Create-Move-Group pattern occurs at least three times during the session for each individual (see yellow ellipses). Note that Inspect can be observed as a continuous action, either in parallel with or immediately after Create, Move or Group actions. Thus the pattern of constructing external representations (Inspect-Create-Move-Group) is not one directional chain-like pattern only but interacting with the Inspect action frequently.

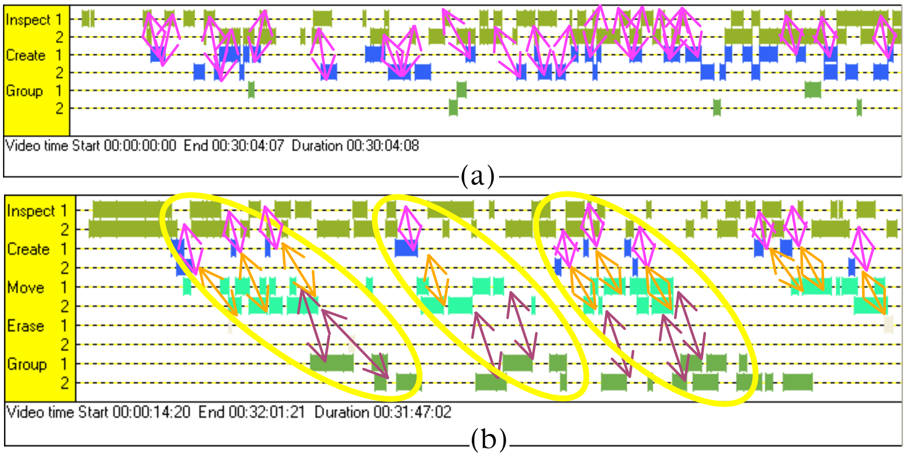


Figure 12. Individual actions over time to construct external representations (a) Net Meeting (b) 3DWorld

6. Discussion

Based on our insights from the baseline/workplace studies, the communication content in face to face sketching sessions is predominantly about the designing rather than about the tools they are using or where the other person is located. This is explained by the familiarity of this environment for the designers and the physical access they have to each other. We noticed a similar phenomenon in the remote sketching environment, where the designers talked about the design rather than the software or the awareness of each other. However, in the 3D virtual world we found that the conversation was predominantly about the software, and then only secondarily about the design and about their awareness of each other. The large percentage of the discussion on the software can easily be associated with the novelty of the experience, and the split between designing and awareness of others is due to the significance of the information about the other designer's location with respect to the design model they are creating. This result emphasizes two aspects regarding the nature of the 3D world that is different to remote sketching: 1. Participants may communicate about their existence since they are in a virtual world, 2. participants may need to communicate about their actions, and location or presence of the objects since they can choose a different viewpoint to visualize the current representation.

Comparing the design tasks in Net Meeting and 3D World sessions, we showed that in Net Meeting the architects explored the design ideas more frequently, Figure 9, with the highest occurrences of segments on proposing and analyzing design solutions. Further these actions frequently triggered each other over the timeline of the design session. In protocol studies, this behavior 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. 1991). 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". Then analysis of tentative solutions (in other words exploration) could be means to an evaluation which is an expected behavior during the conceptual phase of designing. In the Net Meeting session, the designers designed in a similar cyclic pattern where they propose and then analyze solutions, and in between evaluate them, Figure 10(a).

In the 3D World session, no significant patterns for designing were observed, Figure 10(b). This indicates a different behavior to the analysis-synthesis-evaluation cycle. In the 3D World, the designers set up goals in terms of building parts of their design or plan their actions. Then they analyzed the external representation, in terms of attending to parts and relationships, rather than thinking about the problem at an abstract level. This shows that designers' aim in the 3D world session was to construct a representation of the design which we call "design making" rather than design exploration.

Comparing the operations on external representations in Net Meeting and 3D world sessions, we observed significantly different ratios in occurrence of actions; particularly of Create, Move and Group actions, Figure 11. This difference is mainly to do with the nature of representations the designers were dealing with; they construct with lines in a 2D media in Net Meeting, and with objects in a virtual environment in the 3D world, Figures 6 and 7.

Constructing external representations was a more complex issue in the 3D world session. The architects were engaged in the Inspect-Create pattern during the Net Meeting session, Figure 12(a), while they were engaged in a more complex pattern involving Inspect-Create-Move-Group actions during the 3D World session, Figure 12(b). In the 3D World the designers were synthesizing objects, through Create-Move-Group actions and continuously inspecting how they looked. This can also be interpreted as an "analysis through synthesis" process. Thus in the 3D world the designers were engaged in that similar pattern however with different tools; in Net Meeting they were dealing with abstract concepts, in 3D world with objects.

The results show that the designers' behavior was different when they were engaged in remote sketching via Net Meeting and when they were engaged in modeling via the 3D World. They would not have focused on the details of how objects would come together and be synthesized if they were not using a 3D environment. In the same sense they would not be engaged in design process on an abstract level i.e. through design exploration, if they were not using the remote sketching environment. Thus the distinction between the nature and benefits of the two design environments were revealed by analyzing the design behavior of the participating designers: 3D World is for design making, remote sketching is for design exploration. In parallel to this view, there are also participant comments in the recorded sessions that they considered the 3D world environment as a modeling tool rather than a conceptual tool.

Further studies will focus on engaging more designers in the 3D World environment. In these studies the designers will be encouraged to engage in design exploration rather than only design making. They will be given a new design brief where they need to develop concepts, explore possible design solutions and evaluate them. We will increase the time dedicated to training on the extended virtual world, to assure that they utilize the software efficiently during the experiment rather than learning it.

7. Conclusions

Introducing new tools to the design process requires understanding of what purpose they serve. A design environment could be beneficial either for conceptual phase, detailing phase or modeling phase, however analysis of design behavior is needed for understanding the benefits of the tools/environments. This case study was an attempt to characterize and compare the design behavior of two architects using two different tools/media for designing. We demonstrated architects developed abstract concepts, analyzed synthesized and evaluated them when they were involved in remote sketching via Net Meeting shared whiteboard. The same architects focused on synthesis of the objects and the making of the design, when they were involved in 3D modeling via the extended virtual world.

Acknowledgements

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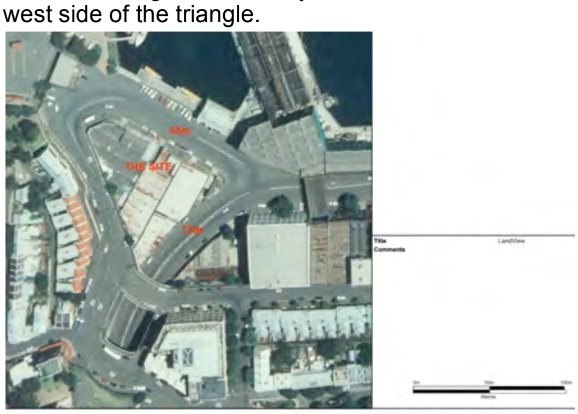
Appendix

Brief for a Harbourside Gallery (Architect Version)

During this design session you are asked to prepare a block model esquisse scheme for a proposed art/craft gallery on this site. The site and information below provide details about the location and use of the site. There are 30 minutes available for this investigation.
This project is to prepare a block model esquisse scheme for a proposed art/craft gallery on this site. You should assume that all existing buildings have been demolished before your scheme commences construction. There is no floor space ratio or height restriction applicable for this project so you may choose to liberate as much or as little of the site for open space as suits your scheme.

Site

The site is a triangular block as shown below. Site area is approximately 2800m2.North is to the top of the picture where the harbour and wharves are visible. There are roads on all 3 sides of the site at varying heights relative to the ground floor of the existing buildings. You will see that one road crosses the other on an overhead bridge immediately to the south of the site, then ramps down along the west side of the triangle.



Accommodation Required	Area (m2)
Galleries and performance space	
Permanent exhibition suite	1500
Sculpture garden	600
Temporary exhibition suite 1	750
Temporary exhibition suite 2	150
Forum	750
Front of house public areas	
Entrance/foyer	xx
Reception	30
Cloak store	20
Café (with after hours access)	200
Shop	100
Shop storage	30
Ticket office	25
Members lounge	60
Back of house support areas	
Staff entry	xx
Loading dock	to suit truck 12.5 x 2.5 x 4.5
high	
Unloading	60 (min. opening 4.5 x 4.5)
Bay for forklift	10
Exhibition receiving and preparation	200
Restoration and repair workshop	200
General storage	50
Chair storage	30
Cleaning	10
Board room	60
Director	30
Assistant directors and manager	20 x 3
Curators	15 x 12
Accounts	10 x 4
Security	20
Technical support	30 x 2
Volunteers	20
Toilets and showers	xx

Notes

No car parking required
Maximize energy efficiency and passive solar principles
All galleries to be naturally lit
Forum minimum span 25 metres
Separate delivery for café and shop

The participants were also given a collage of the photos showing the site and the surrounding area (Figure A1)

Figure A 1 collage of photos

JS Gero and U Lindemann (eds), *Human Behaviour in Design'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 27-46

ON SOCIAL DYNAMICS FACTORS IN MULTI-STAKEHOLDER DECISION MAKING IN THE EARLY STAGE OF PRODUCT DEVELOPMENT

PING GE AND PING-HUNG HSIEH
Oregon State University, USA

Abstract. Social dynamics exists wherever more than one human being is involved in making a decision. In particular, when design decisions are influenced by a group of stakeholders who may have different interests and background, the decision making process is affected by both technical and social dynamic factors, and the design results are consequently a product of the joint influence. Though important, the role of human and social dynamics factors in design process is not well understood. Furthermore, means are lacking for measuring the effect of these factors on the design results. In this work, our study is focused on design problems concerning understanding customer needs at the early stage, in particular, *identifying quality requirements and their relative importance by a group of stakeholders*. We introduced one among many human and social dynamics factors, i.e., *trust*, and investigated its role in the early stage design decision making of product development. Derived from the definition and principle forms of general trust, the trust concept used in the prioritizing problem we use in the study is specified. The existing measurement scales used in social science are modified for measuring the trust in terms of trustworthiness. The possible scenarios of integrating the trustworthiness from this work in group-prioritizing customer requirements are discussed to show the potential of developing a systematic design methodology with social dynamics consideration in the early stage of product development.

1. INTRODUCTION

It is not uncommon to observe situations where decisions involve multi-stakeholders in product development. Usually, given a certain design problem, a group of stakeholders with different backgrounds and interests are brought together and try to find solution(s) that are agreeable to each of them, as shown in Figure 1. Because of different background and interests, every single stakeholder may hold his/her unique understanding and interpretation of the same things, and negotiations are often needed to find a common ground among the stakeholders. On the other hand, it is possible that the importance of each stakeholder can differ from each other, and therefore, their opinion may weigh differently in the final results. However, even when one or several authoritative figure(s) (such as a project leader or management) has to make a decision, he/she consciously or unconsciously takes into account opinions or concerns from those crucial parties that may affect the next step implementation process of their decisions. Existing efforts have produced a wealth of methods/tools to support teamwork and group decision making. But the research questions still remain: 1) What are the underlying factors that bring together multi-stakeholders' diverse perceptions? and 2) How do these factors contribute to the final consensus?

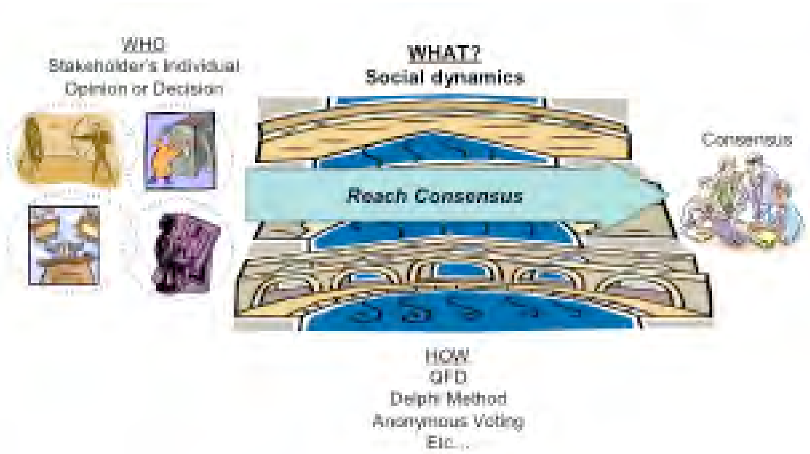


Figure 1. Reaching consensus in a multi-stakeholder environment

Product quality plays an important role in successful product development and this fact has forced product development companies to include understanding customer needs as an important part in their practice. Kano's model indicates that the better their needs and desires are understood and fulfilled, the more the targeted customers are satisfied, and therefore, the more desirable quality the product delivers (Ullman 2003). As shown in Figure 2, there exist three levels of product quality attributes: basic, performance, and excitement. In most product development, performance related product quality attributes take a majority part of the overall quality requirements. For instance, based on a survey published in *Time* (Nov 13, 1989), the major categories of performance requirements associated with product quality include *Reliability*, *Maintainability*, *Durability*, *Looks, Design*, the use of latest *Technology* and the number of *Features*. For a certain product development, the identification and specification of those essential performance-level, and maybe also several excitement-level, product quality attributes are among those early stage decisions to be made as part of design problem appraisal.

Figure 2. Kano's model of customer satisfaction

Customer survey is commonly used to obtain raw customer data and a process then takes place to extract information on what is a good quality product. The goal of the process is to decide on a list of Requirements that capture and represent the essential product quality attributes. As suggested by Hauser et al. (1988) in House of Quality, the extraction process of these Requirements that capture and represent the essential product quality attributes involves both the voice of customers and the inputs from product development stakeholders. The development stakeholders are consist of representatives from marketing, sales, service divisions, and engineering stakeholders from design, manufacturing, and supply chain. As a result, the decisions on these Requirements reflect an agreement on the understanding and interpretation of the product quality attributes by all the stakeholders including customers.

Based on their investigations of Sweden industrial practice, Engelbrektsson et al. discovered that customers (end users) often have difficulties in verbalizing all requirements for future product (Engelbrektsson 2004; Karlsson 1996). In addition, requirements have been found to change during the development of the product or system as the customer and the product development team gain experience and insight (Hsia 1993). There are also evidences that the traditional marketing methods such as conjoint analysis may be insufficient in providing the desired information, in particular to supply the detailed information required by engineers.

In order to avoid confusion with the existing notion of Customer Requirements (CR), we propose to use Quality Requirements (QRs) to represent the agreement among the multi-stakeholders on the essential product quality attributes because they tend to reflect the true nature of the extraction process. The product quality attributes may mean different things to the different stakeholders: to customers (end users, etc.), they should represent what the customers wants and needs to facilitate their daily life and work; to engineering stakeholders, they may have more emphasis on advanced technology and better design; to marketing stakeholders, they usually mean better price, packaging, brand, neat advertising campaign, etc. Besides the corporate strategy and practical constraints (such as technology readiness, budget, personnel and time), the engineering stakeholders can bring in some performance related product quality attributes that may greatly affect the customers' satisfaction about the product (particularly when using the product) though they may not be explicit in the customer survey and/or marketing analysis. There may exist negotiations and compromises between the QRs directly derived from raw customer data and the inputs from engineering stakeholders. In case where there might be a lack of sufficient resources to gather the hard evidence from the customers as desired, the involvement and influence of the engineering stakeholders in the QR extraction process maybe even more. Besides a development company's economic objectives, more and more companies are investing on organizations and activities that satisfy regulations concerning compelling societal concerns, such as environmental sustainability. These concerns may not be directly required by the consumers, but they must be considered and complied by the product developers in order to get the regulators' permission for their products' market release. The attributes addressing these concerns are incorporated into the product quality requirements based on the development stakeholders' understanding and eventually reflected in the final QR related decisions, as show in Figure 3. Furthermore, individual stakeholder preference can also lead to different levels of benevolence toward the product and team, which might influence the group decisions.

Demand modeling approaches have been identified to be useful in predicting customers' demand for a product and also play an important role in assessing the profit or revue that a product can generate. Li et al. proposed the Comparing Multi-attribute Utility Values Approach (Besharati 2002), followed by a Customer Expected Utility Approach (Li 2000) by Besharati et al. Wassenaar et al. proposed an Integrated Latent Variable Choice Modeling for an enhanced demand model by combining a latent variable model and a multinomial logit choice model (Wassenaar 2003; Wassenaar 2004).

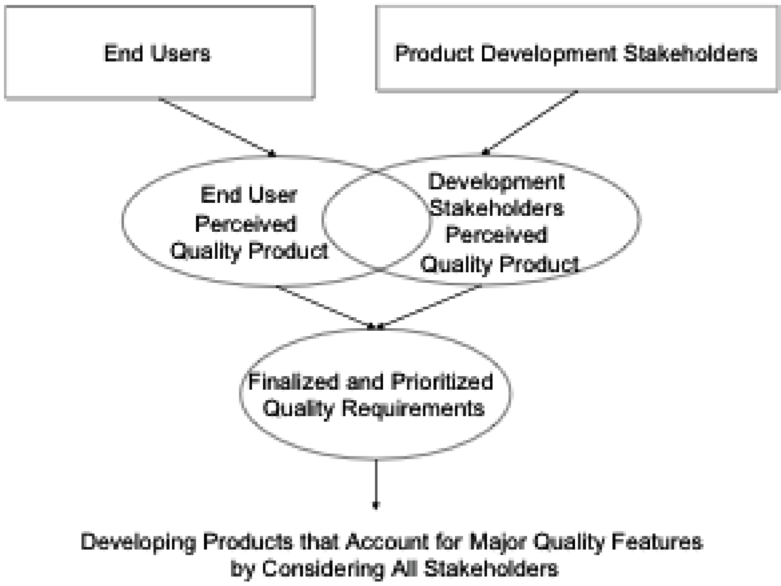


Figure 3. Understanding customer needs by multi-stakeholders

By using a latent variable construct, this approach enables to establish an explicit relationship between the marketing-oriented product attributes (such as those used in conjoint measurement, more reflect the customers' perceived product attribute levels) and engineering oriented product attributes (such as those related to engine performance, more reflect true engineering performance and requirements). Compared to the existing conjoint measurement approaches, this approach seems to have more consideration on incorporating the engineering development stakeholders' inputs in understanding customer needs. However, it is still not clear how to capture and assess the contributions of important social dynamics factors in understanding customers' needs by multi-stakeholder, such as different knowledge/experiences, communication skills, interpersonal trust, personality, politics, etc. The investigation of the existing approaches on understanding customer needs shows that, though the social dynamic factors and their role in understanding customer needs for product development are important, they are not well understood. We argue that, if we can somehow identify these social dynamic factors and understand their internal mechanism in a multi-stakeholder group design decision process, we may be able to understand the negotiation process among the multi-stakeholders much better and fundamentally improve the effectiveness and efficiency of understanding customer needs.

The involvement of the multiple product development stakeholders (as multi-stakeholders from now on) has bestowed the QR extraction process with both technical and social dynamic characteristics. The multi-stakeholders are valued by their individual knowledge and specialized expertise. However, in the mean time, this also creates the barriers that could prevent them from smooth communication solely based on the technical basis and terms. As a result from different interest and background, each stakeholder may have his/her understanding and interpretation of the customer data, company's marketing strategy and societal trend (such as environmental regulations). When negotiating for a design decision, each stakeholder may bring an individual "voice" to the table based on their understanding of or perceived what are the essential quality attributes. The negotiation process can be influenced by a set of social dynamics factors, such as knowledge/experiences, communication skills, interpersonal trust, personality, politics, etc. Along negotiations the "voices" of different stakeholders are heard, understood, and interpreted by others, and combined, integrated, evolved to a final group agreement. The final QRs decision represents a group understanding and interpretation of what are the essential quality attributes with the influences of the social dynamic factors among the group members though they may not be visualized externally. Assuming all stakeholders are equally involved and authorized, the negotiation among them about a design decision would be on a democratic basis. If not equally powered, their negotiation mechanism can be less democratic and easily manipulated. If the group is dominated by some extroverts, the voice of the non-extroverts might be poorly represented, or even worse, not be heard at all. We can enumerate many other such examples when a negotiation process is hindered by some implicit human and social factors and the teams have to struggle laboriously in the dark.

By looking into the existing work on social network, it has inspired us to conjecture that the social dynamic factors in the negotiation process might be reflected in parts of the social network among the stakeholders (such as an advisory network, to whom are you going to ask for advice, etc.) (Krachhardt 1993; Katz 2003). According to the existing social network literature, interpersonal social effects are authoritatively involved in building a social network based on social, informal interactions. Among the many studied social factors, the authors recognized the significance of trust in strategic decisions, such as prioritizing the customer requirements and other important tasks in engineering design (Korsgaard 1995; Eisenhardt 1989). During our investigation, the idea has emerged that trust in others' individual opinion or decision on a certain design problem may be an underpinning factor affecting the negotiation process among multi-stakeholders when trying to reach consensus at the early design stage. Existing literatures in marketing and management have investigated trust definition, trust measurement, antecedents of trustworthiness, and behavior implications of different types of interpersonal trust (McAllister 1995). For example, possible antecedents that affect the trustworthiness among group members in a group decision setting include an individual's knowledge/capability, integrity, and benevolence of peers, etc. On the other hand, environmental factors, such as targeted customer market, corporate culture, and corporate infrastructure, can also influence the trust network among multi-stakeholders. It is necessary and possible to study trust network and its role in engineering decision making, so that knowledge can be acquired on the characteristics of trust network in multi-disciplinary product development teams, and methods/tools can be developed to assess and incorporate their impact into group decision making.

In the proposed work, we focus on understanding different forms of trust network and their possible impact on design decisions concerning understanding customer needs. This work investigates the role of trust in a cross-functional multi-stakeholder group decision making problem, i.e., prioritizing customer requirements at the early design stage. Two principle forms of trust network are studied and hypotheses are developed. The existing measurement scales used in social science are modified for measuring the interpersonal trust in terms of trustworthiness, and a preliminary questionnaire is constructed. With a proper measurement mechanism, a trust network among stakeholders can be concluded, and the trust's effect on the group QR decisions be accounted in terms of trustworthiness. The trust measurement may then be used to weight each stakeholders' contribution towards the final decision. Given the limited length of the paper, the integration of the proposed trust measurement in the negotiation process to finalize the QR relative importance is only discussed briefly in this paper, and will be the focus of another work.

2. Background Review

Integration of human and social dynamics effects into the early stage decision of collaboration design require the consideration of both technical and social aspect in solutions. In this section, we review existing work in three most relevant areas: *quality decisions at the early design stage*, *modeling customer demand*, and *social dynamics in group decision making*.

2.1. UNDERSTANDING QUALITY ATTRIBUTES

A useful way to build quality into products is Quality Function Deployment (QFD). QFD supports the fundamental processes at an early stage of product development with strong integration of the customer's voice (VOC) (Akao 1990; Cohen 1995). QFD helps to develop specifications or goals for the product, how the competition meets the goal, what is important to the customer and numerical targets to work towards (Ullman 2003). QFD provides a method to convert the customer wants and needs into engineering specifications. Given constraints on resources (e.g. time, money and personnel) it is not only necessary to know what the customer wants, but how relative important it is for him. An initial distinction between the customer requirements (CR) are provided by the categories wants (i.e. like-to-have), needs (must-have) and desires (i.e. wish-to-have) (Lai 1998). The customer himself might not be capable to rank the importance of the customer requirements, because for him everything might be as important and yet the CR have to be traded off. QFD proposes the use of the planning matrix, where as the costumer importance, the satisfaction of the customer, the competitive satisfaction performance, the goal, improvement ratio, sales importance, are used to find a normalized weight (Cohen 1995) of each CR. In extensive customer inquiries the weights of each CR might be found. Ullman describes several techniques to assess either ordinal or relative importance with the customer together (Ullman 2003). The key requirements for extensive customer inquiries are a) the targeted customer has to be clearly determined and b) there have to be sufficient resources to gather the data. Often in engineering projects neither of these requirements are fulfilled. An alternative to extensive customer inquiries is that the cross-functional stakeholder group decides on the importance of each CR on their own (Cohen 1995). It is supposed that within the stakeholder group the voice of customer is represented adequately. Using the alternative brings uncertainty to the obtained CR, there will be a gap between what the customer will perceive as product quality and what the group of stakeholders perceives the customer will perceive. To make matter more uncertain strategic aspects of the organization and societal concerns (e.g. environment) have to be integrated in the determination of relative importance as well. According to Lai et al. (1998) only an effective group decision making process may apply to achieve correct CR and their ranking in such a case. Lai et al. are proposing a technique to integrate communication of team members and preference for CR of each individual team member. Their proposed technique allows individuals to stick to their own set of criteria despite the group decision making. Lai et al. assume that preference of every stakeholder is equally important and neither consider power or expertise as distinctive factors for a certain stakeholder's contribution.

2.2. MODELING CUSTOMER DEMAND

Conjoint analysis or conjoint measurement (Green 1975; 1978) assumes that a set of product attributes can be identified to affect customers' buying preference. Typical product attributes here include brand name, service option, price, appearance, description used to advertise the products, psychological images, convenience of use, etc. The value ranges (numerical or nominal) of these attributes are also known. Customer evaluation responses on their preference to the representative combinations of the above product attributes' values are then collected for conjoint analysis. The analysis result includes utility scales for all the product attributes. Then the composite utility of a single combination of the product attributes' values can be obtained, currently by using an additive model without considering interactions among the attributes. By comparing the utility of different combinations of the product attributes' values, knowledge can be obtained on what are customers' preferred combinations for a product. When applying to understanding customers' needs for product development, its limitation includes: 1) the nature of a product or service may not be well captured by a set of product attributes mostly for marketing purpose; 2) unable to combine the preference of customers with development stakeholders' inputs given their constraints with budget, corporate strategy, and social concerns.

Demand modeling approaches has been identified to be useful in predicting a customers' demand for a product and plays an important role in assessing the profit or revue that a product can generate. Li *et al*. proposed the Comparing Multi-attribute Utility Values Approach (Besharati 2002) to estimates customers' demand by looking at multi-attribute utility values based on conjoint analysis. In Customer Expected Utility Approach (Li 2000) by Besharati *et al.*, the relationship between the customer purchases decision and certain thresholds of product attributes is investigated. Wassenaar *et al.* proposed an Integrated Latent Variable Choice Modeling for an enhanced demand model by combining a latent variable model and a multinomial logit choice model (Wassenaar 2003; Wassenaar 2004). The proposed approach takes into account of "psychological factors" that affect customers' choices, such as the discrepancies between the actual product attribute level and the perceived attribute level by customers. It appraises the contribution of various product attributes to the customers' perceived product performance, and their affect on customer choices. As a result of using a latent variable structure, this approach enables to establish an explicit relationship between the marketing-oriented product attributes (such as those used in conjoint measurement) and engineering oriented product attributes (such as those related to engine performance). Compared to conjoint measurement approaches, this approach seems to have more consideration on incorporating the development stakeholders' inputs in understanding customer needs. Michalek, *et al.* developed a coordination framework to integrate marketing models of users and producer preferences with engineering design models of product performance (Michalek 2004). What is lacking in the existing approaches is that they are unable to reflect the contributions of important social dynamics factors in multi-stakeholder decision making process, such as knowledge/experiences, communication skills, trust, personality, politics, etc.

2.3. SOCIAL DYNAMICS IN GROUP DECISION MAKING

A wide range of social network analysis (SNA) and social capital has been reviewed. A key to understand interpersonal relations across an organization is to analyze the underlying social networks. Power (Cross 2002), affect, production, politics, culture (Waldstroem 2001), trust, open communication, and joint problem solving arrangements (Noorderhaven 2002), are only a few factors to mention reflecting relationships between actors. Social network analysis proposes among others, a three-step approach to circumscribe dependencies between workers. It is to differentiate between an advisory, a trust and communication network which might be found in teams, as well as in whole organizations. The whole point of these network analyses is to reveal the informal relations between the persons in the organization. The literature points out the significance of the connections and the impact of changes to those networks (Krackhardt 1993). In strategic decision making situations, trust in the final decider is critical for its outcome (Korsgaard 1995; Eisenhardt 1989). McAllister (1995) documented trust as determinant for that interdependent actors work effectively together. Trust is a key value for team work and its performance. The role of trust stands out, because it affects many other interpersonal issues. Trust directly influences the quality of team work and its performance. It influences the way we listen to, share with, respect and rely on each other. A lack of trust affects communication, cooperation and decision making (Mayer 1995; Mayer 1999; Kanawattanachai 2002) of the team. Trust is like the mother for social interactions. As a result, in the proposed work, we focus on introducing Trust and Trustworthiness.

3. Trust And Trustworthiness

Researchers in the organizational sciences have argued that working effectively among interdependent constituencies is the only possible way that leads to efficiency within complex systems of coordinated action. Several studies (Pennings 1987; Seabright 1992) have shown that trust among stakeholders is considered to be a determining factor for such efficiency. Hence, developing and maintaining trust relationships is especially important for stakeholders in a design team. In this section, we will review general trust, define interpersonal trust, and discuss its measurement.

3.1. PRINCIPAL FORMS OF INTERPERSONAL TRUST

Following McAllister (1995), interpersonal trust can be defined as "the extent to which a person is confident in, and willing to act on the basis of, the words, actions, and decisions of another." Interpersonal trust can be measured in two dimensions: the extent of cognition-based trust and the extent of affect-based trust, both of which are supported by empirical evidence from the social-psychological literature (Lewis 1985; Johnson-George 1982; Rempel 1985; Pennings 1987; McAllister 1995). Cognition-based trust exists because "we choose whom we will trust in which respects and under what circumstances, and we base the choice on what we take to be 'good reasons,' constituting evidence of trustworthiness" (Lweis 1985); whereas, affective foundations for trust consist of the emotional bonds between individuals. Although empirical findings reveal that some level of cognition-based trust is necessary for affect-based trust to develop (McAllister 1995), each form of trust may acts in a unique manner and has a different impact on the outcome, e.g., the final ranking of QR's in this study. *Ceteris paribus*, a team of product designers who were put together purely based on the member's technical skills just for the project on hand may perform differently from a team whose members have known and liked each other. Hence, when discussing the impact of interpersonal trust on social network, these two forms of trust must be measured and investigated.

3.2 MEASURES OF TRUST

Drawing on previous work on measures of interpersonal trust (Cook 1980; Johnson-George 1982; Rempel, Holmes 1985; Rotter 1971), McAllister (1995) developed a measure to assess affect- and cognition-based trust levels. The measure consists of 11 items, 6 of which are for assessing levels of cognition-based trust, and 5 for affect-based trust. Table 1 gives the wording for the trust measure. A 7-point Likert ratings scale, 1 being strongly disagree and 7 being strongly agree, is used to measure respondents' agreement with various statements about a specific peer at work. Reliability estimates (Cronbach's 's) for the cognition- and affect-based trust measures are .91 and .89, respectively, suggesting that the items are all measuring the same dimension of trust. Both exploratory findings and confirmatory analysis in McAllister (1995) shows that the two-factor representation of affect- and cognition-based trust fits the data well, and the two factors are reliable.

TABLE 1. Measures of interpersonal trust (McAllister 1995)

Items	
Affect-based trust	
A 1	We have a sharing relationship. We can both freely share our ideas, feelings, and hopes.
A 2	I can talk freely to this individual about difficulties I am having at work and know that (s)he will want to listen.
A 3	We would both feel a sense of loss if one of us was transferred and we could no longer work together.
A 4	If I shared my problems with this person, I know (s).90he would respond constr.86uctively and caringly.
A 5	I would have to say that we have both made considerable emotional investments in our working relationship.
Cognition-based trust	
C1	This person approaches his/her job with professionalism and dedication.
C2	Given this person's track record, I see no reason to doubt his/her competence and preparation for the job.
C3	I can rely on this person not to make my job more difficult by careless work.
C4	Most people, even those who aren't close friends of this individual, trust and respect him/her as a coworker.
C5	Other work associates of mine who must interact with this individual consider him/her to be trustworthy.
C6	If people knew more about this individual and his/her background, they would be more concerned and monitor his/her performance more closely.[r]

[r]: Item was reverse coded.

3.3. TRUST AND TRUSTWORTHINESS SCORES

To obtain trust and trustworthiness scores, each stakeholder of the design team will need to fill out a survey questionnaire (Table 1) with respect to each of his/her teammates (McAllister 1995). A seven-level Likert scale is used for the answers (Likert 1932). The average scores from items A1 – 5, and from C1 – 5 are calculated as the respondent's affect-based and cognition-based trust scores on his/her teammate. Denote and as the i^{th} respondent's affect- and cognition-based trust scores on the j^{th} member of the design team. Finally, the average of all items in Table 1 is defined as the total trust score. In the following section, we would like to offer a theoretical discussion on how difference in the composition of total trust may affect the decision making process.

4. Hypothesis On Trust Network In Engineering Design

A team of experts can be assembled based on the expertise required for the task on hand, and thus creating a cognition-based trust network. In addition, emotional congruence among experts can also be considered in team composition and thus creating an affect-based trust network with both technical competence as well as affection. How does the extent of cognition- and affect-based trust influence team's performance and resulting product innovation? How does the time factor change group decisions when members of a cognition-based team invest time and emotion and grow more affective toward each other? In this section, we will theorize the effect of cognition- and affect-based trust networks on group decisions, specifically on team's overall performance and product innovation, and lay out a foundation for future empirical study.

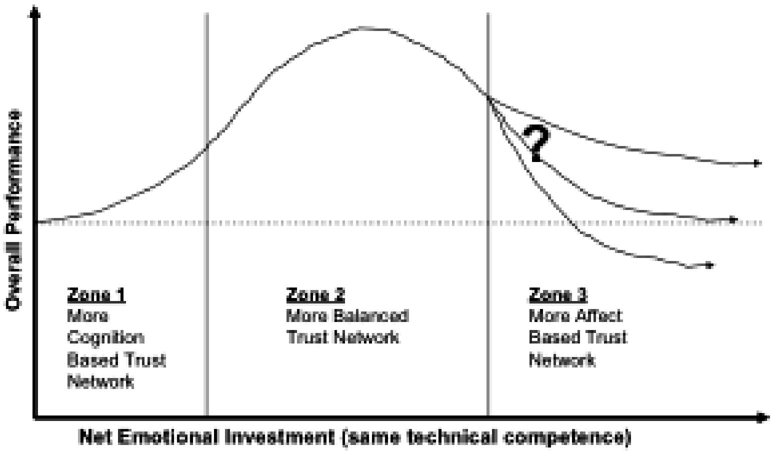
Figure 4 summarizes our hypotheses of the effect of emotional investment on overall performance and the extent of innovation. According to the PDMA Handbook of New Product Development (2004), "innovation" is defined as:

- new idea, method, or device;
- the act of creating a new product or process;
- the act includes invention as well as the work required to bring an idea or concept into final form.

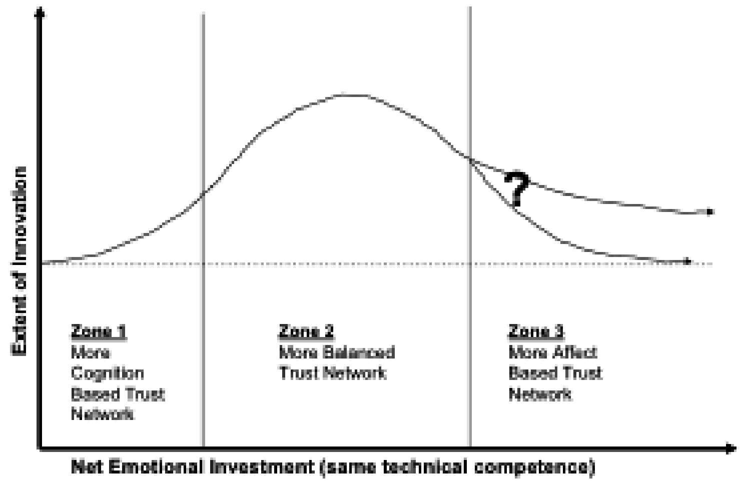
Technical competence among all teams is assumed to be equal. Teams with no or little affection among team members fall in zone 1 whereas teams with great affection fall in zone 3. As shown in III, interpersonal trust among team members can be measured based on the answers of the questionnaire in Table 1 as: $T^{A}_{i,j}$, i.e., affect-based score, and $T^{C}_{i,j}$, , i.e., cognition-based score. The average affect-based score of among all the team members can be calculated and denoted as T^A , and in the mean time, the average cognition-based score as T^C .

For a network (team) with solely cognition-based trust and with no or little affection among team members, it is considered to be in zone 1, where $T^A << T^C$. For a network with great affection among team members (i.e, an affect-based trust network), it is considered to be in zone 3, where $T^A >> T^C$. For a balanced network (i.e., the affection among team members "fits" just about right), it falls in zone 2. When comparing networks from two different zones, we assume they have same technical competence; the only difference is the amount of net emotional investment among team members.

For a network with solely cognition-based trust (zone 1), team member relies on each other's expertise and thus alternatives to a decision problem submitted for group's consideration come more directly from members' own expertise. That is, team members would not feel comfortable presenting wild ideas that often fall outside of their own expertise. Therefore, we hypothesize that the extent of product innovation from a mainly cognition-based trust network will be incremental and the performance of the network will simply "meet the expectations". In other words, the network's overall performance is the accumulation of all members' expertise.



(a)



(b)

Figure 4. The effect of net emotional investment on: (a) overall performance, and (b) extent of innovation

For a balanced network (zone 2), a combination of mutual respect on each others' expertise and pleasant atmosphere allows team members comfortably to exchange ideas that may not be within one's own expertise. Such informal communication promotes innovation, and we hypothesize that radical innovation of a product often comes from a network of members who are both technically competent and emotionally congruence. Since members enjoy working together, we also expect high performance.

The above hypotheses in Zone 1 and 2 are consistent with most of our observations of college student design teams and industrial multi-functional product development teams. Our hypotheses of a balanced network outperforming and being more innovative than a dominating (either cognition- or affect-based trust) network are also in line with the congruence theory in the marketing and management literature (Fry 1987; Venkatraman 1989). Currently, it is inconclusive how the characteristics of the trust network would affect team performance and product innovation in Zone 3. So here, we would like to lay out several questions we have summarized from our investigation as a starting point for understand pattern(s) behind them if any.

1) When affect-based trust becomes dominant over cognition-based trust (zone 3), members may overlook infeasible alternatives to avoid confrontation. As a result, the overall performance of the team may suffer. Is it true that the overall performance of an entirely affect-based trust network (far right in zone 3) will be better than or equal to that of a purely cognition-based trust network (far left in zone 1)? Could too much emotional investment lead to limited vision and strategically disastrous decisions so that the overall performance is worse? (as shown in Figure 4 a) with a question mark)
2) Because of their close relationship, members in an entirely affect-based trust network team may even be able to anticipate each other's ideas, i.e., no more sparks. The "surprise" factor is diminished as members become more emotionally congruent, and radical innovation cannot be expected. So the trust network in a team has a dominating affect-based nature, its innovation may not be as high as when the trust network is more balanced. But how low the team innovation will get? Is it still higher than that of a team with a dominating cognition-based trust network? Or is it about the same? (as shown in Figure 4 b) with a question mark)
3) It seems to make sense that both peak overall performance and extent of innovation would appear in Zone 2. But, will the highest overall performance and highest extent of innovation (i.e., the peaks of the two curves in Figure 5) occur at the same location?

Additional theories are needed to complete our hypotheses on how the nature of trust network would affect team performance and product innovation. As a part of our future work plan, more theoretical development and case studies will be underway to validate these hypotheses.

Further investigation of the above hypotheses and questions has potential benefits for several areas of research and practical development. Based on our observation and investigation so far, it seems that certain customer groups are more easily tuned into or better relate to products with certain combination of product innovation, technical performance, appearance, and other factors. Understanding the effect of trust networks on team innovation potential and performance may provide guidance on product team composition in consideration of targeted customer market. It is not uncommon to hear unpleasant teamwork experience in both classrooms and industry. It is important to ask the question: how to ensure positive personal growth and motivate others in a teamwork environment? It would be interesting to see how individual behaves and evolves in different trust networks based on the knowledge acquired through this work.

5. Unifying Group Decision For Understanding Customer Needs

The measurement developed above may be integrated into the process of deciding the relative importance of quality attributes (QR) collaboratively by multi-stakeholders. As shown in Figure 5, the measurement method proposed in this paper can be used to construct a trustworthiness matrix ([(T^Ai,j, T^C*i,j*)], i, j = 1, …, m) to quantitatively represent the characteristics of the trust network among the stakeholders.

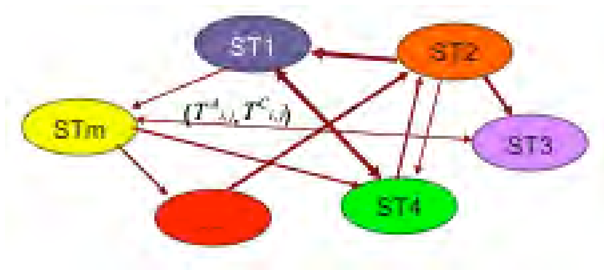


Figure 5. Trust network among multi-stakeholders

The trustworthiness matrix is used to weight all other stakeholders' opinion or decisions by each stakeholder. Trustworthiness toward another person upon his/her decision in ranking QR maybe used to weight the individual ranking list and therefore integrates individual sets of criteria/decisions to make a group decision. After each stakeholder has explained his/her set of criteria and his/her individual ranking, the priority lists would be aggregated using an integration methodology, as shown in Figure 6 (Meier and Ge 2004).

6. Conclusions And Future Work

Our work is motivated by the practical need of understanding social dynamics and their role in understanding customer needs by multiple stakeholders with diverse interest and background. Based on theoretical investigation, here we propose: 1) use trust network to help visualize the social dynamics, and 2) use trustworthiness measure to quantify their effect.

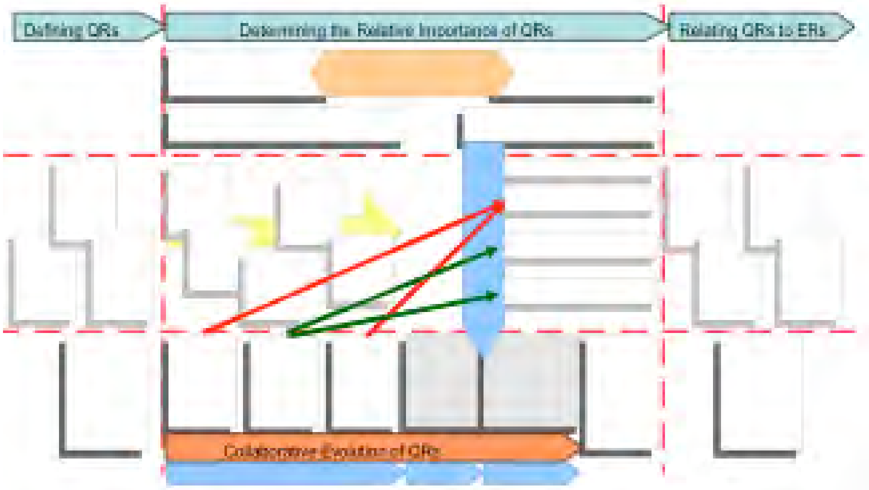


Figure 6. Integrating trust's effects among stakeholders for understanding customer needs (Meier and Ge 2004)

This work represents general ideas, hypothesis, and their possible implications in engineering design. The future efforts are in three areas:

(1) Testing the hypotheses in Section IV

Empirical study is required for the validity and reliability of the measurement instrument for trust network in group decision making proposed in this work. Two types of cases studies will be included: team-based student design projects, and industrial project. Statistical techniques will be adopted to analysis the results. Then necessary modifications will be made to have acceptable trust network characteristics as shown in Figure 4.

(2) Fundamental understanding of teamwork dynamics

The static and dynamic aspect of the trust network will be investigated, including the following research questions:

- Statics

  - Theoretical foundation: Trustworthiness can be affected by an individual's knowledge/capability, integrity, and benevolence of peers. On the other hand, environmental factors, such as targeted customer market, corporate culture, and corporate infrastructure, can also influence the trust network among multi-stakeholders. What are the factors that affect trustworthiness among the stakeholders at the early design stage (i.e. antecedents)?
  - Implication: how may the nature of a trust network be influenced through team composition based on the identified antecedents?

- Dynamics
  - Theoretical foundation: how does trust network in a certain team evolve along a time line, say from the early stage to a later stage?
  - Implication: how to encourage positive growth (emotionally and professionally) of team members through interpersonal trust?
- Leadership
  - How to encourage and motivate others and so the team can stay in Zone 2 in Figure 4?

(3) Integration mechanisms and the use in different types of design problems

An updating URN-scheme method has been developed (another paper) to integrate the trustworthiness into ranking problems, such as deciding the relative importance of quality attributes at the early design stage. Engineering design involves many scenarios where multi-stakeholders have to come to some kind of consensus. Social dynamics can exist at any stage along a design process, including *Determing QRs*, *Ranking QRs*, *Relating QRs to Engineering Requirements* (ERs), *Embodiment* (not shown in Fig. 6 due to space limitation), and *Detailing* (not shown in Fig. 6 due to space limitation), etc. It is important to identify and understand social dynamics factors and their influence on design decisions at each stage. The integration methodology can be further developed and adapted into other design stages. Further more, real world design problems should be used to demonstrate the use of these methods.

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DESIGN BEHAVIOUR MEASUREMENT BY QUANTIFYING LINKOGRAPHY IN PROTOCOL STUDIES OF DESIGNING

JEFF WT KAN AND JOHN S GERO
University of Sydney, Australia

Abstract. This paper proposes approaches to measure linkography in protocol studies of designing. It outlines the ideas behind using clustering and Shannon's entropy as measures of designing behaviour. Hypothetical cases are used to illustrate the methods. The paper concludes that these methods may form the basis of a new tool to assess designer behaviour in terms of chunking of design ideas and the opportunities for idea development.

1. Motivation

The motivation of this exploration was to find a quantitative method to compare the team designing behaviour. Increasingly designers work across geographically distant locations, groupware and collaborative software have been developed to support temporally and geographically dispersed work teams. However, despite these developments, face-to-face interaction remains one of the most important elements in developing ideas (Salter and Gann 2002). Bly and Minneman (1990) together with other studies (Gabriel 2000; Vera et al. 1998) suggested that with the introduction of technology, designers will adapt their activities accordingly. These studies on team designing were mostly done at a macroscopic level and were not able to differentiate microscopic design behaviour. In order to develop tools that support the process of distant collaboration, a closer look at how design teams design is required as we currently have insufficient knowledge about these activities.

2. Linkography and its Use

Linkography is a technique used in protocol analysis to study designer's cognitive activities. It was first introduced to protocol analysis by Goldschmidt (1990) to assess design productivity of an individual designer. In this technique the design process is decomposed by parsing the recorded design protocol into small units of design moves. Goldschmidt defines a design move as: "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt 1995), or "an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed" . A Linkograph is then constructed by discerning the relationships among the moves to form links. It can be seen as a graphical representation of a design session that traces the associations of every design move. Figure 1 is an example of linkograph from Goldschmidt (1992). The design process can then be looked at in terms of the patterns of the linkograph which displays the structural design reasoning. Three distinct patterns had been identified: chunk, a group of moves that are almost exclusively links among themselves; web, a large number of links among a relatively small amount of moves; and sawtooth track, a special sequence of linked moves. Goldschmidt also identified two types of links: backlinks and forelinks. Backlinks are links of moves that connect to previous moves and forelinks are links of moves that connect to subsequent moves. Conceptually they are very different: "backlinks record the path that led to a move's generation, while forelinks bear evidence to its contribution to the production of further moves" (Goldschmidt 1995).

Link index and critical moves were devised as indicators of design productivity. Link index is the ratio between the number of links and the number of moves, and critical moves are design moves that are rich in links, they can be forelinks, backlinks, or both. In her exposition, design productivity is positively related to the link index and critical moves, that is, a higher value of link index and critical moves indicates a more productive design process. The rational was productive designers think through a group of interrelated issues before move on to another group of potentially interconnected issues, hence higher interconnectivity among move and higher number of critical moves. With this as a benchmark, Goldschmidt (1995) extended the use of linkography to compare individual design processes with team design processes.

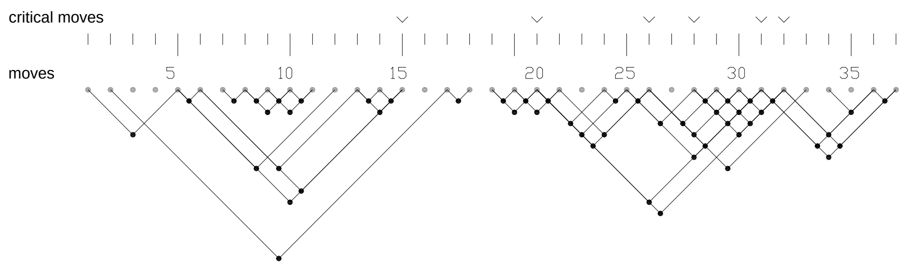


Figure 1. Linkograph from Goldschmidt (1992) with the position of critical moves indicated by "v".

2.1 DESIGN MOVES, IDEA GENERATION BEHAVIOUR, AND THE PROGRESS OF DESIGNI*N*G

What is an idea? How to define the boundary of an idea? Idea generation and creativity shared some common characteristics. Finke et al (1992) considered creativity not as a single unitary process but a product of many types of mental processes collectively setting the stage for creative insight and discovery. We consider design moves as the externalization of the mental processes. The collective moves can be seen as the clustering of interaction among ideas which can be seen as a behaviour characteristic of a design session. The progress of a design session can be observed through the analysis of the linkography. Linkography has been used for investigating the structure of design idea generation processes and for comparing design productivity (Goldschmidt 1990; Goldschmidt 1992; Goldschmidt 1995). Goldschmidt uses linkographs as a bridge between the design process and the design product so as to assess productivity.

Van der Lugt (2003) extended Goldschmidt's linkography to trace the design idea generation process and empirically verified the correlation between creative qualities of ideas and the well-integratedness of those ideas. He extended the linkography with link types: supplementary, modification, or tangential links corresponding to small alterations, same direction, or different directions association respectively. He found that a well-integrated creative process has a large network of links, a low level of self-links, and a balance of link types. Dorst (2004) traced linking behaviour of designers with regard to design problems and design solutions to reveal the reflective practice of designers.

With an understanding of the construction of a linkograph, one is able to comment on the design behaviour without studying the design protocol. Goldschmidt (1992) suggested that the linkograph pattern of productive designers will be different from that of less productive designers. Productive designers will elicit moves that have a high potential for connectivity to other moves, while less productive designers will have more random trails with moves that did not had a high potential for contribution to the design concept. Besides, designers start the design process with exploring different options and then select one to develop which will produce a very different linkograph compared to designers using a holistic approach without exploring different options. However, the interpretations of the linkograph lack objectivity.

3. Statistical Description of Linkography

If we take away all the linking lines in the linkograph in Figure 1 and only consider the linked nodes but not the moves, we will get nodes in a two dimension space, Figure 2. Treating each node as a point in the X-Y plane we can statistically describe a linkograph in terms of the total number of nodes, the mean values of X and Y – that is the centroid, and the deviations in X and Y axes.

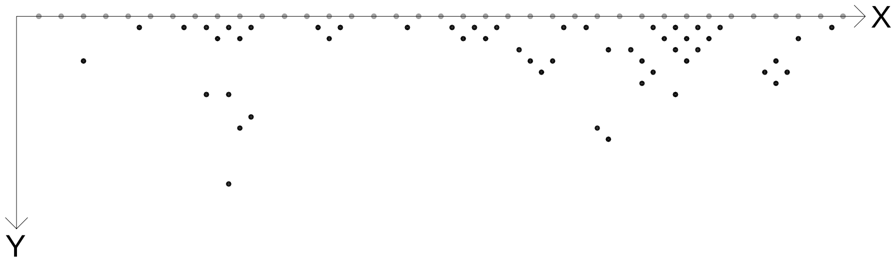


Figure 2. Reducing the graphical links to nodes in a 2 D space

The total number of linked nodes indicates the level of saturation of a linkograph. Normalizing this number against the number of moves will be the link index as described by Goldschmidt (1995). Table 1 and Figure 3 show the statistic scatter plot of the reduced linkograph.

TABLE 1. Descriptive statistic of the example linkograph

	N	Minimum	Maximum	Mean	Std. Deviation
X	52	3.00	36.50	22.01	9.41
Y	52	7.50	0.50	1.76	1.56

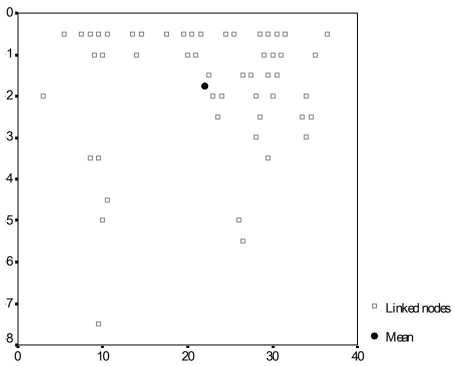


Figure 3. Scatter plot of the example linkograph with the mean value.

A higher mean value of X implies that more linked nodes appear at the end of a session and a lower value suggests that more linked nodes are present in the beginning of the session. A higher mean value of Y indicates longer linking lengths. However, the mean values do not include the dispersion of the distribution, therefore, we need to measure the standard deviations which suggest how concentrated the nodes are clustering around the means. The lower the value the closer those nodes are toward the mean. Tables 2 and 3 relate the appearance of linkographs, with the same number of nodes, to the statistical values.

TABLE 2. The shape of linkograph, with the same number of nodes, in relation to mean and standard deviation of X. A higher value of X-mean signifies there are more activities at the end of the session. [needs graphics inserted]

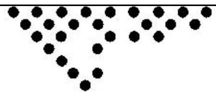
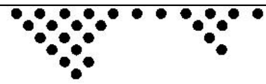
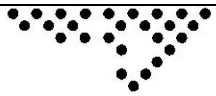
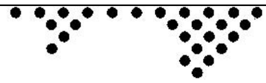
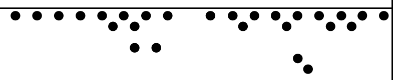
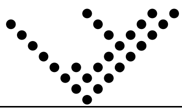
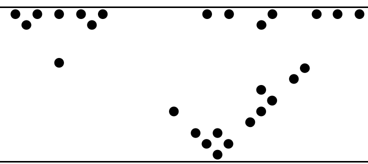
X (Moves) Axis	Small standard deviation (σ)	Large standard deviation (σ)
Small mean		
Large mean		

TABLE 3. The shape of linkograph, with the same number of nodes, in relation to mean and standard deviation of Y. A lower value of Y-mean indicates shorter linking distance.

Y (Links) Axis	Small standard deviation (σ)	Large standard deviation (σ)
Small mean		
Large mean		

3.1 CLUSTER ANALYSIS OF LINKOGRAPHY

As we can see in Tables 2 and 3 the linked nodes in a linkography may form clusters. These clusters resemble the chunks of ideas that are interlinked. We examine this with the example linkograph from Goldschmidt. There are two obvious chunks in this linkograph, the first chunk is from move 1 to move 18 and the second chunk from move 19 to 37.

TwoStep Cluster

SPSS TwoStep Cluster algorithm (SPSS 2002) is used in this study, this algorithm can handle both continuous and categorical variables. In the first step of this procedure, the records are pre-clustered into many small sub-clusters according to the selected criteria. Then, the algorithm clusters the sub-clusters created in the pre-cluster step into the desired number of clusters. If the desired number of clusters is unknown, it automatically finds the appropriate number of clusters according to the criteria. In this study the X (Moves) and Y (Links) variables were treated as continuous and Euclidean distance was used. Akaike's information criterion was used for clustering, and we did not assign the desired number of clusters. Figure 4 is the result, the TwoStep Cluster algorithm is able to discern the two chunks. Table 4 shows the cluster distribution and Table 5 shows the cluster profile.

TABLE 4. Cluster distribution of the example linkograph

		N	% of Combined	% of Total
Cluster	1	17	32.7%	32.7%
	2	35	67.3%	67.3%
	Combined	52	100.0%	100.0%
Total		52		100.0%

TABLE 5. Cluster profile of the example linkograph

Centroids		X		Y	
		Mean	Std. Deviation	Mean	Std. Deviation
Cluster	1	10.06	3.42	1.94	2.11
	2	27.81	4.59	1.67	1.24
	Combined	22.01	9.41	1.76	1.56

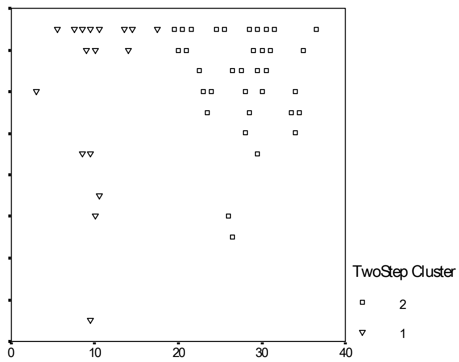


Figure 4. Scatter plot of the two clusters generated by the SPSS TwoStep Cluster algorithm.

4. Using Entropy to Measure Linkography

4.1 ENTROPY

In Shannon's (1948) information theory, the amount of information carried by a message or symbol is based on the probability of its outcome. If there is only one possible outcome, then there is no additional information because the outcome is known. Information can then be defined related to the surprise it produces or the decrease in uncertainty. Given that event E1 has a lower probability than event E2, I should be more surprised if E1 had occurred, hence I get more information. The entropy H, the average information per symbol in a set of symbols with *a priori* probabilities, is

$$H = p1*h(p1) + p2*h(p2) + \dots + pN*h(pN) \tag{1}$$

Where $p_1, \dots p_N$ are probabilities corresponding to $S_1, \dots S_N$ states and h(p) is the information-generating function devised by Shannon which equals $-\log_b(p)$

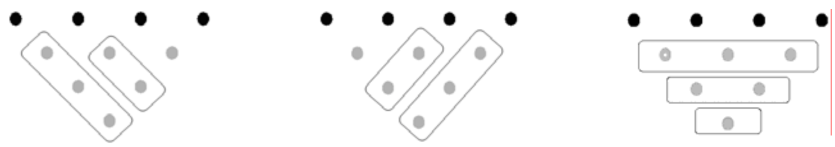
$$\text{Therefore } H = -\sum_{i=1}^{n} p_i \log_b(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \tag{2}$$

In this study we shall count entropy in rows of forelinks, backlinks, and horizontal links (horizonlinks) according to the ON/OFF of a link, Figure 5. Following Shannon's theory, formula (1), in each rows H becomes:

$$-p(\mathrm{ON})\mathrm{Log}(p(\mathrm{ON})) - p(\mathrm{OFF})\mathrm{Log}(p(\mathrm{OFF})) \quad \text{where } p(\mathrm{ON}) + p(\mathrm{OFF}) = 1 \tag{3}$$

The reason for measuring forelink and backlink entropy is because of their conceptual differences as described in the previous section. Here we introduce another link type called *horizonlink*. Horizonlink bears the notion of length of the links which is a measure of time (separation) between linked moves or we can view it as a measure of the distances of the linked moves. This reflects the cohesiveness of the session.

The maximum entropy (most random) of each row occurs when the ON/OFF of the links are most unpredictable, that is, half of the nodes in the row are linked and half of the nodes in the row are un-linked. Figure 6 plots the value of H against formula (3).



(a) (b) (c)

Figure 5. (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks.

The graph in Figure 6 is symmetrical, the slope of the graph decreases sharply as the probability moves away from 0 and 1. This indicates that when the links moves away from determinate values of 0 and 1 (all un-linked and all linked) the H value increases rapidly. In principle this is different from Goldschmidt (1995) interpretation of productivity where more critical moves (moves with more than 7 links) and high value of link index, disregard of the total number of possible link, are valued as more productive. However, Kan and Gero (2005) argue that a fully saturated linkograph indicates no diversification of ideas, hence less opportunity for quality outcomes. This graph shows that when $p(1)$ is between {0.35, 0.65}, H is over 0.93 that is if the links in a row is in between 35% and 65% it will received a very positive value (rich design process). If the links is less then 5% or over 95%, it will receive a very low H value (below 0.29).

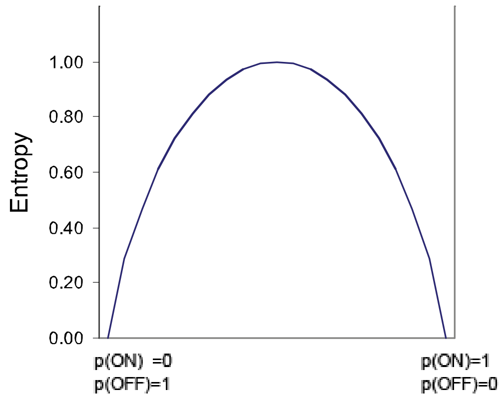


Figure 6. Maximum entropy when p(ON)=p(OFF)=0.5

In practice it is unlikely to have a fully saturated linkograph that has more than 7 moves. Figure 7 illustrates a typical linkograph in relation to the saturation of links; there are more *n* to *n-1* links than *n* to *n - i* links. The reason for that is people will try to maintain a coherent of conversation/thought in a conversation (Grice 1975; Pavitt and Johnson 1999) and people have limited short-term memory (Miller 1956).

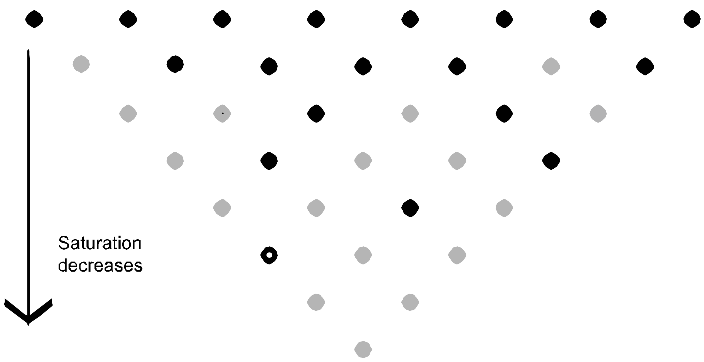


Figure 7. Typical distribution of links in a linkography of a design process

If we follow Miller's "magic number seven plus or minus two", any rows in a linkograph will seldom have more than 9 links. Taking the 35% linkage as denominator, therefore, any rows with row length more than 26 moves will not have a high H value.

This graph resembles the Wundt curve by Berlyne (1971), Figure 8. He used variables such as complexity or what he considered as surprise as stimuli that triggers curiosity. Berlyne's theory suggested that if the information received is too novel or too complex the hedonic value will decrease, hence less interesting.

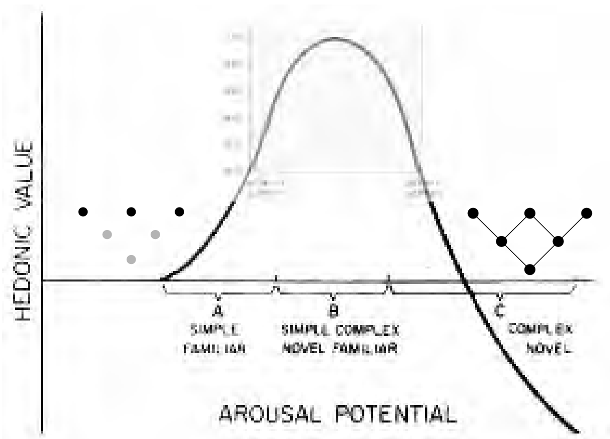


Figure 8. Wundt curve overlay with entropy curve.

Our hypothesis is that higher value entropy implies a process with more opportunities for ideas development.

4.2 HYPOTHETICAL CASES

Four hypothetical design scenarios with only five moves or four stages are used to examine these concepts further. Table 6 shows some of the possible linkographs together with the interpretation of the design processes they encapsulate. Tables 7, 8, and 9 are the entropy, using formula (3), of the forelinks, backlinks, and horizonlinks respectively. Table 10 is the cumulative entropy which maps well on to our understanding of those scenarios.

5. Conclusion

Studies in design collaboration (Cross and Cross 1995; Gabriel 2000; Olson and Olson 2000; Oslon et al. 1992; Zolin et al. 2004) had shown that there is a multiplicity of factors that contribute or affect the process and product of the collaboration. Some of the factors are: role and relationship, trust, social

TABLE 6. Some possible linkographs of five design moves and their interpretations.

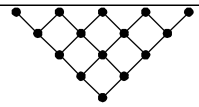
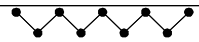
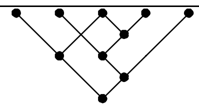
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.
Case 2		All moves are interconnected; this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred, therefore also very low opportunity for novel idea.
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing indicating some opportunities for ideal development.
Case 4		Moves are inter-related but also not totally connected indicating that there are lots of opportunities for good ideas with development.

TABLE 7. Entropy of forelinks

	Forelink Entropy				
	Move 1	Move 2	Move 3	Move 4	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0.811	0.918	1.000	0	**2.730**
Case 4	1.000	0.918	1.000	0	**2.918**

TABLE 8. Entropy of backlinks

	Backlink Entropy				
	Move 2	Move 3	Move 4	Move 5	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0	1.000	0.918	0.811	**2.730**
Case 4	0	1.000	0.918	1	**2.918**

TABLE 9. Entropy horizonlinks

	Horizonlink Entropy			
	n-1	n-2	n-3	**Total**
Case 1	0	0	0	**0**
Case 2	0	0	0	**0**
Case 3	0	0	0	**0**

Case 4	0.811	0.918	1.000	**2.730**

TABLE 10. Cumulative entropy of each case

Case 1	Case 2	Case 3	Case 4
0	0	5.459	8.566

skills, common ground, organization context, and socio-technical conditions. Most of these factors are underpinned by communication, either verbal or non-verbal, with or without technological mediation.

We selected linkography as a tool to re-represent the communication content and then abstract information out of the linkograph. The advantage of using linkography is twofold. First it is scalable in two dimensions, 1) this method is not tied to the number of designers being studies. Goldschmidt (1995) used linkography to compare the process of three designers with the process of a single designer, and 2) the length of the linkograph can be of any duration. Second it is flexible, the design moves and how the design moves are linked can be coded separately depending on the focus of the study (Dorst 2004; Kan and Gero 2004; Van-der-Lugt 2003). These studies are either done qualitatively or at the macroscopic level.

In this paper we outlined two approaches to measure linkograph which reflect the idea development behaviour of a design session. Cluster analysis was able to discern the number of chunks in a linkograph. In the entropy measurement, we proposed to measure three types of links. Forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation. These approaches form the basis of a new tool to assess designer behaviour and provide the opportunity to study the impact of various forms of computational technology on collaborative design. This will provide feedback to both the developers and users of these tools.

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MULTI-LEVEL STUDIES OF DESIGN IDEATION COMPONENTS

Preliminary Results

JAMI J SHAH
Arizona State University, USA

STEVE M SMITH
Texas A & M University, USA

and

NOE VARGAS-HERNANDEZ
Arizona State University, USA

Abstract. Although various ideation methods exist to guide designers generating concepts, the ideation process itself is hardly understood. Understanding the ideation process would allow the evaluation of current ideation methods, creation of new methods, improve its teaching, among other benefits. This paper discusses results for experiments on Ideation Components at the Engineering Design and Cognitive Psychology levels as an important step towards the development of a comprehensive Design Ideation Model. Cognitive Psychology and Engineering Design have traditionally studied Ideation from different perspectives, our strategy is to conduct parallel experiments at both levels and compare results; this is possible through an aligned experimentation framework. Results will allow relating cognitive theories and models with engineering design ideation elements. Results are discussed for experiments on three Ideation Components: Frame of Reference Shifting, Incubation, and Example Exposure.

1. Introduction

Although various ideation methods exist to guide designers generating concepts, the ideation process itself is hardly understood. Understanding the ideation process would allow the evaluation of current ideation methods, creation of new methods, improve its teaching, among other benefits. The primary goal of this joint research project between engineering design researchers and cognitive scientists was to produce the knowledge needed to not only evaluate idea generation methods but also to distinguish between their necessary and superfluous components. This is seen as an intermediate step towards the development of new theoretically based design idea generation methods to replace ad-hoc methods. An understanding of the interaction of human variables, method variables and design problem attributes, and the relationship of ideation processes to design outcome, will help companies determine which method to use under given conditions and how to constitute design teams. This study could also provide guidance to educators in finding better ways of teaching design synthesis.

1.1 IDEATION COMPONENTS

The groundwork for the formal study of Design Ideation techniques was laid on previous NSF project, (Shah et al. 2000; Shah et al. 2003). Experiments were conducted directly on ideation methods as a whole, or indirectly on Ideation Components. Ideation Components (Kulkarni and Shah 1999; Kulkarni 2000) are defined as mechanisms believed to intrinsically promote ideation or to help designers overcome mental blocks. The experimenting on Ideation Components rather than on whole methods has the advantage of reducing experiments and focusing the attention in a few components instead of a specific combination of a particular ideation method. Another advantage is that Ideation Components are commonly accepted and understood in Engineering Design research and Cognitive Psychology; sometimes differences are grammatical, for example what design researchers call incubation cognitive psychologists call interruption.

1.2 EFFECTIVENESS METRICS

When assessing the effectiveness of ideation methods one can focus on the ideation process (as in a protocol study), or the outcome (such as sketched ideas). A decision was made to focus on the outcome of the process where ideations could be evaluated for their effectiveness, for this reason a set of effectiveness metrics was developed. Four metrics have been defined in the previous work (Shah et al. 2000; Shah et al. 2003) for measuring the effectiveness of ideas generated, these are: Quantity, Quality, Novelty and Variety. Quantity refers to the numbers of ideas generated. Quality defines how well an idea solves the intended problem. Novelty indicates how unexpected an idea is. Variety describes how well covered is the solution space.

2. Alignment

The current NSF project proposes the following approach: A connection could be established if similar results are obtained when equivalent experiments are run at these two different levels (Lab and Design). As a consequence of this connection, more of the simpler Lab experiments could be run, and hence, collect more empirical data on specific ideation methods and Ideation Components. Eventually, a better understanding of ideation could lead to a theoretical foundation of Design Ideation. The fundamental issue was how to compare results from two different levels (Lab and Design experiments). The alignment approach was based on two key concepts: Agreement on the Ideation Components to study and on the Effectiveness Metrics for assessment.

There is little empirical evidence available to support the usefulness and effectiveness claims of the various ideation methods. As explained in the previous section, experimenting on Ideation Components in the established experimental framework is an advantageous approach to decipher ideation methods. But this requires a better understanding of the causes and effects of Ideation Component. Two groups have been studying ideation for many years: Cognitive Psychologists and Design Researchers (i.e. "Designologists"). Experimenting at different levels of ecological validity), both provide important elements to the understanding of Ideation Components and ideation in general. Cognitive Psychology has a better understanding of the individual idea generation process since their Lab experiments use fewer and simpler variables. Design Research has a better understanding of the requirements of real world design (e.g. engineering and economical limitations) since their Design Experiments use more and complex (high level) variables as shown in Figure 1.

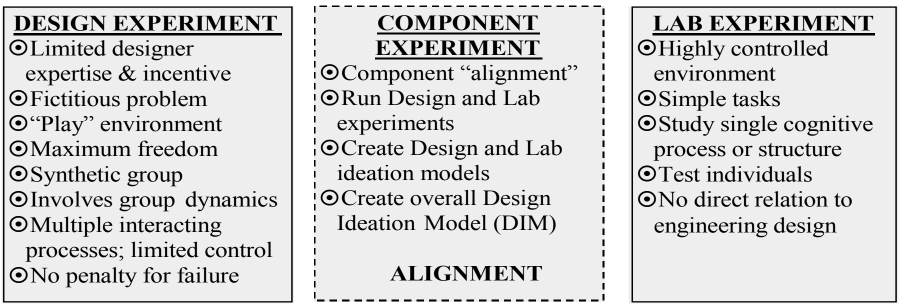

Figure 1. Levels of Ecological Validity

3. Approach

More than a dozen Ideation Components were identified in previous work (Kulkarni 1998; Kulkarni 2000; Kulkarni and Shah 1999; Shah et al. 2001; McKoy et al. 2001). Only the most relevant were selected for experimentation: Frame of Reference Shifting (FORS), Incubation, Example

Exposure, Provocative Stimuli, Suspend Judgment, and Flexible Representation. The two-level strategy, shown in Figure 2, consists of conducting Design Experiments (by design engineers at ASU) and Lab Experiments (by cognitive psychologists at TAMU) on the same Ideation Components.

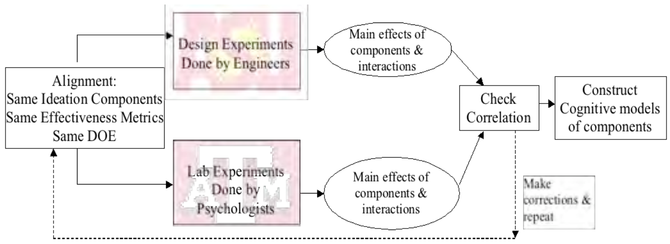

Figure 2. Experimentation Approach: A Two-Level Strategy.

The influence of each component in the design ideation process can then be measured. With this, a model of cause (i.e. component) and effect (metrics) can be derived that provides an understanding of the ideation process based on components and outcomes. This is the stage of current research and the results and models will be presented in this paper. As mentioned before, this is considered an intermediate step; after this independent modeling, results at the design level can be compared to the results at the lab level. Alignment makes this possible: the same Ideation Components were used and the same metrics applied to the outcome. Each side tells a different and important story, while Cognitive Science focuses on the development of models and theories based on simple tasks and problems, Design Research simulates real world better through (more complex) experimentation. Both sides of the story will be useful for the development of a cognitive model of design ideation that is supported on experimental results. The extent of alignment is still in the process of being verified and only preliminary results will be shown.

4. Results

These are some of the major findings for the experiments on Frame of Reference Shifting (FORS), Incubation (I), and Example Exposure (E) for their main effects and their interactions.

4.1 ENGINEERING DESIGN EXPERIMENTS RESULTS

- Incubation has a clear positive effect on all measures in the predicted direction; quality & best quality are affected to a somewhat lower degree
- Example exposure does not have a universal effect: examples can cause conformity, have no effect, or they can make one go into new directions;

it depends on the place one was at in design space prior to seeing the example

- FORS: some evidence that it enhances ideation for novelty measures, but not for other measures.
- Benefits of Incubation not seen if FORS is present and vice versa. The benefits of the two comps are not additive, may be redundant. An explanation is that after incubation, if FORS takes place, you get no benefit from the incubation. For both quality measures and both novelty measures, incubation has a negative effect in presence of FORS. The effect of FORS was negative on incubation for all measures, somewhat borderline for variety. Demonstrates the importance of studying interaction effects: both incubation and FORS are beneficial on their own, but detrimental together.

4.2 COGNITIVE PSYCHOLOGY LAB EXPERIMENTS RESULTS

- Simple main effect of example exposure benefited quantity, variety and average novelty; did not affect best novelty or best quality
- Simple main effect of incubation had beneficial effect of the same three outcomes; did not affect best novelty (best novelty scores have ceiling effect); detrimental effect on average and best quality.
- FORS had the same simple effect as incubation: quantity, variety, average novelty; no effect on best novelty; detrimental on quality measures
- Incubation effect is consistent and as predicted
- FORS is as consistent as incubation and in the predicted direction
- In the presence of incubation, FORS has detrimental effect on quantity, variety and novelty, and a beneficial effect on quality and best quality.
- In the presence of FOR, incubation had a detrimental effect on quantity and variety; no effect on novelty and beneficial effect on average quality
- Alignment of Design and Lab experiment results:
- Incubation increases quantity, novelty, and variety. Quality is only increased in Design experiments and decreased in Lab experiments.

5. Conclusions

Based on these results a preliminary model can be constructed that explains cause (i.e. ideation component or components) and effect (i.e. metrics) at each Design and Lab levels. These independent models can subsequently be explained using available Cognitive psychological models. Cognitive psychological models have dealt with the ideation process by focusing on different aspects of the process. For example, the Darwinian Model (e.g., Simonton 1998) focuses on production, particularly the quantity and variety of ideas that can be generated. Another approach to explaining the ideation process involves Associative Hierarchies & Remote Association (e.g., Mednick et al. 1962). Other cognitive approaches to the ideation process have focused on Analogies & Mental Models, that is, drawing one's ideas from familiar domains of knowledge that seem similar or analogous to a design that one is developing (e.g. Gentner and Gentner 1983; Holyoak and Thagard 1997). This approach is related to the theory of Structured Imagination (Ward et al. 1997), which describes imaginative ideation as beginning with familiar concepts. Some cognitive theories have focused on Intuition & Unconscious Activation (e.g. Bowers et al. 1995). The Roadmaps Theory of creative ideation (Smith, 1995) also focuses on the progress of one's ideation process as one moves through a sequence of choices in the development of a design or solution to a problem. Such component cognitive models will have the particularity of being concurrently based in experimental data and cognitive mechanisms. In the future, these models will form part of wider cognitive model of design ideation.

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SESSION TWO

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USING FUNCTIONAL LINGUISTICS TO ANALYSE A 'CONCEPTUAL JOURNEY'

NORA SHAHEED AND ANDY DONG
University of Sydney, Australia

Abstract
The aim of this article is to describe a way to apply the theory of functional linguistics to expose the linguistic techniques that designers use to offer, interrelate and project concepts – what will be called the designer's 'conceptual journey.' Through the analysis of an online design journal, we propose that certain grammatical forms characterize the representation of design concepts and the design process in text. By making use of formal, functional grammatical analysis, the research exposes specific linguistic codes and grammatical forms employed by designers in the way that they account for design practice and the designed artefact in text. As a consequence, the research makes possible computational analysis using computational linguistics to evaluate a large body of design texts in order to learn how the words and grammar designers use to express their work can contribute to empirical understanding of the design process.

1. Introduction

Thinking skills, both intuitive and rational, are considered a critical aspect of design practice. Domain knowledge alone is not enough to reach an innovative solution to a design brief. Experienced designers rely on strategic thinking (Ahmed et al. 2003) and "designerly ways of knowing" (Lawson 2004) in order to produce concepts which satisfy a design brief. Research about how designers think and behave attempt to establish explanatory frameworks and empirical understanding about designing. The most commonly applied research methods include concurrent and retrospective verbal protocol analysis, interviews, and ethno-methodological observations. Each of these methods contributes to understandings of how designers behave but each, as one would expect, suffers from theoretical and practical shortcomings. For example, verbal protocol analysis takes snapshots in time but may miss cognitive states and activities that occur during periods of time the designer spends away from design work (Lloyd et al. 1995). In particular, one of the main shortcomings shared by all of the above methods is scalability. While it may be possible to scale-up tools and methodologies from cognitive science, social psychology and anthropology to study the design process, it is not *a priori* obvious how this could be done. There is a lack of scalable methods to study designing over long stretches of time. Associated with this scalability problem are also questions of context, that is, studying designers in authentic situations rather than laboratory situations, and questions regarding what evidence to use as the basis for the analysis, for example using the type of materials that designers produce in the course of their actual work rather than surrogate materials.

In this paper, we propose and introduce functional linguistic analysis as one step towards a broader aim of developing a suite of computational linguistic tools to study designing. Design researchers have not broadly taken up the study of natural language using word-based or text-based analysis procedures except for interesting exceptions such as Mabogunje's (Mabogunje and Leifer 1997) work on associating the quantity of noun phrases as a surrogate measure for creativity, and Brereton's (Brereton et al. 1995) research into the linguistic strategies of persuasion that designers use to persuade their team members to adopt design concepts. Most of these approaches use text analysis in a highly focused way rather than to examine the system of linguistic behaviours to search for evidence as to how design practice is produced through language.

Influenced by the seminal work in functional linguistics in the Department of Linguistics at the University of Sydney by Michael Halliday (Halliday 2004), advances in verbal protocol analysis to study designing by the Key Centre of Design Computing and Cognition (e.g. Purcell et al. 1996)), and our own prior empirical and theoretical work in language use in design (Dong 2005), we have become increasingly interested in the linguistic behaviour of designers and the relationship of their linguistic behaviour to the production of design concepts.

There are several linguistic analysis techniques that offer methods to analyze linguistic behaviour, each with their own salient features. However, our interest is not in the linguistic system per se of designers or the cognitive structure producing the linguistic system (Croft and Cruse 2004). Rather, our interest is on what actions language performs during design practice and the relationship between the designers' linguistic behaviour to the production of representations of the design process and design concepts. As such, we chose the analysis technique of systemic functional linguistics (SFL). One further advantage of this theory is that it is "capable of providing a descriptive framework of a language that can be used for the large scale analysis of texts." (Fawcett 2000)

SFL theory is concerned with the system of grammar within a genre of text and how the grammar produces meaning and relates experiences in the text. The text itself is considered to be strongly associated with a social situational context within which the text is produced. Within each specific genre, SFL theory holds that the system of grammar of a language constrains the choices available to a speaker to generate meaning using language. SFL specifies a lexico-grammatical framework which constrains the features available to speakers. The constraints imposed by the structure of a grammar yield the potential to analyze how the structural consequences of that choice relate to how the speaker utilized language as a tool for representing knowledge or for making meaning (Halliday and Matthiessen 1999). In this research, the structural and functional characteristics of language are believed to correspond to the way in which designers describe and represent their 'conceptual journey' in text.

For the purpose of the analysis in this paper, we pay close attention to the grammatical structures associated with describing a designer's 'conceptual journey' using the system of TRANSITIVITY, or process type. (Consistent with the notational standards of SFL, systems of grammar are denoted using all capital letters.) The system of TRANSITIVITY is the major system of grammatical choice involved in the way that people express experiential meaning (Eggins 2004), that is, in the way that people express reality. Thus, the system of TRANSITIVITY can be construed as the set of grammatical choices that designers use to express the realities of their design process and the designed object. In this preliminary analysis, we explore the grammar of describing the design process and designed object based on the TRANSITIVITY system. Section 3 provides more detail about the TRANSITIVITY system. Future analyses will delve more deeply into the grammar relating to more specific design cognitive activities, such as referring to tacit knowledge, within each stage.

2. Conceptual Journey

A 'conceptual journey' is our term to describe the activities undertaken by a designer to construct and represent a design concept. The diagrammatic representation of a conceptual journey is depicted Figure 1 based on the Pahl and Beitz design process (Pahl and Beitz 1999).

Even though the original engineering-based Pahl and Beitz design process diagram is used to describe the different phases of the process of the design as a function of time, our conceptual journey diagram is not concerned with time, work load allocation to each of the phases, or sequential flow. The diagram is instead intended to inform our categorization of the main types of activities commonly associated with design concept formation. In this paper concept formation deals with the production of a description of the form, function and feature of a product that satisfies a set of requirements (Ulrich and Eppinger 2004).

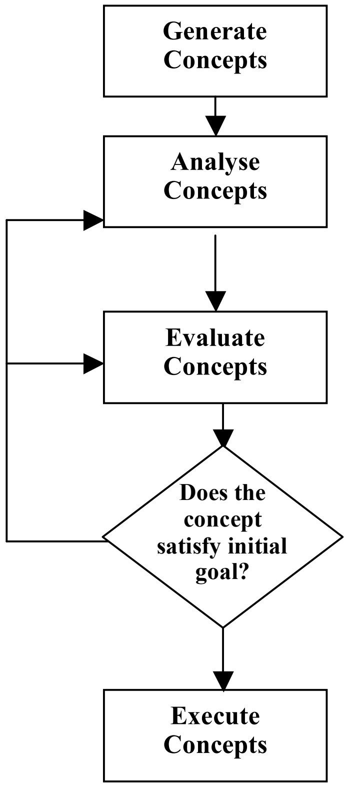

Figure 1. Conceptual Journey diagram

This definition of concept formation will assist us to use the attributes of functional linguistics to determine the grammatical forms of language that may indicate which stage of the conceptual journey the designer is currently engaged in.

2.1 PHASES OF A CONCEPTUAL JOURNEY

Before proceeding to apply the linguistic analysis technique, we will define each phase (generate concepts, analyse concepts, evaluate concepts and execute concepts) in the conceptual journey.

- *Generate Concepts* This phase of the conceptual journey relates to the processes related to the construction of representations of concepts/ideas. That is, the designer is engaged in the process of producing knowledge representations, what Visser has proposed as a cognitive definition of design (Visser, 2004). The designer may conceive of diverse, potential design concepts (by brainstorming for example) yet not worry if the generated concepts meet the criteria of the design brief. The designer may describe various attributes of the concept. The resultant concept, when named and made to exist, might later be modified through the following (analyses and evaluate concepts) phases.

- *Analyse Concepts* This phase of the conceptual journey relates to those activities done to scrutinise the essential details of the concepts (posited from the generate phase) in order to, in the next phase, evaluate the appropriateness of the concept relative to the design brief. This is may be achieved by breaking down the concepts into components or essential features and then applying specific analytical tools such as finite element modelling or simulation.

- *Evaluate Concepts* This phase of the conceptual journey is similar to the second phase but instead of specifically materializing aspects of a concept, this stage ascertains the value of the concepts against the design brief. In this phase the concepts are examined and judged, involving the designer to measure the worth of the concepts. This stage of concept formation is often called concept selection whereby designers apply various filters to eliminate any concepts that do not satisfy the design brief.

- *Execute Concepts* This phase of the conceptual journey relates to the production of the embodiment of the concept itself.

3. The TRANSITIVITY system and describing the conceptual journey

Given the description of the conceptual journey, the next step in the functional linguistic analysis is to ascertain the grammatical forms of text that may indicate in which stage of the conceptual journey the designer is currently engaged. In order to make this ascertainment, we need to investigate grammatical forms of clauses and how the grammatical forms enable the designer to express the realities about designing through text.

Expressing the realities about designing would be, according to Halliday (Halliday 2004), part of the ideational meta-function of language. In order to understand how grammar is implicated in the realization of the ideational meta-function of language, functional linguistics theory classifies clauses as processes in the TRANSITIVITY system. Of the processes, material ('doing'), mental ('thinking'), behaviourial ('behaving'), relational ('being'), and existential ('existing') appear to have the most relevance to expressing the realities of the design process.

Doing processes are referred to as **material** processes and are concerned with tangible actions. Thinking processes are referred to as **mental** processes, and are concerned with consciousness - perception, cognition, reaction and intention. Behaving is referred to as **behavioural** processes; they deal with physiological and psychological behaviour. In functional linguistics theory, only conscious beings can behave. Clearly, designed objects may also have a behaviour, but functional linguistics would classify those behaviours as attributes and thus a part of the relational process. Being processes are referred to as **relational** processes and are concerned with relationships of possession, identity and description. A related process to **relational** is **existential** which represents reality by only positing the existence of a phenomenon. For a complete description of the TRANSITIVITY system, we refer the reader to Eggins (Eggins 2004).

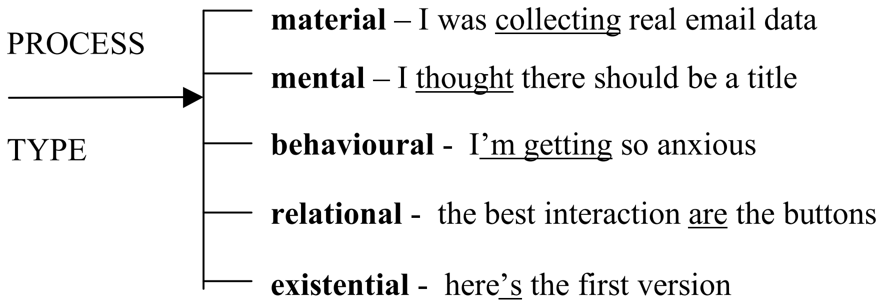

Figure 2. The process types in the conceptual journey

The TRANSITIVITY system does not adequately take into account the Evaluate stage of the conceptual journey diagram. Evaluation is instead part of the APPRAISAL (Martin 2000) system, which is the subject of a separate research project in applying functional linguistics to the study of design text.

The diagram in Figure 2 demonstrates the process types and representative sentences (taken from the student blogs as described in Section 4) that relate to each of the process types. Table 1 to Table 5 show the three sentences in Figure 2 partitioned into functional annotations focusing on the details of the roles of the terms in the various clauses. This segmentation of text into clauses is the first step in SFL analysis; a clause typically consists of a verb phrase and its non-clausal arguments. All three tables have the same 'process' labels (indicated by middle column). The value changes depending on which kind of material, mental or relational process is being defined. Subsequently, it is the middle column – the 'process' label – that inevitably indicates what kind of functional process a clause will denote. For example, in Table 1 the 'process' label is the word 'complemented.' As the word 'complemented' is an action word, the sentence is considered to construe a material process. In Table 2 the 'process' label is the word 'annoyed' which is a word in the process of perceiving, thinking or feeling; thus the sentence is a mental process. Finally, in Table 3 the 'process' label is the word 'are', identifying the sentence as a relational process.

Table 1. Material (action)

I	was collecting	real email data
Actor	Process	Goal

Alternate definitions for 'collecting'
=> accumulate
=> take-in
=> amass
=> acquire

Table 2. Mental (conscience processing)

I	Thought	there should be a title
Sensor	Process	Phenomenon

Alternate definitions for 'thought'
=> deliberate
=> weigh

Table 3. Behavioural (behaving)

I	'm getting	so anxious
Behaver	Process	Circumstance: Manner

Table 4. Relational (identifying)

The best website interaction	Are	the buttons
Carrier	Process	Attribute

Table 5. Existential (existence of)

Here	's	the first version
Value	Process	Existent

Now that we have identified the grammatical attributes of the sentences, we can relate these processes to the corresponding phases of the conceptual journey diagram. Figure 3 shows this integration.

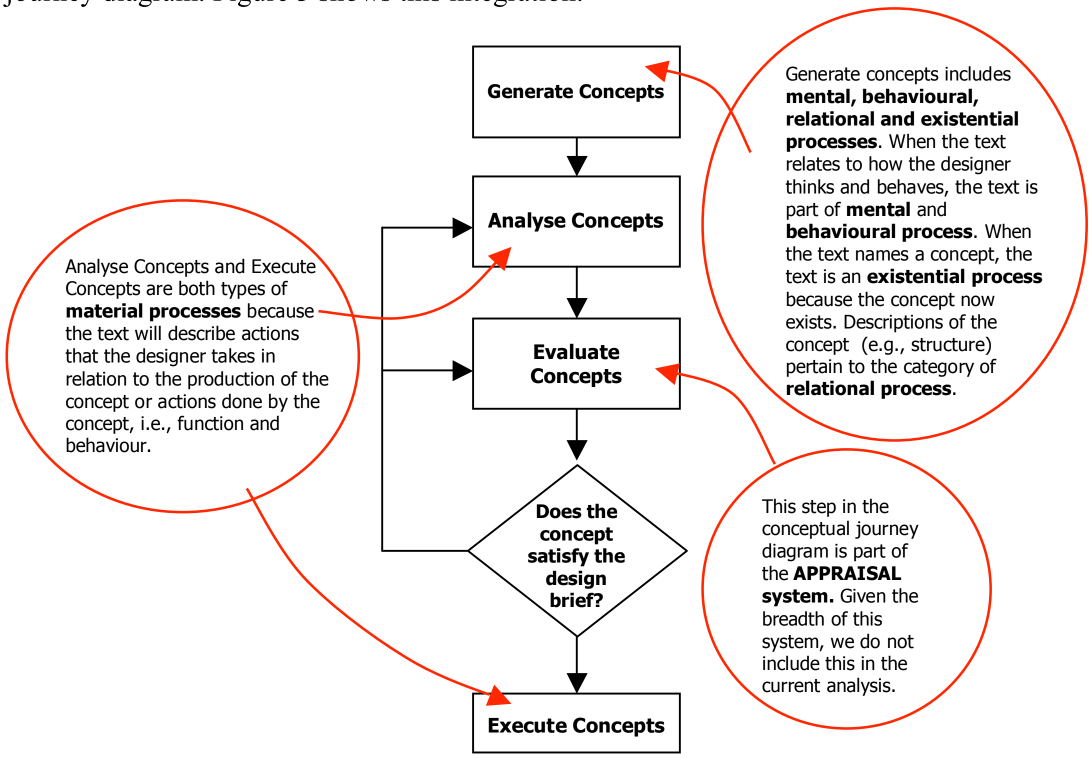

Figure 3. Identifying the TRANSITIVITY processes in the conceptual journey

4. Initial research

Using the rules for the process tags described in Figure 3, we conducted an initial functional linguistic analysis of a set of design students' "blogs." In the blogs, the students were to reflect about their design process and the designed object, an information visualization of an abstract phenomenon. Generally, the students wrote entries into their logs at least twice per week because they were assessed on the quality of their reflections.

To illustrate what the analysis entails and what information can be derived from a functional linguistic analysis, a short excerpt from a blog entry is included below. To conduct an analysis of TRANSITIVITY process, the analyst highlights the verbs according to process type: the material process is highlighted with green, the mental with yellow, the behaviour with purple, the relational with blue, and the existential with red.

MAY 10, 2004

im not sure if this will work but...heres the first version. my idea is that the planets rollover to show labels (thus giving visual and textual representations, but as the textual is only from use interaction the visual takes preference),

Figure 4. Excerpt from a blog

In this excerpt, there are no mental or behavioural processes. That is, the student does not indicate that she is engaged in mental activities or behaviours relating to design concept. Instead, most of the entries relate to relational and material processes. In this excerpt, the student names the existence of an idea cued by the use of the word *here*. The demonstrative pronoun *here* has no representational meaning other than to posit the existence of something (the concept), and, as required in English grammar, to provide a subject for the sentence. The two relational processes are indicated by forms of the verb *be*. In the first instance, the student relates her state of being to a level of assurance about the concept she is about to name. Then, having named the concept, she proceeds to define the identity of her *idea*. In each instance of material processes, the actor (the subject of the sentence) is the design concept itself, that is, an artefact noun. The concept does things such as *giving visual and textual representations*, what could be considered the behaviour of the concept. The function of an element of the concept, *the planets*, is keyed by the verb *rollover* as in a Web roll-over. Thus, one could state that in this entry, the student is describing the function, structure and behaviour of a concept. In relaying her stance towards the concept, she seems to be hedging (*not sure*), that is, projecting the concept as a possibility rather than a defined. That is, she is still open to feedback and critique and maintains a space of negotiation. In this one excerpt, the student appears to be, in accord with the conceptual journey diagram, engaged in generating, analyzing and executing a concept.

In further analyses of other entries, initial patterns emerge. The students' blog entries appear to contain nearly all phases of the conceptual journey. That is, the entry includes grammatical processes related to Generate, Analyse and Execute. It would appear that the student compresses into present-time scale a series of thoughts and actions to blend them into a reflection about the design process and activity. The text enables a reflexive meaning-making process in which efforts to understand the design process and the designed product through representations of these are recorded in text. That is, at the same time that the designers are issuing representations of designs in text, they are creating them. The design text is what Austin would call performative (Austin 1962).

5. Conclusion

The TRANSITIVITY system in functional linguistics offers a useful and rigorous way to annotate design text against what a designer is thinking (mental), doing (material), and naming (relational) and how the designer is behaving. Through relational and existential processes, concepts and the attributes of concepts are realized.

Functional linguistics offers several key benefits towards the study of human behaviour in design through the text that the designers produce. Practitioners of functional linguistics claim that because functional linguistics prescribes a rigorous set of rules to ascertain the appropriate process label and the grammatical “parse”, the need for multiple coders, as is usually required by verbal protocol analysis, is diminished. However, further studies are needed to ascertain whether inter-coder reliability issues regarding the labelling of complex or ambiguous clauses exist.

Second, because functional linguistics separates language into the semantic meta-functions and the functional roles of grammar (the processes that realize the meta-functions), it becomes possible to rigorously define the grammatical and semantic forms that specific types of entries in the blog should take. This makes it possible to write computational systemic functional linguistic parsers that tag the text into part of speech, separate sentences into clause boundaries, and then tag the clauses according to the appropriate process. While the work in computational SFL parsers is still an ongoing task in computational linguistics, one of the key preliminary tasks is to catalogue the grammatical and semantic forms corresponding to the processes in a specific genre of text. This forms the basis of ongoing research.

Finally, based on the initial research, that functional linguistic analysis could be used to determine what type of activities the designer is engaged in during the conceptual journey. With this knowledge, teachers can use functional linguistics to assess students’ designer process while researchers might use the data as a way to filter the design text to particular areas, such as focusing on mental activities.

We are continuing to complete the set of rules to identify the appropriate process labels and to assess the capability of the process labels to identify representations of the conceptual journey in the design text. In doing this process, we are also creating the set of grammatical forms associated with each of the process types to enable a computational systemic functional linguistics parser to categorize clauses into respective process types. It is our intent to progress towards a computational system to parse design text more precisely than we have been able to do before with latent semantic analysis and lexical chain analysis. Such a parser of design text could then be part of an intelligent agent which acts as a design process critique by understanding the conceptual journey that the designer represents through text.

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COMPARISON OF DESIGNERS USING A TANGIBLE USER INTERFACE AND A GRAPHICAL USER INTERFACE AND THE IMPACT ON SPATIAL COGNITION

MI JEONG KIM AND MARY LOU MAHER
University of Sydney, Australia

Abstract. Developments in digital design workbenches that combine Augmented Reality (AR) systems and tangible user interfaces (TUIs) on a horizontal display surface provide a new kind of physical and digital environment for design. The combination of tangible interaction with AR display techniques change the dynamics of design communication and have an impact on the designers' perception of 3D models. We are studying the effects of TUIs on designers' spatial cognition and design communication in order to identify how such tangible systems can be used to provide better support for design. Specifically, we compare tangible user interfaces (TUIs) with graphical user interfaces (GUIs) in a collaborative design task with a focus on characterising the impact these user interfaces have on spatial cognition.

1. Introduction

Digital design workbenches, table-top Augmented Reality (AR) systems equipped with tangible user interfaces (TUIs), have been proposed as an alternative for the design review meetings since they allow designers to intuitively modify the spatial qualities of 3D designs and keep communication channels open by preserving traditional mechanisms such as verbal and non-verbal communication. This research focuses on the way the digital design workbench supports design thinking and design communication. Several researchers have proposed that such tangible interaction combined with AR display techniques might affect designers' cognition and communication (Tang 1991; Bekker et al. 1995). However, they have not posed any evidence in a systematic way. To date, the central preoccupation of research on TUIs has been in a developmental direction, which usually describes the fundamental ideas behind their tangible systems, their prototype implementation, possible application areas and some initial usability results.

We aim to obtain empirical evidence about the potential impact of TUIs by investigating if and how the tangible presence of the virtual objects on the design workbench affects designers' spatial cognition and design communication in collaborative design. This paper presents some preliminary results of a pilot study using protocol analysis.

2. Tangible Presence and Spatial Cognition

Since a human's cognitive ability is strongly bounded, to carry out complex reasoning without the aid of tools is very difficult. Norman (1991) defined tools as cognitive artefacts, which are external aids that enhance cognitive abilities. Thus, we predict that designers' perception of spatial knowledge will be improved when using TUIs, and this may be due to the tangible presence of virtual objects.

2.1. TANGIBLE USER INTERFACES AND PHYSICAL INTERACTION

Arias et al. (1997) argued that new HCI approaches need to combine physical and digital environments to augment the weaknesses of the other by using the strengths of each since the "reflective conversations" are very different between the two environments. AR technology blends reality and virtuality to allow the seamless interaction between physical and digital worlds. Thus AR research has focused on the linkage between digital information and physical objects by superimposing, tagging and tracking objects. The term "augmented reality" is often used to refer to such TUIs in which 2D and 3D computer graphics are superimposed on physical objects. TUIs provide a physical interaction by turning the physical objects into input and output devices for computer interfaces, which restores the richness of the physical world in human-computer interaction.

According to Wang et al. (2001), the strengths of physical interaction can be explained by two aspects. Firstly, physical interaction provides direct, naïve manipulability and intuitive understanding. It is very natural to pick up and place a physical object; certain characteristics such as size and shape can be used to communicate meaning. Secondly, it provides tactile interaction as an additional dimension of interaction. Seichter and Kvan (2004) posed the concept of "augmented affordance" to explain physical interactions using TUIs in AR systems. From this point of view, TUIs can be seen as offering a conduit between the real or perceived affordances implied by the physical properties of the interface tool and the affordances created by the digital behaviours in the virtualised interface. The term "affordance" refers to the perceived and actual properties of the thing that determine just how the thing could possibly be used, which results from the mental interpretation of things, based on our past knowledge and experience applied to our perception of the things (Gibson 1979; Norman 1988).

2.2. DESIGNERS' SPATIAL COGNITION AND SPATIAL REPRESENTATION

As a consequence of the diversity of approaches and related disciplines, there is little consistency in what is meant by the term "spatial" (Foreman and Gillett 1997). We associate the designers' perception of the form and spatial relationships of the design components with the designers' spatial cognition. The meaning of 'space' to the designers is not an abstract of empty space, but rather of the identity and the relative locations of the objects in space. Space then is decomposed into particular objects and the spatial relationships among them. The spatial relationships may include functional reasoning since design is required to satisfy intended functions. In addition, it has been argued that touch is also a spatial modality, where the close linkage between motor and spatial processes has been emphasized. Kinaesthetic information through a haptic system provides us with the ability to construct a spatial map of objects that we touch (Loomis and Lederman 1986). It is the movement of a hand repeatedly colliding with objects that comes to define extra-personal space for each individual, as a consequence of repeatedly experienced associations (Foreman & Gillett 1997). Thus, the movement simulated by the mouse in desk-top systems lacks tactile and kinaesthetic feedback that normally accompanies movement.

Based on the assumption that people often use general purpose verbs and prepositions when the context is sufficiently clear to disambiguate them, we will investigate language as spatial representation. Language draws on spatial cognition so that we can talk about what we perceive and it thereby provides a window on the nature of spatial cognition (Anibaldi and Nualláin 1998). Gesture is also recognized as a good vehicle for capturing visual and spatial information as it is associated with visuospatial content. The movement of hands can facilitate recall of visuospatial items as well as verbal items (Wagner et al. 2004). People produce some gestures along with their speech, and such speech-accompanying gestures are not just hand moving. Speech and gesture are both characterizing the spatial relationships among entities, which are closely related to and may even be beneficial for cognitive processing (Lavergne and Kimura 1987; Goldin-Meadow 2003).

2.3. DIGITAL DESIGN WORKBENCHES

We reviewed various digital design workbenches: metaDESK, iNavigator, BUILD-IT, PSyBench, URP, MIXdesign and ARTHUR system. Ulmer and Ishii (1997) constructed the metaDESK system with a focus on physical interaction to manipulate the digital environment. Standard 2D GUI elements like windows, icons, and menus, are given a physical instantiation as wooden frames, 'phicons, and trays, respectively. iNavigator is a CAD platform for designers to navigate and construct 3D models, which consists of a vertical tablet device for displaying a dynamic building section view and a horizontal table surface for displaying the corresponding building plan geometry. From the user's perspective, the display tablet is served as "a cutting plane" (Lee et al. 2003). BUILD-IT developed by Fjeld et al. (1998) is a cooperative planning tool consisting of a table, bricks and a screen, which allows a group of designers, co-located around the table, to interact, by means of physical bricks, with models in a virtual 3D setting. A plan view of the scene is projected onto the table and a perspective view of the scene is projected on the wall. Brave et al. (1998) designed PSyBench and inTouch, employing telemanipulation technology to create the illusion of shared physical objects that distant users are interacting with. Although still in the early stage, it shows the potential of distributed tangible interfaces. URP developed by MIT media lab is a luminous tangible workbench for urban planning that integrates functions addressing a broad range of the field's concerns such as cast shadows, reflections and windflow into a single, physically based workbench setting. The URP system uses pre-existing building models as input to an urban planning system (Underkoffler and Ishii 1999). MIXDesign allows architects to interact with a real scale model of the design by using a paddle in a normal working setting, and also presents an enhanced version of the scale model with 3D virtual objects registered to the real ones (Dias et al. 2002). ARTHUR system is an Augmented Round Table for architecture and urban planning, where virtual 3D objects are projected into the common working environment by semi-transparent stereoscopic head mounted display (HMDs). Placeholder objects (PHOs) and wand are used to control virtual objects (Granum et al. 2003).

These various configurations of digital workbenches, with and without augmented reality, show a trend in developing technology that supports designers in creating and interacting with digital models that go beyond the traditional human-computer interface of the keyboard, mouse, and vertical screen. The different configurations described above draw on specific intended uses to define the components and their configuration. Few of the publications about digital workbenches evaluate the new interface technology with respect to spatial cognition or improved understanding of the spatial relationships of the components of the digital model. In this paper, we consider the existing digital workbenches as defining a class of design environments that use TUIs to be a departure from the traditional GUIs that designers are currently using to create and interact with a digital design model. While TUIs and GUIs will continue to be alternative design environments for digital models, we focus on the differences between them in order to clarify the role and benefit of TUIs for designers.

3. Comparing GUI-based with TUI-based Collaboration

In devising an experiment that can highlight the expected improvement in spatial cognition while using TUIs, various scenarios have been considered: Face-to-face collaboration with physical models versus TUI-based collaboration with tangible digital models; Face-to-face collaboration with pen and paper versus GUI-based collaboration with mouse and keyboard; GUI-based collaboration with intangible digital models versus TUI-based collaboration with tangible digital models. We chose the third category for this research because it will enable us to verify if and in what way tangible interaction affect designers' spatial understanding of 3D models in computer-mediated collaborative design.

3.1. DESIGN COLLABORATION IN GUI VS. TUI ENVIRONMENTS

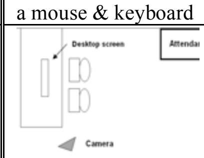
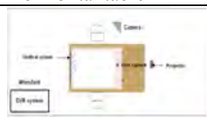
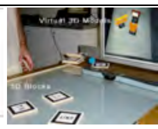
A GUI is a graphical user interface to a computer, which features a pointing device, icons and menus, and desktop on the display screen. Thus, we consider a 3D CAD system for the design environment in a GUI environment. Current CAD systems allow designers to explore design alternatives as modifiable models, but they produce indirect interaction with 3D models using a mouse. Despite the physical form, the mouse has no physical contextual awareness and lacks the efficiency of specialized tools. It is regarded as a time-multiplexed input device controlling different functions at different times (Fitzmaurice 1996). The ability to use a single device for several tasks is a major benefit of the GUI, but given the nature of interaction where only one person can edit the model at a time, the GUI environment may change interactivity in collaborative design (Magerkurth 2002).

On the other hand, TUIs have been offering an alternative to standard computer user interfaces, where physical objects are representations and controls for digital information, thereby restoring some of the tangibility of physical models. We consider a digital design workbench for the design configuration in a TUI environment. The digital design workbench is specifically configured for 3D design and visualization (Daruwala 2004), where designers can manipulate 3D virtual objects in a semi-immersive environment in real time and can be spatially aware of each other as well as the design. The direct hands-on style of interaction afforded by the physical objects provides designers concurrent access to multiple, specialized input devices. That is, they are "space-multiplexed" input devices, which can be attached to different functions, each independently accessible (Fitzmaurice 1996). Using AR techniques, TUIs merge the display and task space, which may support shared understanding due to the interaction that draws out ideas in a conversational manner (Arias et al. 2000).

3.2. EXPERIMENT SET-UP

We chose ArchiCAD as an application for the GUI-based collaboration and a design workbench constructed by Daruwala and Maher (2004) for the TUI-based collaboration. Inspired by the fact that tabletops and walls are the main working surfaces during collaborative design sessions (Ma et al. 2003), they proposed a customized digital workbench that provides both horizontal and vertical display surfaces to facilitate multiple views of the 3D model. The digital workbench environment is designed to demonstrate a range of novel input techniques for 3D design, so it is not engineered as a targeted end-user application. We included a collection of 3D blocks with tracking markers in ARToolKit to offer a form of tactile influence on the design as handles to the virtual objects.

TABLE 1.Two experiment settings

	GUI-based collaboration	TUI-based Collaboration
Hardware	Desktop computer	Digital design workbench
Input	Mouse & Keyboard	3D blocks
Application	ArchiCAD	ARToolkit
Display	Vertical LCD screen	Vertical LCD screen & Horizontal table
Task space	a mouse & keyboard	Horizontal table
Settings	 	 

To simulate a situation similar to a design review meeting where designers review the current state of the 3D plan and modify it, we developed two renovation scenarios of the same degree of difficulty: the layout of a home office apartment and the layout of an interior design office. Designers are required to collaborate on renovating the studio to satisfy intended functions to a pre-defined set of specifications in design briefs.

TABLE 2.Experiment design

	Experiment 1		Experiment 2		Experiment 3	
Sessions	1st GUI: A	2nd TUI: B	1st TUI: A	2nd GUI: B	1st TUI: B	2nd GUI: A
Subjects	Two architecture students		Two architecture students		Two architecture students	
Activity	Renovating the studio by placing the furniture, which are provided through the library					

*Task A (A): Home office apartment, Task B (B): Interior design office

We recruited three pairs of 2nd architecture students as subjects for the pilot study. They did not have access to a pen device or to the 2D view in

ArchiCAD to make the conditions similar to the TUI-based collaboration. A set of 3D objects were made available in the application's library in order for them to focus on design configuration rather than designing the furniture components during the design sessions. The working time in each design environment was limited to 20 minutes.

4. Segmentation and Cognitive actions

We have done a pilot study that is an adaptation of protocol analysis, a methodology for studying problem solving processes that has been widely used in design cognition. Rather than ask the designers to think aloud, we recorded their conversation and gestures while they were collaborating on a predefined design task. The data collected for analysis includes verbal description of spatial knowledge and non-verbal data such as gestures. We focus on capturing the contents of what designers do, attend to, and say while designing, looking for their perception of discovering new spatial information and actions that create new functions in the design.

4.1. SEGMENTATION

Segmentation is dividing the protocol into small units according to a rule. One way of segmentation is to divide protocols based on verbalization events such as pauses or syntactic markers for complete phrases and sentences (Ericsson and Simon 1993). Another way is looking at the content of the protocol, and divide the protocols into small units along lines of designer's intentions (Suwa et al. 1998). We take the latter approach, thus a change in subjects' intention or the contents of their actions flagged the start of a new segment. Consequently, a single segment sometimes comprises one sentence, and sometimes several sentences.

TABLE 3. Segments of the protocols from one of the TUI sessions

SN	Time	Transcript	Intentions
9	1:40	S: Cos I've seen in how in some studio apartments how they've got these bookshelves that partition the room ….and then just chuck some crap in there	S is retrieving previous knowledge on bookshelves that partition the room.
10	1:49	A: Okay. Um. Should we go about rearranging it? S: Alright, so..we're gonna move these, like, that way A: So, first, these are all living stuff but you're uh…	They are rearranging 3D blocks by moving all living stuff to other side.
11	2:04	S: How about if we partition in there and we… A: …Put some bookshelves like this. Uhh.. yeah… some bookshelves	A is putting bookshelves on the horizontal surface attending to partition

4.2. COGNITIVE ACTIONS

For each segment, we classified designers' cognitive actions into four categories including visual and non-visual information based on Suwa's definition (1998): 3D modelling actions, perceptual actions, functional actions and design communication. The three categories correspond to the levels at which incoming information is thought to be processed in human cognition. 3D modelling actions correspond to sensory level, perceptual actions to perceptual, and functional actions to semantic. Another action category, the design communication, is included to reveal specific aspects of the collaborative interactions. We paid attention to the information of whether or not actions are new for each design action and the dependency on each other in order to measure the correlation between them and designers' spatial cognition. The first category, 3D modelling actions, refers to physical actions that are functionally processed with design thinking. This category includes the selection, placement and relocation of pieces of 3D blocks made by designers.

The second category, perceptual actions, refers to actions of attending to visuo-spatial features of the artefact or spaces they are designing with. Perceptual actions are inherently dependent on physical actions. The attention to the feature or relations, creation of new space or relations, and unexpected discovery of objects or spaces that occurred were investigated as a measure of designers' perceptive abilities for spatial knowledge. The third category, functional actions, refers to actions of conceiving of non-visual information, but something with which the designers associate visual information. Whenever instances of functional actions were found it was necessary to interpret what perceptual actions or 3D modelling actions were dependent on them (Suwa et al 1998). In terms of functional actions, we focused on discovering 'Re-interpretation', which was applied to a segment when a designer defined a different function from previous one when s/he revisited. The fourth category, design communications, refers to actions of communicating with one another regarding design ideas and the completion of the design task itself.

5. Analysis

The following analysis is a preliminary interpretation of the data collected. We focussed on finding patterns of designers' behaviours and cognitive actions by interpreting the information shifts, specifically looking for significant differences in the data collected from the GUI sessions and the data collected in the TUI sessions.

5.1. OBSERVATION OF DESIGNERS' BEHAVIOURS

Through the observation, we noticed that designers in the GUI sessions discussed ideas verbally and decided on a solution before performing 3D modelling actions whereas designers in the TUI sessions communicated design ideas by gesturing at and moving the objects visually and decided on the location of each piece of furniture as they were manipulating 3D blocks.

That is, designers in the GUI sessions spent a lot of time explaining their ideas to one another verbally while designers in the TUI sessions used 3D blocks to test and visualize design ideas.

Figure 1. GUI-based collaboration

In terms of collaborative interactions, the TUI environment enabled designers to collaborate on handling the 3D blocks more interactively by allowing concurrent access to the 3D blocks and to produce more revisited 3D modelling actions before producing the final outputs. These results may be caused by the different properties of the tools. Designers in the GUI environment shared a single mouse compared to multiple 3D blocks, thus one designer mainly manipulated the mouse and the other explained to his partner what they were focusing on. On the other hand, with the direct, naïve manipulability of physical objects and rapid visualization, designers in the TUI environment seemed to produce more multiple cognitive actions and completed the design tasks faster.

Figure 2. TUI-based collaboration

The above results motivated us to be interested in the revisited 3D modelling actions in terms of idea developments and designers' spatial cognition. We speculate that the revisited 3D modelling actions in the TUI sessions uncover information that is hidden or hard to compute mentally and suggest that this will play an important role in supporting designers' spatial cognition and producing a design solution.

5.2. COGNITIVE ACTIONS IN THE GUI AND TUI SESSIONS

Looking into the content of cognitive actions, we found different patterns of behaviour between the GUI and TUI sessions. In terms of perceiving the location of an object or space, designers in the GUI environment focused on the individual location itself while designers in the TUI environment attended more to spatial relations among objects or spaces. For example, when designers worked on the layout of a sink in the home office apartment, designers in the GUI session just clarified the location of the sink without noticing the problem in relation to the bedroom whereas designers in the TUI sessions found that the current location of the sink is wrong by perceiving the spatial relation with the bedroom.

TABLE 4. Perceptual actions on the location of a sink

Session	Transcript (GUI)
GUI 2	B: Kitchen and dining area, A: Yep B: Which she does not yet have… well she has a sink [laugh] in her ba-bedroom, and then living/meeting area A: Yep… and a working area
	Transcript (TUI)
TUI 1	A: It shouldn't be near the bathroom or I mean, I think it shouldn't be near the bedroom, sorry. It shouldn't have a kitchen sink. B: Yeah that's what I was thinking. Why is it next to the bed? A: It's a bit odd, and it's also just….not…normal
TUI 3	B: coz.. The sink sink, sink dosen't need to be in the bedroom A: needs to be in the kitchen B: yeah sink in the kitchen. sink over here for now A: mm hmm

When placing an object in the GUI environment, designers put it in a relevant area simply considering the function of the object, and sometimes they attended to the shape or style of the object itself. On the other hand, designers in the TUI environment created and attended to a new spatial relation created by placing an object, with respect to other objects or space around it. For example, regarding the placement of a new desk, designers in the GUI session emphasized the function of a desk for a computer programmer and placed it in the corner. However, designers in a TUI session considered two locations for the desk, in the corner or near the window, and then they decided to put it near the window because the designer can look out the window by creating a spatial relation between the desk and window.

TABLE 5. Cognitive actions on the placement of a desk

Session	**Transcript** (GUI)
GUI 2	B: we need a work table A: desk and stuff B: she's **a prgrammer right? so she'd need**.. A: that one's got a little computer thing on it B: hummm (as in yeah) A: that one? B: yeah A: and that can go in the **corner**….
	Transcript (TUI)

TUI 3	B: we need a desk, first of all, for his um office area.. maybe one of this.. is it like a desk? A: ok B: maybe in the **corner** there B: now we want the desk to go **near the windows** A: ok B: so **he can look out the window**

In comparison to the GUI system, the TUI system allowed designers to discover hidden spaces among objects or features of an object unexpectedly when they were revisited. These perceptual actions can be classified as unexpected discovery, which is one of the crucial acts in creative activities (Suwa et al. 1999). The following are examples of unexpected discoveries and re-interpretation extracted from the verbal protocols of the TUI sessions. Re-interpretation was associated with unexpected discoveries in the protocols, which is a driving force for exploration of new design ideas. Thus we hypothesize that the TUI system supports creative design by discovering or generating new ideas, which may be related to the improvement and changes of the designers' spatial cognition. In the next phases, we will look more in depth into this aspect of the protocols.

TABLE 6. Unexpected discoveries and Re-interpretation in the TUI sessions

Transcript	Interpretation
B: **Just little bit layout is not very**…. A: You don't like how they have drawers in the middle? B: No, I mean A: You end up with **empty space** in the middle. how this sofa faces onto her	B felt that the layout is little bit strange and then A is discovering **an empty space** in the middle. **(Unexpected discovery)**
B: and ahh… the dining table can go… can go her… near the kitchen A: I'm thinking of having the dining.. The kitchen and dining area closer to.. B: Closer to the bed? A: Yeah. pit it closer to this section here B: That ahh **That might get crowded over there**. I could…move it around here?	B is discovering that **the area is getting crowded** (feature) by placing the dining table and sink near the bed **(Unexpected discovery)**
S: (Interrupt) ya know how they have those kitchens that are just two long rows? A: Oh yeh S: And then that would be like, become like the bar. **The breakfast bar**.	After discovered **the shape of kitchen** to be two long rows (Unexpected discovery), A is **defining a new function** of the cabinet in the kitchen. **(Re-interpretation)**

5.3. DISCUSSION ON THE EXPERIMENT SET-UP

The original intention of doing a protocol analysis of the design communication was based on the assumption that the designers would express their spatial reasoning using words. From the transcription of their discussion, we would be able to code and analyse differences in spatial cognition in the two environments. From our pilot studies, we found it difficult to analyse the designers spatial thinking through the contents of verbal data since their design ideas or intentions were not described fully in the conversation. While the designers using the GUI environment discussed their spatial considerations verbally, the designers in the TUI environment expressed their ideas by manipulating 3D blocks visually rather than explaining them verbally.

Our original intention in studying collaborating designers rather than using the think aloud method for an individual designer was based on the observation that tangible interaction allowed the task space to be within the communication space, therefore improving design communication. In our pilot studies, a designer was often interrupted by the other designer. This caused a problem in capturing an individual designer's cognitive actions. We also think that the task space factor might affect behaviours in terms of design and expressional body motions, and hence design communication. Thus, it is not clear if the some results of the pilot study are caused by the impact of tangible interactions or the task space factor.

In future studies, we will consider different experimental situations including a single designer using the think aloud method, a simple WIMP-based application for the GUI sessions in addition to the same task space in the GUI and TUI environments. We will also consider adding several spatial constraints to design briefs to further stimulate designers' cognitive activities and asking designers to draw their final design after experiments, which can reveal how much the designer perceives her/his design layout while s/he is navigating it.

5. Conclusion

The results of the pilot study indicated that the GUI and TUI sessions produce different outcomes in terms of designers' cognitive actions. Compared to the GUI sessions, designers in the TUI sessions exhibited the following patterns of behaviour:

- performed multiple cognitive actions in a shorter time
- re-visited a previous design frequently while coordinating design ideas
- created and attended to spatial relations such as local and global relations
- discovered spaces or features of an object unexpectedly
- produced more re-interpretation actions

From the above results, we can assume that the TUI system is an effective design environment for the spatial layout design since it encourages designers to attend to or create spatial relations between artefacts or spaces. However, more protocols have to be analysed to reinforce these findings. In the next phases, we will develop a coding scheme derived from our observations in the pilot study and theories of spatial cognition, and will analyse the results using both qualitative and quantitative methods.

While there may be significant differences in spatial cognition in using TUIs, we do not think that digital workbenches will replace GUI systems. Rather, new developments in TUIs will provide alternative design environments that complement existing GUI systems. Knowledge of the implications of the differences in spatial cognition provide a basis for developing and implementing new design environments as well as provide guidelines for their most effective use.

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USING WIKIS AND WEBLOGS TO SUPPORT REFLECTIVE LEARNING IN AN INTRODUCTORY ENGINEERING DESIGN COURSE

HELEN L CHEN, DAVID CANNON, JONATHAN GABRIO, LARRY LEIFER, GEORGE TOYE, TORI BAILEY
Stanford University, USA

Abstract. An observation and a pedagogical challenge often found in project-based design courses is that students see what they have produced but they do not see what they have learned. This paper presents preliminary findings from an NSF-sponsored research project which experiments with the use of weblogs and wiki environments, two open source tools, to facilitate student integration and synthesis of learning in *Designing the Human Experience*, an introductory freshman seminar on design engineering at Stanford University. Coupled with *Folio Thinking,* a coached process of creating learning portfolios and supporting reflection, this study explores how the combination of this innovative pedagogy along with these new forms of social software can positively influence students' knowledge, awareness, and skills in design engineering.

1. Weblogs and Wikis

Social software designed to support group interaction has evolved, since the appearance in the 1960s of multi-user computers and networks, in a variety of forms such as multi-player games, chat rooms, instant messaging, and bulletin boards. More recently, weblogs (or blogs) and wikis (web pages that any user can edit) have captured the imagination of members of both the corporate world and higher education community as valuable knowledge management and group communication tools. Schofield (2003) suggests that the rapid rise of interest in software to support group interaction can be attributed to an emerging web-based platform based on blogs, wikis, and RSS feeds (a format for syndicating news and content), on ease of use, and on the ubiquity of web access. In the professional and personal worlds, social interactions increasingly occur and move fluidly between virtual and face-to-face environments. This is particularly true for today's college students who have been described by Prensky (2001) as "digital natives" of the world and languages of computers, video games and the Internet. Higher education is only now beginning to explore the potential educational value of blogs and wikis as a means to promote deeper learning and integration of learning experiences from inside and outside the classroom (Williams & Jacobs 2004)

2. Folio Thinking and Reflection

Folio Thinking is an instructional method grounded in the process of students creating learning portfolios. Learning portfolios are purposeful collections of artifacts that represent the learning experiences of the portfolio owner, who might be an individual or a group of individuals—students, project teams, faculty, an academic program, or an institution. The Folio Thinking pedagogical approach is designed to enhance self-awareness by enabling students to make their knowledge explicit and visible for themselves as well as for others. Folio Thinking also deepens learning by enabling students to make meaningful connections—for example, connections among discrete bits of knowledge and between their learning experiences and a more comprehensive model of (the real work of) engineering.

Written reflection is often considered to be a required component of a learning portfolio and is what distinguishes a learning portfolio from a scrapbook, photo album, or web page. These reflections may be associated with individual artifacts and with groups of artifacts. The set of artifacts contained in a portfolio, together with reflections and annotations, tell a unique story about some aspect of the owner's "learning" by helping the owner make visible and explicit her knowledge, experience, and growth. For example, Professor Leifer's graduate course, "Team Based Design Development with Corporate Partners," has maintained a web based course portfolio for ten years (Leifer 1998). These artifacts may have been created by the portfolio owner in the context of the experience being represented—such as a design brief, measurements, diagram, or a drawing. Or, the artifacts may not have been created by the owner but still serve as a representation of the owner's learning experience —such as a client's business card or a photograph of a prototype.

The product alone is not all that makes the portfolio a powerful educational tool. The very process of creating the portfolio is an important learning experience (Cambridge 2001a; Hutchings 1998; Lyons 1998; Shulman 1998; Porter et al. 1995; Belanoff et al. 1991). By linking the process of design to the process of creating a learning portfolio, students have a concrete context in which they can openly and consciously engage in reflection. Creating a portfolio also prompts students to physically juxtapose learning experiences that are otherwise separated by time and space and make meaningful connections among those experiences that can lead to powerful new insights about themselves and their learning career. For students who are contemplating deeply their experiences and the relationships among those experiences, the artifacts may serve as objects to facilitate thinking and remembering (Brereton 1998; Pea 1993).

We purposefully chose to couple the implementation of wikis and weblogs (the technology) with Folio Thinking (the pedagogy). It is our working hypothesis that the combination of Folio Thinking practices with the wiki and blog technology will increase: 1) **awareness** of what is learned and 2) **articulation** of connections between learning and the design process. Folio Thinking will enhance the interactive nature of wikis and blogs by encouraging students to make their knowledge explicit and visible not only for themselves but also for course instructors, team coaches, and their peers.

3. Weblog and Wiki Requirements

Our primary research interest focuses on how to encourage and facilitate reflective thinking about the design process. However, technology was a necessary foundation for our efforts. We chose web-based software to enable the students to gather, organize, and share their writing, photos, videos, presentations, and other digital creations. More specifically, we used a software package of a variety often called 'social software' or 'community building' software, called Tikiwiki which supports both wiki pages and weblog functionalities. (Tikiwiki is based on the very popular Apache, MySQL, PHP combination of open-source software packages.)

The necessary features underlying our choices of weblogs and wikis are as follows:

Weblogs

1. Distinct, dated entries usually made up of text containing news, commentary, notes, and personal reflections, with links to other artifacts such as websites, photos, or other media
2. Reverse chronological arrangement of entries such that the latest entry appears at the top of the web page
3. Easy upload and editing of entries and artifacts through a web browser
4. Outside commenting on entries from peers, coaches, teaching team, and others at a distance
5. Informal environment with easy and low barriers to posting due to student familiarity with social blogs such as the commercial Xanga, LiveJournal, and Blogger communities

Wikis

1. A group of interlinked pages, each with a unique name
2. Can support both individual and team work
3. Each page editable by a number of people, often a team or the whole community,
4. Use of a simple set of markup punctuation and other non-alphabet character patterns that can be translated into common web page elements
5. Easily edited through a web browser, with previous versions of a page saved and retrievable in the event of mistakes

4. ME013N: DESIGNING THE HUMAN EXPERIENCE

4.1. DESIGNING THE HUMAN EXPERIENCE

Designing the Human Experience is a project-based course that guides students with scaffolding through the design process. The course, most recently given in Winter 2004 and Fall 2004, is motivated by the realization that we live and work in a human-built environment. From a design-philosophy perspective, it is imperative that engineers take responsibility for and help guide the ethics and other ramifications of these design processes. The objectives for the course are to: (1) enable students to begin thinking and acting like design engineers without committing to being one; (2) make students aware of what it means and how it feels to think and act like a design engineer; and (3) allow faculty, advisors, and potential employers to see individuals mature from having relatively undifferentiated intelligence into professional minds with documented skills and experience, some becoming design engineers, but all understanding where design thinking fits into our everyday lives. Thus, the course emphasizes direct experience, practical design thinking, and the building of real product prototypes. No prior design experience or fabrication skills are required. The ideas developed in the course are grounded in the students' collective background life experiences and observations of "human needs."

Designing the Human Experience activities and discussions revolve around two design projects. Four to five students work together as teams on project assignments that build on the knowledge, skills, and experience that students gained in the previous assignment, getting closer and closer to full scale, externally sponsored design challenges with real world complexity. In Winter 2004, the teams worked on the design of an interactive kiosk for an exhibit on revolutionary crowds at the campus museum. In Fall 2004, the project assignments included the building of a "precious" object with specific technical parameters, and the design of a collaborative workspace for computer science students. For each project assignment, the course required both individual and team documentation describing the design process, goals, methods, results, conclusions and broad takeaways or lessons learned. Much of this documentation was completed in the course wiki pages and 'idea logs' (weblogs). Capturing learning experiences through the creation of design documentation as the design project takes place is an important first step in creating a learning portfolio. As a result, students are faced with the challenge of articulating the knowledge they are acquiring and the relationship of this knowledge to their evolving model of design engineering.

At key times during the course, students shared their portfolios in conversations with the instructor, design team coaches, and peers. Feedback from the instructor was largely given to the students during these discussions rather than in written form. Students were also encouraged to read and comment on each other's idea logs in the course website.

4.2. STUDENT POPULATION

All of the students were first year undergraduates in the first or second quarter. One third of the students were female. Several of the students did have prior design experience from high school but for many, this course was their first exposure to the work of design engineering and the challenges of working in a diverse design team.

4.3. PRELIMINARY FINDINGS

In Winter 2004 and Spring 2004, students in Designing the Human Experience used these tools to build electronic portfolio collections both as individuals and as teams, thereby creating tangible evidence of how they formulated and addressed various design challenges. Both quantitative and qualitative data were collected from surveys, interviews, classroom observations, and curricula materials. All of the students were interviewed at the end of both ten-week quarters about their experiences in the class. Although analyses are ongoing, we provide some selected examples and preliminary findings demonstrating how students have become more aware of their developing knowledge and skills, and the explicit connections that are made among aptitudes, knowledge, and skills and the real work of engineering.

One of our research interests was aimed at increasing student awareness of what they were learning about design. Table 1 gives some sense of student perceptions about what they learned about design more generally, beyond the scope of their specific projects. The slight differences between the two courses may be attributed to different class project assignments. Table 2 represents students' reports on the impact of the course on their confidence in their abilities to do design work as well as their continuing interest in design as a result of taking this course. At least two-thirds of the students in both classes viewed the experience as a positive one resulting in greater motivation, self-confidence, and interest.

TABLE 1. Percentage of Students Reporting "Moderate Progress" or "A Great Deal of Progress" Resulting from Taking ME013N: Designing the Human Experience

Progress made, because of this course, in your:	**Winter 04 (N=14)**	**Fall 04 (N=21)**
Understanding of what designers do in industry or as faculty members.	71%	71%
Understanding of design as a field that often involves non-technical considerations (e.g., economic, political, ethical, and/or social issues).	75%	61%
Knowledge and understanding of the language of design in engineering.	57%	71%
Knowledge and understanding of the process of design in engineering.	85%	75%
Ability to do design.	71%	62%

TABLE 2. Percentage of Students Reporting Increases in Design-related Confidence, Motivation, and Interest Resulting from Taking ME013N: Designing the Human Experience ('...' indicates 'moderately improved' or 'greatly improved')

The course was offered as an "experience" in design-thinking. As a result of your experiences in and through the course:	**Winter 04 (N=14)**	**Fall 04 (N=21)**
Your confidence that majoring in a design-related field is the right choice for you	65%	60%
Your confidence in your ability to become a designer has ...	78%	66%
Your motivation to become a designer has ...	64%	75%
Your sense of responsibility for your own learning has ...	71%	72%
The likelihood you will continue to take design-related classes has ...	71%	76%
The likelihood you will pursue a design-related career has ...	56%	71%

The relationship between the course and one's sense of responsibility for one's own learning is notable, particularly in Fall 2004 where there was a greater emphasis on the wikis and idea logs due to the resolution of prior technology glitches, a quicker roll out of the software, and the development of better scaffolding materials. Of the various course elements such as the course Tikiwiki site and both the individual and team idea logs/wiki pages, over 72% of the students indicated that the Broad Takeaway assignments were the most "important" or "crucial" to their understanding of design thinking. The 'Broad Takeaways' were extended reflections founded upon the earlier reflective notes and artifacts captured during the class; in these, students were expected to review and cite previous posts and course materials where appropriate. The following examples from student 'ePortfolios' may provide some additional insight into the relationship between the Broad Takeaways and increased student responsibility for learning.

Three Examples of Artifacts and Reflections from Student ePortfolios: Evidence of Learning?

Example 1 illustrates how students began to use the wikis and weblogs as a place to integrate design-related thoughts, resources, and experiences from outside of class into their current work. This article was scanned in by the student and included in a post along with accompanying reflections. From the perspective of the teaching team, this was a rich opportunity to gain some insights into how students, outside the class in activities that would normally be considered unrelated to the class assignments, were interpreting and applying the design principles presented in class.

Example 1: Late Night Revelation

1954 Article about the Economic Notion of Saturation of Market

As I was cleaning my room I chanced upon an article which I discovered a few weeks ago and wanted to comment on. I realized that it had a lot to do with design and our current class disposition to design.

the article is as follows:

OCTOBER 1954

The question is after reading this article... does it follow that a majority of designers are designing for "replacement needs"? I think so. Since, designers are constantly trying to make what exists better so that someone wants to buy a better version of what they already have. It is rare that we see a whole new market open up to provide "new" products to people. Yes, technology creates new niches but there is always a huge market for "redesign" Hence, I believe the biggest challenge that designers will face in the future is being wholly original in their concepts and ideas... at some point every idea is "tainted" by the influence of design in the world around us.

I would reflect more... but I'm dead... really really tired... so good night/good morning computer!

BYE

Example 2: This student artifact illustrates how skilled some of these "digital natives" are with their familiarity with Photoshop and digital video editing programs. In our final end-of-the-quarter presentations, all of the student teams used some kind of digital video as an illustrative example of observations or their prototype.

Example 2: People-based design

I have to admit that I am ridiculously proud of my team name idea. I think that "Humanitechie" and "Habitat for Humanitechie" very neatly capture the conundrums contained in our project. We had to design technology-containing environments for people, but for people who were used to their familiar, inflexible technology in the first place. The difficulty in trying to balance new technology with old habits cropped up frequently in our arguments.

Having "people" be the defining point of our designs, rather than "preciousness," was both more and less vague. It was less vague in the sense that we all know what people are; we are people. Whereas we do not have a firm hold on what preciousness "is," we do know who people are. That was evident in our ease of identifying problems with our project; we have a sense of how people will respond to our design, and although we often couldn't define the basis of that response exactly, we still know that there will be one.

Of course, "People" is more vague in regards to what exactly "people" is. Stanford's much-touted diversity is still just a tiny bit of the full range that exists. Everyone is different, as we've been told for as long as we can remember, and I'm unsure as to how that can fit with a project for such a specific demographic. Humanitechie tried to take into account people's differences in its design, but we still had to categorize to a certain extent in order to get anywhere. Though this sounds exclusivist, I don't think that we had a narrow-enough focus.

In the end, our name became exactly what we avoided. We couldn't categorize all computer science and graphic design people as "Humanitechies." We thought that building around a predetermined person with predetermined habits would only lead to a rearrangement of existing space and surfaces, so we went far off in the other direction. We came up with "cool" technology that could enhance teamwork, but I don't think that our ends justified our means. "People-centered design," the term I used in Humanitechie's executive summary, is an ideal that we didn't quite reach.

Example 3: This last artifact is a couple of paragraphs from a representative capstone reflection on the course as a whole. The impact of reflection on this student's learning lies primarily in how the student views the reflective activities that were integrated into the curriculum throughout the academic quarter. Evidence of how reflective thinking has influenced this student's learning is most clearly illustrated in these two paragraphs:

Another change in thinking I took from this class is not really design related, but from the wiki posting and reflection. I've never had a class that encourages so much reflection, and while it is tedious, I'm realizing how helpful it is. I'm understanding more and more the importance of taking responsibility for my own learning; this is something I am definitely going to keep doing for the rest of my college education, and even life. Knowledge is power, but if you're not aware of what you know, how can you use that power?

Also, I'm planning to use the takeaway of reflective thinking intensely for my college years, and beyond. While I've been aware of my education before, I think it's truly the mark of a higher education that the student takes responsibility for what they are learning, and is fully aware of the value of their time.

5. Conclusions and Next Steps

This paper presents preliminary findings and examples of several artifacts and reflections from student ePortfolios developed for an introductory freshman seminar on design engineering. We have only begun to analyze the large amount of data that we were able to collect. Our findings thus far suggest several provisional conclusions, and avenues for future work: Keys to initiating and maintaining the students' engagement in written and illustrated reflection in the wiki and weblog online environment include:

- Expressed reflection as a core expectation: establishing the use of the environment as a central part of the course from the first day;
- Concreteness: giving regular, clear, small assignments for reflection about specific class-related experiences, along with examples of good reflective writing, photography, drawing, excerpting from things encountered, seen, or read, etc.;
- Feedback: regularly engaging the students in conversations about what they are experiencing, how to generalize from the artifacts in their personal ePortolios, giving feedback to the whole class and to individual students, and encouraging the students to browse, learn from, and respond to what other students were creating;
- Robustness: keeping the software and hardware consistently reliable so that students could rely on not losing any of their hard-thought-out work.

This kind of reflective activity enhanced the students' experience beyond the often ephemeral details of each project, enriching this experience with a more general and overarching, personally-constructed viewpoint on design processes and how we experience and create the designed world. In future iterations of the course, we hope to examine other factors which may contribute to and influence students' learning in these classes. Some of our research questions include:

- Gender differences: what effect might gender differences have on self-confidence, awareness, and interest in continuing to take design courses that incorporate Folio Thinking pedagogy, idea logs, and team wikis?
- Self-selection: given the way that the courses were described in the introductory seminar catalog, are the students who are interested in these kinds of courses more amenable to reflective expression and learning?
- Long-term effects: if we were able to interview these students in their junior or senior year, would these students be any different in their thinking about design, their undergraduate education, learning styles, and choice of major, from students who had expressed interest in the course but did not actually take it?
- Textual analysis of reflection: Can we develop a rubric or other assessment tool to objectively evaluate the kinds and depth of reflection engaged in by the students, using proxy measurements such as coding and analysis of the text they wrote in their ePortfolios?

We believe that like email, wikis and weblogs will be increasingly included in the repertoire of familiar modes of interaction that students can be expected to use in their learning processes. These channels seem particularly suited to supporting the process of coached reflection, and we anticipate they will play a greater role in students' reflective learning experiences in engineering design and more broadly in higher education.

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CONTACT AUTHORS' EMAIL ADDRESSES

Bailey, T	tlbailey@stanford.edu
Bilda, Z	zafern@arch.usyd.edu.au
Cannon, D	dmcannon@cdr.stanford.edu
Chen, H	hlchen@stanford.edu
Dong, A	adong@arch.usyd.edu.au
Gabrio, J	jgabrio@stanford.edu
Ge, P	christine.ping-ge@oregonstate.edu
Gero, JS	john@arch.usyd.edu.au
Hsieh, P-H	Hsiehph@bus.oregonstate.edu
Kan, J	jeff_kan@hotmail.com
Kim, MJ	mkim9133@arch.usyd.edu.au
Leifer, L	leifer@sunrise.stanford.edu
Maher, ML	mary@arch.usyd.edu.au
Marchant, D	David.Marchant@woodsbagot.com.au
Shah, JJ	jami.shah@asu.edu
Shaheed, N	nsha7234@mail.usyd.edu.au
Smith, SM	stevesmith@tamu.edu
Toy, G	toye@withinc.com
Vargas-Hernandez, N	noevh@asu.edu

AUTHOR INDEX