INTERFACE DESIGN (6A)

IS AN ON-VIRTU DIGITAL SKETCHING ENVIRONMENT COGNITIVELY IDENTICAL TO IN-SITU FREE-HAND SKETCHING?

An Empirical Study of Protocol Analysis

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Abstract. This study demonstrates that an on-virtu digital sketching environment is cognitively almost identical to in-situ free-hand sketching. The former can support the designers' drawing activities with good resolution, and can provide remote communication in a face-to-face atmosphere. The study's empirical examination of the environment rested on protocol analysis and coding schemes of the design-prototype and the reflection-in-action. The results indicate that the two environments are similar in terms of design-process speed, design process, and design content. The results provide implications for CAD and design practice.

Keywords: computer-aided conceptual design: free-hand sketches; protocol analysis; design prototype.

1. Background

Conceptual design is perhaps the most crucial task in an industrial design development cycle. It sets up the direction for the following design process, and it embodies most of the innovative value of the product. It often involves interdisciplinary collaboration from customers, designers, and engineers. It can also have a powerful impact on manufacturing productivity and product quality since many essential decisions are made at this stage (Wang et al., 2002). Tremendous effort in design cognition research has been focusing on the roles of free-hand sketches in the conceptual design process (Purcell and Gero, 1998). Three major roles of sketches have been proposed by Suwa, Purcell, and Gero (1998). Therefore, free-hand sketches are indispensible to designers, especially in the conceptual design process.

Similarly, computer-aided conceptual design (CACD) systems have constituted an important topic for CAADRIA and design computing studies (van Dijk, 1995). Researchers have prototyped many inspiring CACD systems to prove the value of their underlying concepts (Gross and Do, 2004), and all of these systems rest on a digital sketching environment that mimics free-hand sketching behaviors. Despite all the inspiration and knowledge provided by CACD systems, there has been no empirical examination of whether digital sketching environments and free-hand sketches produce similar results in terms of the design process and results.

As the use of the Internet and Web became prevalent and globalized, there has been an increasing need for continuous collaboration among geographically far-flung design teams in design practice. A cursory observation of the current commercial CAD tools reveals that very few available tools support the conceptual design stage, where fuzzy customer requirements are transformed into functional specifications and multiple alternative designs (Wang et al., 2002). Therefore, this study serves to establish a computer-aided collaborative conceptual design environment with the support of designers' sketching behaviors and of communication in separate locations.

1.1. PROBLEM

There are problems in current computer-aided collaborative conceptual design environments with the support of designers' sketching behaviors and of communication in separate locations. First, regarding the fulfillment of designers' needs, the sketching environments are either too simple with low resolution, such as Internet whiteboards, or too complicated with multiple pull-down menus, such as three-dimensional modeling software. Second, most of the current sketch-based CAD systems do not fulfill the need for remote communication between collaborators. Finally, the CAD systems resolving the aforementioned problems do not provide cognitive empirical evidence comparable to the situation with pen-and-paper sketching and face-to-face communication. Given the low involvement therein of information technology, this study focuses on the third problem.

1.2. PURPOSES AND OBJECTIVES

The first objective of this study is to use current commercial hardware and software to establish an on-virtu digital sketching environment that fulfills the needs of remotely collaborative conceptual design. The second objective is to conduct an empirical examination of protocol analysis to compare the two sketching environments to each other. The third objective is to propose some suggestions for a future remote-collaboration conceptual design system.

2. Literature Review

The literature review covers protocol analysis and design paradigms.

2.1. PROTOCOL ANALYSIS

Since the first design protocol study in 1970, protocol analysis has been widely applied in the design community (Cross, 2001, Cross et al., 1996). Currently, protocol analysis has become one of the standard experimental techniques for exploring the process and the cognitive activities of designing (Ericsson and Simon, 1993; van Someren et al., 1994). Many important developments in the field have been scattered in different journal articles, books, and conferences (Cross, 2001; Cross, 2007; Cross et al., 1996; Eastman et al., 2001; Michel and Board of International Research in Design, 2007). Concurrent and retrospective protocols have been developed (Dorst and Dijkhuis, 1995). In terms of collaborative design, the dissemination of a concurrent protocol is natural because collaborative-design members have to communicate verbally with one another to carry on the design process.

2.2. DESIGN PARADIGMS

Two design paradigms in design studies are information-processing (Simon, 1992) and reflection-in-action (Schön, 1995), exploring issues concerning the design process and the cognitive behaviors of designers respectively. The representative coding schemes are of two varieties: the design prototype (Gero, 1990; Gero and McNeill, 1998), which provides an ontology of designed objects and their relationships in the design processes, and reflection-in-action (Valkenburg and Dorst, 1998), which provides a descriptive method for understanding the reflective aspects of the collaborative design process.

Before encoding the protocol, the transcripts have to be parsed into segments according to the designers' intentions (Ericsson & Simon 1993; McNeill, Gero, et al., 1998). Tang and Gero (2001) suggested that the number of segments in a design process corresponds to the design experience and the design performance.

2.2.1. Design Prototype

Function corresponds to three points: the users' needs, the services that the system provides, and the purpose of the artifact. Behavior corresponds to two points: the system's documented and actual requirements, and how the system and its sub-systems work. Structure corresponds to two points: the design of the system and its physical form (Kruchten, 2005). The number of functions represents the consideration of the requirements and the problems of the design project. A proper number of functions indicate that a designer spent enough time understanding the design problem, and similarly, an excessive number of structures in a design process indicate that a designer focused chiefly on drawing without sufficient understanding of the problem.

2.2.2. Reflection-in-action in a Design Team

Valkenburg and Dorst (1998) devised a coding scheme that consists of four activities: naming, framing, moving, and reflection. During the naming activity, the team is explicitly pointing to parts of the design as being important or is looking for relevant issues requiring special focus. During the framing–activity, the team is setting the context for the next activities or is framing a (sub) problem or a (partial) solution to explore further. During the moving activity, the team is trying to solve a problem by, for example generating ideas, drawing, and comparing concepts. During the reflection activity, the team is evaluating earlier activities to know what to do next.

We selected representatives of two design paradigms whose task was to encode our data. The rationale behind our selection concerned the representatives' ability to explore design processes rigorously. Most of the coding schemes facilitated exploration of design-process aspects, such as the roles of sketches and of communication. Few of the schemes focused on the entire design process and did so with strong theoretical supports. Design prototype and reflection-in-action were based on design paradigms and emphasized the nature of designing. Moreover, both of them have been applied in analyzing collaborative design processes.

3. Research Method

Using concurrent protocol analysis, this study provides an empirical comparison between in-situ free-hand sketches and an on-virtu digital sketching environment in collaborative design processes. The in-situ environment using **traditional media** centered on a huge table space for face-to-face collaboration with pen and paper. The on-virtu environment involved two separate rooms with two designers collaborating remotely. The latter environment also featured a 21.3-inch LCD tablet monitor with superior resolution and sketching software for each collaborator, and the operation therein was almost identical to that of the free-hand sketching. A shared digital whiteboard enabled each participant to see the other participant's drawings in real time. Video conferencing on another LCD monitor enabled participants to see each other and to communicate freely. Four digital cameras captured both the microscopic and the macroscopic views of the two spaces.

The current study is a typical protocol study. The data-collection rested on think-aloud protocol-analysis procedures in which subjects conducted collaborative design. According to the experimental procedure, the instructions and the design brief were announced, the warm-up was executed, the main experiment was conducted, a 5-minute subject-themed presentation of the design results took place, and an interview was conducted at the end. The 5-minute presentation and corresponding drawings were used as materials for expert judgment of the design results.

A design competition devised for this research served to help recruit subjects who were third-year industrial-design students in Taiwan. A group of two students qualified to join the competition, and they were free to select their partners from their classmates. In all, 10 groups of students—two-thirds of the class—participated in the design competition, and each team had to finish two design tasks respectively using *in-situ* and *on-virtu* environments in about 60 minutes. The two design tasks were (1) to design a USB flash drive that can protect you, and (2) to design a USB flash drive that can wake you up. The two design experts regarded the difficulty levels of the design tasks to be similar to each other. Marketing and supportive information about current USB drives were provided. It should be noticed that twenty subjects in total along with 20 design processes is a large number in design studies using protocol analysis.

2.1. ON-VIRTU ENVIRONMENTAL SETTING

Figure 1 illustrates the on-virtu collaborative design using **digital media** where two subjects, marked (1), were located separately in two rooms. The experiment instructions and the design briefs, marked (3), were provided. Four cameras, marked (5), and two digital cameras, marked (4), recorded the design process, with two experimenters, marked (2), taking memos for observational findings respectively in two rooms. The digital media included a WACOM digitizer and an ALIAS Sketchbook Pro, to establish a digital sketching environment. An LCD monitor and a web cam with MSN software in each room provided a face-to-face video image, and the subjects were virtually co-located. The settings for the digital media functioned to create a digital sketching environment that was almost no different from the traditional sketching environment.

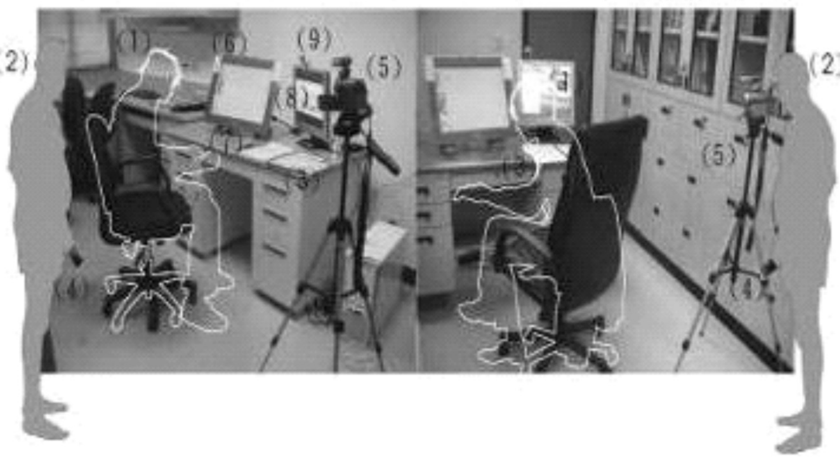

Figure 1. The experimental setting using digital media.

4. Findings

For each comparison, each team had two segment numbers, one for using digital media and the other for using traditional media. Table 1 shows the number of segments of each team using different media.

TABLE 1. The score of expert judgment and ranks for each design team.

Design Team	A	D	C	F	G	H	E	I	B	J
Digital Media	301	272	305	245	219	221	248	213	222	216
Traditional Media	253	280	235	275	294	290	246	251	201	196

To understand whether or not the different media influenced the segment numbers of the design teams' design processes, this study conducted Pearson's Chi-Square Test using SPSS crosstabs. Two categorical independent variables were design team and media, and the dependent categorical variable was segment numbers from encoded protocol data. The results show that there was no significant difference between the segment numbers in design teams when using different media (χ^2= 7.3, df = 9, p = .605).

To further understand the correlation between the segment number of digital media and that of traditional media, this study conducted Spearman's nonparametric analysis. Significant correlation was found (r = .964, p = .000, N = 10). This indicates that the design process of a design team produces a similar segment number, regardless of whether the team is in an on-virtu or an in-situ sketching environment. Therefore, the two sketching environments would appear to cause no difference in segment number, and thus to have little or no effect on design-process speed. On the basis of the segments, we continued to encode them using design prototype and reflection-in-action.

4.1. THE ENCODED PROTOCOL USING DESIGN PROTOTYPE

To coders encoded the raw protocol in terms of FBS. The segment number of the encoded protocol of the different categories in the design prototype is shown in Table 2. The table presents both the results of the traditional-media design process and the results of the digital-media design process.

TABLE 2. The segment number of the encoded protocol of the different categories for each team in terms of design prototype.

Team	*Traditional Media*			*Digital Media*		
	F	*B*	*S*	*F*	*B*	*S*
A	36	716	27	35	651	16
B	32	474	10	19	476	6
C	36	474	15	26	483	21
D	19	187	10	13	156	6
E	31	352	14	27	369	7
F	18	414	12	12	393	11
G	16	333	10	14	344	14
H	11	316	8	15	304	15
I	19	497	18	14	460	27
J	19	344	12	20	349	12

To understand the difference between the processes of the different media in each team, this study conducted a chi-square test to measure whether or not the use of different media changed the design process in terms of FBS. Two categorical independent variables were types of media and types of FBS, and the categorical dependent variable was the number of segments in each category. The process-related differences between each team's media are not statistically significant ($\chi^2 < 5.99$, df = 2). The environments of different media did not result in design-process differences regarding the function-behavior-structure triad. We can assume that the two design processes of each team are the same in terms of design prototype despite the teams' use of different media.

4.2. THE ENCODED PROTOCOL USING REFLECTION-IN-ACTION

Similarly, the raw protocol was encoded by two coders using reflection-in-action, and the analytical process is the same as in section 4.1. The frequency of encoded protocol using reflection-in-action is shown in Table 6. The table presents 20 design processes, 10 teams, and the two types of media.

TABLE 3. The segment number of the encoded protocol of the different categories for each team in terms of reflection-in-action

Team	*Traditional Media*				*Digital Media*			
	F	*M*	*N*	*R*	*F*	*M*	*N*	*R*
A	16	632	36	95	23	547	34	98
B	15	390	32	79	12	402	19	73
C	10	430	36	49	8	456	26	40
D	7	159	19	31	8	126	13	31
E	12	304	31	50	18	316	27	42
F	14	344	18	69	14	333	12	57
G	16	279	16	48	15	299	11	47
H	12	267	11	45	13	268	9	44
I	14	447	17	56	10	418	14	59
J	22	294	19	40	11	325	13	32

To understand the difference between the processes of different media in each team, this study conducted a chi-square test to measure whether or not the use of different media changed the design process in terms of NFMR. Two categorical independent variables were types of media and types of NFMR, and the categorical dependent variable was the number of segments in each category. The differences between media in each team are not statistically significant ($\chi^2 = < 7.81$, df = 3). The environments of different media did not induce differences in the distribution of the design-process encoded protocol. We can assume that the two design processes of each team are the same in terms of NFMR. Quantitative findings show no difference between the in-situ and the on-virtu environments for the ten design teams. These similarities are of statistical significance according to a chi-square test regarding the design-process speed, the design content, and the design process. Therefore, the current empirical study concludes that this on-virtu digital sketching environment is identical in several regards to the in-situ free-hand sketching. The significance is twofold. First, CACD systems could feature this environment when implementing their design-aid ideas, and the final products will be more feasible to designers. Second, on-virtu collaboration on conceptual design is possible since it affects neither the design process nor the results. This study should influence design practice for remote collaboration.

5. Conclusions

This study establishes an on-virtu digital sketching environment being identical in several regards to in-situ free-hand sketching. The former environment can support the designers' drawing activities with good resolution, and remote communication with a face-to-face atmosphere is entirely possible. The environment was empirically examined through protocol analysis and coding schemes of two varieties: the design-prototype variety and the reflection-in-action variety. The results indicate that the two environments are similar to each other in terms of design-process speed, design process, and design content.

The results provide implications for CAD and design practice. For CAD systems, the environment discussed in this study might be a foundation for the establishment of future computer-aided collaborative conceptual design systems that can fulfill the needs of designers. Our digital environment settings demonstrate not the diversity of engineering tools and the dynamics of design environments, but the essential elements attributable to remote-collaboration conceptual design that requires high levels of freedom and visual representation. However, more studies should compare the current digital settings and the computer-aided conceptual design systems provided by research groups and related industry in the field.

For design practice, remote collaboration is feasible in the preliminary design process, which indicates the era of global design teams in separate locations. Moreover, this study shows that the requirements of CAD systems for designers differ from the corresponding requirements for engineers. Although designers might not need sketches to produce a design (Bilda, Gero, and Purcell, 2006), the features of free-hand sketches are still indispensible for stimulating creativity in design. However, even if it is possible to conduct collaborative conceptual design, many variables affect the remote design process.

Future research should treat the abilities possessed by designers using digital media. It has been proposed that different media could affect the behaviors of designers, especially digital media. The designers of younger generations have grown up in highly digital environments. It would be interesting to explore the influences of digital media on their design processes.

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