

# **Comparing Collaborative Co-located and Distributed Design Processes in Digital and Traditional Sketching Environments: A Protocol Study Using the Function-Behaviour-Structure Coding Scheme**

## **Abstract**

This study compares the design processes of designers in both digital and traditional sketching environments, where the digital environment emulates the traditional face-to-face, pen-and-paper environment. The design processes were empirically examined through protocol analysis using a coding scheme based on the function-behaviour-structure ontology. The distributions of the different types of segments, and their transitions in the two environments were quantitatively compared using Chi-Square tests and Paired-T tests. The results indicate that the design processes in the two environments were not statistically different in terms of their distributions and transitions. The higher-level cognitive activities were not affected by the change of medium. Some implications for design computing and design practice are discussed.

Keywords. Computer-aided design; drawings; collaborative design; protocol analysis; function-behaviour-structure

Conceptual design is perhaps the most crucial phase in the design development cycle. During this phase, designers set up the direction for the following design process, incubate creativity, and embody most of the values into design artefacts. Relatively unstructured and ambiguous sketches are created during this process. Designers often place great emphasis on these

sketches, because they are thought to be associated with creativity (Herbert, 1988). In terms of human cognition, sketches promote the dialectical process between a sufficiently specified and coherent physical form, and abstract, conceptual, propositional knowledge (Goldschmidt, 1991, 1994). The use of sketches produces benefits not only as an aid to memory, but also in perceiving visuo-spatial relationships and reasoning about functional issues and goal-setting (Suwa & Tversky, 1996). Sketches are representations of the results of thinking process, decreasing the cognitive load of designers, and they are also involved in provoking creativity during designing (Suwa et al., 1998). In design cognition research, considerable effort has been focused on the roles of free-hand sketches in the conceptual design process and their relationship to designers' cognition (Purcell & Gero, 1998). Free-hand sketches are especially important to designers in the conceptual design process for sketches constitute a particular form of symbolic system characterised by syntactic and semantic denseness and by ambiguity that potentially can be used to generate more lateral transformations for design creativity (Goel, 1995). Syntactic disjointness and differentiation increase the syntactic denseness, for example, a system where each drawing belongs to not only one symbol type and is not clearly differentiated from other drawings has more syntactic denseness. Similar, semantic disjointness and differentiation increase the semantic denseness, for example, a system where the drawings and their referents are not fixed has more semantic denseness. Ambiguity of a system indicates the relationship amongst symbols, drawing and referents are not unchangeable (Goel, 1992). These features of sketches allow new ways of seeing and reinterpreting sketches that could provide new forms and abstract concepts. The convenience and speed of using sketches enable designers to generate and represent ideas easily and quickly.

In design computing research, establishing a computer-aided conceptual design (CACD) system has been an important topic (Dijk, 1995). The disadvantages of the current state of CACD indicate that few digital tools exist to address the early phase of the conceptual design, where fuzzy customer requirements are mapped to function specification and ideas are developed (Wang et al, 2002). Some regard computer-aided design as an inappropriate means for conceptualization (Lawson & Loke, 1997; Purcell, 1998; Verstijnen et al., 1998). This situation may result from the abilities of most current computer-based drawing systems. They are often non-dense and unambiguous in representations that potentially impede transformations, which play an important role in the conceptual design process. However, the computer has emerged as an ideation tool across design domains (Jonson, 2005). Some studies have compared the process of preliminarily computer-aided sketching to the process of free-hand sketching (Plimmer & Apperley, 2002; Bilda & Demirkan, 2003). Currently, a dense and ambiguous representation for CACD is still difficult. To solve this problem, other research has proposed proof-of-concept CACD systems that provide support for different cognitive activities involved in the conceptual design process. In this category, many promising CACD systems have been prototyped to demonstrate their concepts (e.g. Gross & Do, 2004), all of them are based on a digital sketching environment that mimics free-hand sketching behaviors. Despite all the inspiration and knowledge provided by these CACD systems, two problems remain. The resolution and drawing quality of these CACD prototypes is worse than that of pen-and-paper, and there has been little empirical examination of the usability and validity of these systems.

If CAD systems have a digital environment that adequately emulates the features of pen-and-paper, the design process of a designer in this digital environment would be similar to his/her design process in the traditional pen-and-paper environment. The purpose of this study is to empirically examine the differences between the design processes in digital and traditional environments, where a digital environment is a dense and ambiguous CACD

system emulating pen-and-paper behaviours and a traditional environment is pen-and-paper. The design processes are examined using concurrent protocol analysis in collaborative design teams. The function-behavior-structure (FBS) model of design is utilized to explore the design issues and transitions in the design process. They represent the content of the design process. Encoded results of protocol analysis with FBS would show the differences of the design processes resulting from digital and traditional environments.

## **1. Protocol analysis**

Protocol analysis is a widely used technique to study design processes and the cognitive activities involved in designing (Cross, 2001; Cross et al., 1996; Ericsson & Simon, 1993; Someren et al., 1994). Protocol studies have been extensively used to explore problem formulating, solution generation, and process strategy in the design process (Cross, 2001). The design disciplines examined include architecture, industrial design, mechanical engineering, electronic engineering, and software design, amongst others.

The procedure of protocol studies involves proposing a hypothesis or direction of observation, experimental design and subject recruitment, conducting experiments, transcribing protocols and material generated in the design process, devising coding scheme, encoding protocols, quantitative and qualitative comparison of encoded protocols, and finally proposing results (Ericsson & Simon, 1993; Someren et al., 1994). The most influential steps are selection of a coding scheme and the encoding process.

A large variety of coding schemes have been employed in protocol studies in design. Very few coding schemes have been re-used by researchers other than those who established them. Most of the coding schemes that have been re-used by different researchers were produced in continuous research papers under the same supervision. The Function-Behavior-Structure model of design (Gero, 1990; McNeill et al., 1998) and linkograph devised by Goldschmidt (1990, 1992, 1994, 1995) are examples.

Two types of protocols were divided according to the way experiments proceed (Ericsson & Simon, 1993). Concurrent protocols are obtained from verbalization of a subject's thinking while he/she is working. Retrospective protocols are obtained from verbalization of a subject's recall of thinking after he/she has finished works. Protocol studies of the individual design process have utilized both types of protocols according to the nature of the research problem. Process-oriented design studies tend to use concurrent protocols, while content-oriented design studies tend to use retrospective protocols (Dorst & Dijkhuis, 1995).

Both concurrent and retrospective protocols have been further developed. In terms of collaborative design, the process of obtaining concurrent protocols is natural without interference or requirements from researchers because members of collaborative design teams have to communicate verbally to carry on the design process. The protocol in collaborative design is not the collection of the thinking processes of individual members but the collection of the communicative and argumentative processes of the members. Most study regards this kind of protocol the representation of the design process of a design team.

The latest developments in protocol analysis are scattered in different journal articles, books, and conference publications (Cross et al., 1996; Cross, 2007; Eastman et al., 2001; Michel, 2007; McDonnell & Lloyd, 2007). Improvements on the methodology have been proposed, such as video-recording retrospective protocols (Suwa et al., 2000), linkography (Goldschmidt, 1994), and measurement-based tools (Gero & Kan, 2009; Kan & Gero, 2008).

### **1.1 The Function-Behavior-Structure Ontology**

Two design paradigms in design studies are information-processing (Simon, 1992) and reflection-in-action (Schön, 1995), which explore design process issues and the cognitive behaviors of designers, respectively. Protocol studies in design have utilized these paradigms in encoding the design process. Two coding schemes based on the paradigms are the function-behavior-structure (FBS) approach (Gero, 1990; Gero & Mc Neill, 1998), which provides an ontology of designed objects and their relationships in the design processes, and reflection-in-action (Valkenburg & Dorst, 1998), which provides a descriptive method for understanding the reflective aspects of the collaborative design process. Recent research has shown that these coding schemes can be mapped onto each other (Gero and Kannengiesser 2008). This paper presents the results using the FBS approach.

The Function-Behavior-Structure (FBS) model of designing was initially developed by Gero and his colleagues (Gero, 1990; Tham et al., 1990). The elements of the model have been extended to cover broader cognitive issues (Gero & Kannengiesser, 2004). For example, the FBS model has been adapted into a descriptive model that integrates the design process with processes from cognitive psychology. The model links different operations to types of outcome from both disciplines (Howard et al., 2008). FBS as both prescriptive and descriptive models have been extensively discussed (Vermaas & Dorst, 2007). As a result, FBS model is one of the representative models that could be utilized in understanding the design process and can be used as an ontology. This study applied the FBS ontology as its coding scheme.

To apply the function-behaviour-structure ontology in encoding the protocol, the transcripts have to be parsed first into segments according to the designers' intentions (Ericsson & Simon

1993; McNeill et al., 1998). In terms of encoding, function corresponds to the users' needs, the service the system will provide, ie the purpose of the artifact. Behavior corresponds to the system's expected and actual performances, ie how the system and its sub-systems work. Structure corresponds to the resulting forms of the designed artefacts in terms of its elements and their relationships. Details of the system are shown at Figure 1, including the separation of behavior and documentation. This FBS ontology has been applied and compared in different disciplines (Kruchten, 2005).

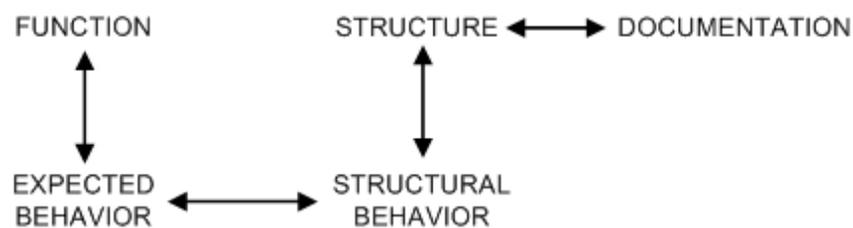


Figure 1. The structure of the FBS ontology (Gero, 1990)

## 2. Methods

This study uses the concurrent protocol analysis approach to produce an empirical comparison between the design processes in digital and traditional sketching environments in collaborative design. The primary experimental variable in this study was the change from one production environment to another. The experimental design section describes details of the experimental settings and procedures, while the analysis section describes the methods by which we statistically examined the design results and the encoded protocols.

### 2.1 Experimental Design

This section describes the experimental design, including participants, the design brief, the settings of digital and traditional environments, and the experimental procedures.

#### *Participants*

A design competition devised for this research was held to recruit participants from third year industrial design students at Chang Gung University in Taiwan. A group of any two students in the third year class was qualified to join the competition, and they were free to select their partners from their classmates. Ten groups of students, two thirds of the class, participated in the design competition, and most of the collaborators had previous experience of working together. Six participants are male, and 14 are female. The average age is 20.35 years with a standard deviation of 0.73 years. Each team had to finish two design tasks, one using the traditional and one using the digital environment, in about 60 minutes. Half of the teams started with the traditional environment, and the other half started with the digital environment. Twenty participants in total is a relatively large number for design studies using protocol analysis.

### *Design Brief*

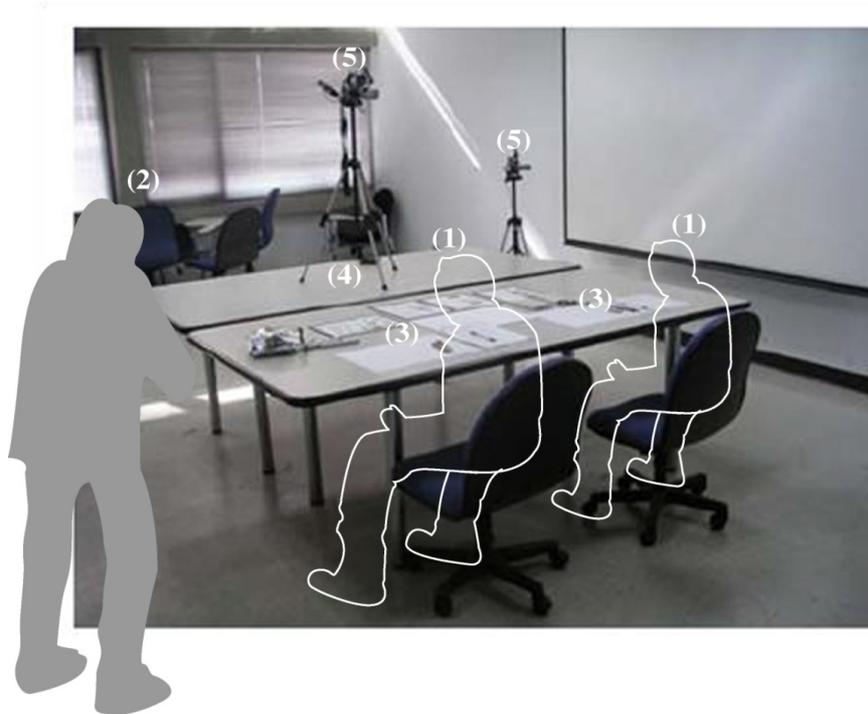
The two design tasks were to design a USB flash drive that can protect you, and a USB flash drive that can wake you up. The level of difficulty for both tasks was measured to be similar by two design experts in the Industrial Design Department of Chang Gung University, while the distinct differences of the requirements could prevent the occurrence of the learning effect between tasks. The design brief provided a brief description of the design task, requirements for the form and style, requirements for the function, the target, and the ways of presenting the final results on a sheet of paper with images. Additionally, marketing and supporting information about current USB drives, and criteria for assessing the final results, was provided.

### *Evaluation*

At the end of the design session, each team was required to produce an A3 poster to represent their results and give a two-minute presentation to explain their ideas. In design competitions generally, judges evaluate design results by examining participants' posters, and only the finalists have the chance to describe their design verbally. In our research, both the final A3 poster and the presentation video of each were provided to the six expert judges to evaluate the final results. The posters and presentation videos helped the judges to perceive the participants' design ideas more completely, and thus to assist them to produce more accurate scores. The seven criteria for evaluation were: design concept, functionality, material utility, scenario, innovation, style and form, completeness. Scores ranged from 1 ~ 9. The design results were ranked according to the sum of the scores of these seven criteria.

#### *Digital and Traditional Environments*

The traditional sketching environment was a large table space (D x W x H = 110 cm x 225 cm x 75 cm) for face-to-face collaboration using pen and paper. The participants could move freely, but most of the collaborators sat side-by-side. Two digital cameras captured both the microscopic and macroscopic views in the space, as shown in Figure 2.



*Figure 2. The experimental setting using traditional media*

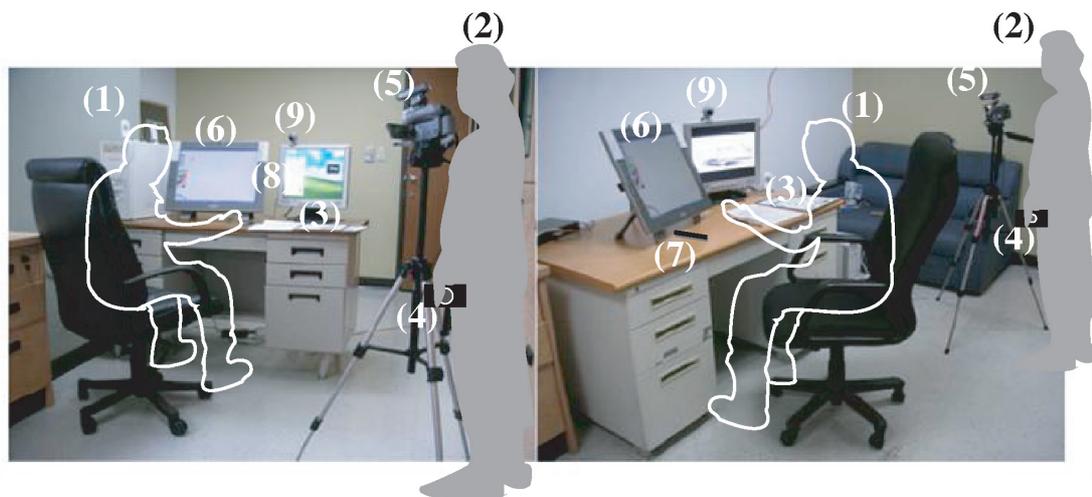
The digital environment was devised to emulate the traditional sketching environment, as shown in Table 1. The digital environment was located in two separate rooms, with two designers collaborating remotely. A 21.3 inch LCD Wacom tablet monitor with high resolution and sketching software was provided for each designer. A digital shared whiteboard enabled each participant to share drawing desktops in real time, using Ultra VNC software. MSN video conferencing software with LCD monitors on both sides enabled participants to see their collaborator's facial expressions and gestures. Two digital cameras captured macroscopic views of both spaces, while CAMTASIA, a monitor recording software, recorded changes in the shared drawing space. Alias Sketches Book Pro was the sketching software that emulated the pen-and-paper environment. With both the Wacom tablet monitor and Alias Sketches Book Pro, we had an environment that fulfils the criteria of ill-structured

representation. This environment enables the designer to draw freely without predefined shapes. Each drawing stroke can be overlapped with one of a different density. It thus has syntactic and semantic density and ambiguity, the features of a pen-and-paper environment.

*Table 1. The comparison of traditional and digital environments*

	Traditional Environment	Digital Environment
Location	Co-located	Emulating being co-located using Ultra VNC (Sharing Desktop)
Communication	Face-to-Face	Emulating being Face-to-Face using MSN (Net Conferencing + extra LCD monitor)
Media	Pen-and-Paper	Emulating Pen-and-Paper using Wacom Cintiq 21 + Alias Sketches Book Pro

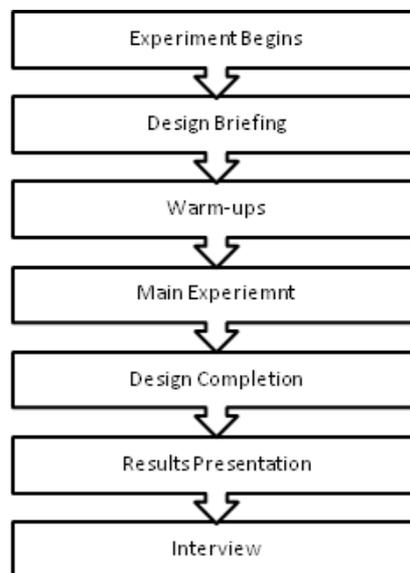
Figure 3 illustrates the digital sketching environment, where two participants, marked (1), were located separately in two rooms. The experimental instructions and design briefs, marked (3), were provided. Two digital video cameras, marked (5), were utilized to record the design process with two experimenters, marked (2), each taking observational notes in one of the two rooms.



*Figure 3. The experimental setting using digital media*

### *Procedure*

Data were collected using the think-aloud analysis protocol because collaborators had to verbalize their thoughts in order to communicate their concepts and to present ideas. The experimental procedures were first, announcing the instructions and design brief, a warm-up exercise, the main experiment, completion of design, presentation of design results for two minutes, and an interview at the end, as shown in Figure 4. The two-minute presentation and corresponding posters were used as materials to evaluate the design results.



*Figure 4. The experimental procedure*

Each team alternatively worked once with the traditional environment and once with the digital environment. Each team had no warm-ups for the traditional environment, and two warm-ups in the digital environment. The warm-ups for the digital environment task were the followings. First, each participant became acquainted with the basic operations of Alias Book Pro by him/herself for 20 minutes. Second, the team members became acquainted with how to communicate and share the drawing table via the integrated systems of the digital environment, for 15 minutes. Both warm-up exercises were guided by instructions. Completing all 20 experiments took two months.

## 2.2 Analysis

The raw materials of the experiments included video footage of the design process and the designers' presentations of the results, sketches produced in the design process, the posters of the design results, and interviews at the end of the experiment. They were utilized to produce scores, segment numbers, and encoded protocols. In the analysis section, we describe how this study quantitatively compared the differences between the design processes of traditional and digital sketching environments using scores, segments and encoded protocols.

### *Scores*

Four judges from academia and two from industry were involved in the evaluation process, which was based on the presentation videos and result posters of each team. They were not aware of the existence of the two types of sketching environments. Each design received scores from the six judges on 7 criteria, ranging from 1 ~ 9, and thus a full mark would be 378 (9 x 7 x 6), and each design received a total of individual 42 scores.

### *Segmentation and Encoding of Protocol*

The audio of the video recording was transcribed into protocols. Two coders conducted segmentation and encoding of protocols based on the videos of the design processes and the corresponding sketches. Protocols were parsed into segments based on the criterion of a single code for a single segment, and they were simultaneously encoded using the function-behaviour-structure coding scheme in a single process. An example of an encoding for team A is shown in Table 2.

*Table 2. An example of encoded results*

Segment Number	Designers	Protocol	F-B-S
5	A1	Anti-lecher Spread	F

6	A2	I feel it might be good to use	B
7	A1	It is too short to protect yourself. How about a taser series?	B
8	A2	And I have been thinking about pushing a knife, but it hurts me	B
9	A1	So do not use a knife to protect yourself. Is there other thing to protect yourself?	B
10	A2	Spread	F
11	A1	Spread and taser	F

A working definition of the function-behavior-structure is the followings. A *function* segment contains content about the intentions, hypothesis, and ideas about the designed objects, and the concerns about how users behave. For example, “so it can wake you up”, “serves like a key ring”, “they may want this to be safe”. A *behavior* segment contains content about the analysis, explanation, evaluation, and integration of how the objects being designed operate and the concerns about the human-machine interactions. For example, “the size is big but easy to carry”, “it could be inflated”, “users can put this into their pockets”. A *structure* segments contains content about the physical features of the objects being designed, such as sizes, color, shapes, materials, and concerns about the similar products that already existed in the market. For example, “metal”, “the size of the surface”, “green light”,. These definitions are established according to the original theory of FBS, the knowledge of industrial design, and the experience from the encoding process. The complete encoding of the 20 design processes took around 18 months.

### *Statistical Examination*

The encoded protocols were utilized as data to compare the design processes in the digital and traditional environments. The values that were compared included:

1. scores of the judges,
2. number of segments,
3. frequencies and distributions of encoded segments of function-behaviour-structure, and
4. transitions between encoded segments.

The number of segments represents the number of issues/topics/ideas considered during the design process. The frequencies of encoded segments in each type of F, B and S represent how many times the team considered this class of issue. The transitions between encoded segments represented two kinds of events: first, activities transforming a design issue into another and, second, transitions between adjacent segments. Gero (1990) has provided clear descriptions of the first kind of event, and precise mapping between the transitions and the activities of a theoretical model of the design process. In this study, we however did not distinguish these two kinds of transitions.

The quantitative data were examined by two statistical methods. First, a Chi-Square test to examine whether the differences between the observed data in digital and traditional environments were statistically significant. If no statistically significant difference existed, Paired-T tests were then done to examine whether the correlations between the observed data in digital and traditional environments were statistically significant. For example, a high correlation between the design processes in digital and traditional environments would indicate that the digital environment did not change the design process. This would imply that the design processes produced by the same team exhibited a high correlation between the design issues considered and the design activities involved in both the digital and traditional environments. The following section presents the comparative results of these analyses.

### **3. Comparative Results**

In this section, we present the comparative results of the design results, the number of encoded segments, and the number of transitions between encoded segments.

#### **3.1 Comparing the Design Results**

We initially examined the differences between the design results, the posters of the final design result and the scores provided by the six judges. We found that it was not easy to distinguish which poster was created in the digital sketching environment and which was

created in the traditional environment. This provided good qualitative results, compared to previous CACD research where the design results provided by CAD were easy to identify. Figure 5 shows the posters produced by Team D in both environments. Others can be found in the Appendix.

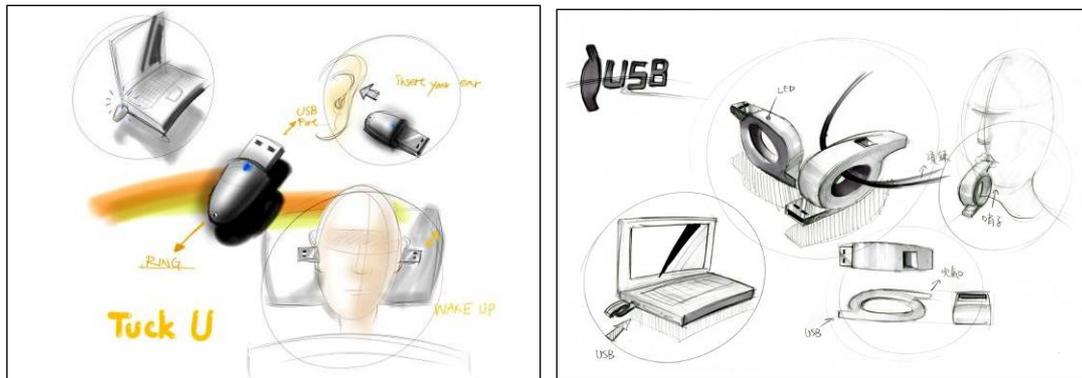


Figure 5. The posters of the final design results of Team A in digital and traditional environments. The left poster was done in the digital environment.

Table 3 shows the judges' scores of the ten teams in both the digital and traditional environments. The average score of design results in traditional environments was marginally higher than that in digital environments. Half of the ten teams, teams A, B, D, F and H, however, had better scores in the digital environment than in the traditional environment.

Table 3. The judges' scores of 10 ten teams in digital and traditional environments

Design Team	A	B	C	D	E	F	G	H	I	J	Avg	S.D.
Digital Env.	301	248	221	222	213	305	272	216	245	219	246.2	33.3
Traditional Env.	260	246	285	201	255	235	282	196	275	294	252.9	34.0

A Pearson Chi-Square test showed a significant difference of scores between digital and traditional environments ( $\chi^2 = 37.94$  df=9 p= 0.00). However, the influence of environment

on the scores was not consistent. The digital environment did not always produce the same effect on the scores.

### 3.2 Comparing Segment Numbers

For each comparison, each team had two segment numbers, one for using digital and one for traditional media. Table 4 shows the number of segments for each team, using the different media.

*Table 4. The number of segments*

Design Team	A	B	C	D	E	F	G	H	I	J	AVG.	S.D.
Digital Env.	702	503	530	178	403	416	372	334	501	381	432.0	138.9
Traditional Env.	780	514	525	216	397	445	359	335	534	375	448.0	152.9

To understand whether the different media influenced the segment numbers of the design processes of the design teams, this study conducted a Pearson 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 shows that there was no significant difference of segment numbers in the design teams across the different media ( $\chi^2 = 7.3$  df=9 p=.605).

To further understand the relationship between the segment numbers for digital media and those in traditional media, this study conducted a Spearman nonparametric analysis to evaluate their correlations. Significant correlation was found ( $r = .964$  p=.000 N=10). This indicates that the design process of a design team produces similar segment numbers, regardless of whether they are in the traditional or digital sketching environment. Therefore, the two sketching environments do not cause differences in the number of the segments in the design process.

### 3.3 Comparing the Distributions of Function-Behaviour-Structure

The raw protocol was encoded by two coders in terms of function, behaviour, and structure. The numbers of segments in the encoded protocols in the different categories of FBS are shown in Table 5, where the results of the design process using both traditional and digital media are presented.

*Table 5. The number of segment in different categories for each team in terms of FBS*

Team	Traditional Media			Digital Media		
	F	B	S	F	B	S
A	36	717	27	35	651	16
B	32	473	9	19	478	6
C	36	474	15	26	483	21
D	19	187	10	13	159	6
E	31	352	14	27	369	7
F	18	415	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
Mean	23.7	410.8	13.5	19.5	399.0	13.5
SD	9.1	142.3	5.6	7.6	130.6	6.8

Figure 6 shows the box plots of the numbers of segments in each of function, behaviour and structure for all the teams when using traditional and digital media. The box plots graphically depict groups of numerical data through their five-number summaries (smallest observation, lower quartile, median, upper quartile, and largest observation).

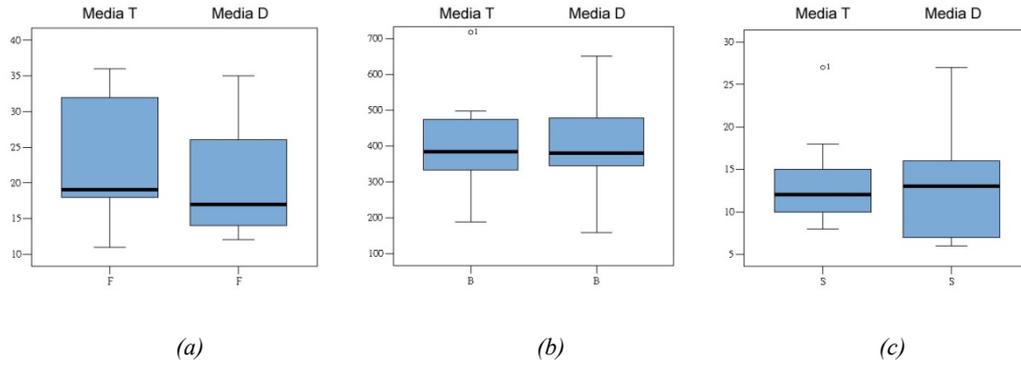


Figure 6. The box plots for the numbers of (a) function, (b) behaviour and (c) structure segments of the ten teams for the traditional media (Media T) and digital media (Media D)

To understand the differences between the processes in the different media for each team, this study conducted Chi-Square Tests to measure whether the digital and traditional environments caused differences on the issues designers considered in the design process, in terms of FBS. The two categorical independent variables were the type of environment and the type of FBS, and the categorical dependent variable was the number of segments in each category of FBS. The differences of processes between environments in each team were not statistically significant ( $\chi^2 < 5.99$   $p > .05$   $df=2$   $N=2$ ). Differences between the digital and traditional environments did not result in a significant difference in the design issues considered in the design process, in terms of function-behaviour-structure.

In order to better demonstrate the similarities between the design processes in both digital and traditional environments, we divided each session into thirds and drawn the box plots for each of the number of segments for function, behaviour and structure, of all teams in both the digital and traditional environments, Figure 7. The box plots graphically depict groups of numerical data through their five-number summaries (smallest observation, lower quartile, median, upper quartile, and largest observation). They display differences between the two environments in terms of FBS and thirds.

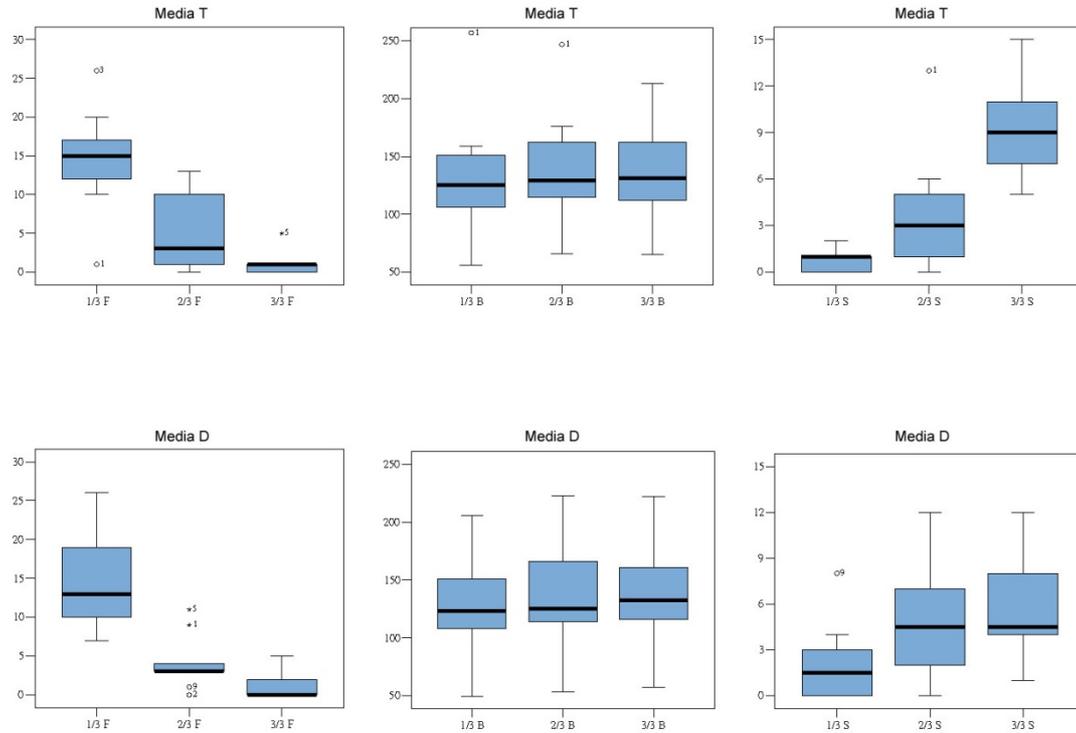


Figure 7. The box plots of the number of Function-Behavior-Structure segments for each one-third of the design process for Teams A~J on Traditional (Media T) and Digital Environment (Media D) .

Figure 7 shows that distributions of FBS segments were similar in both environments. We then assessed this in terms of each team and each category of FBS, to determine statistical correlations. For each team, the numbers of segments in both environments and FBS were organized in terms of a 2 x 3 table. Pearson's Chi-Square was used to test the difference of distribution in FBS. The results showed that the distributions of the 10 teams were not significantly different ( $p > .05$ ) in Table 6. This means that each team had similar distributions of FBS in digital and traditional environments, and thus the digital environment did not cause differences in the design process in terms of FBS, compared to the traditional environment.

Table 6. Pearson Chi-Square values and significances for differences between the FBS distributions of two media in the 10 teams

	A	B	C	D	E	F	G	H	I	J
Pearson Chi-Square	0.384	0.148	0.263	0.693	0.227	0.648	0.688	0.226	0.23	0.993
Sig	0.379	0.145	0.261	0.691	0.222	0.646	0.687	0.222	0.229	0.993

We further examined correlations between the design processes in the two environments in terms of FBS. For each FBS, the segment numbers of the 10 teams and in both environments were aggregated, to form a 2 x 10 table for performing the Paired-T test. The results showed, in function, behavior and structure that the paired segment numbers in both environments demonstrated no significant difference, while there were strong correlations between the numbers of segments for functions and behaviors in digital and traditional environments, as shown in Table 7.

Table 7. The results of Paired-T test, correlations and their significance of the relationship of the numbers of segments for function, behavior and structure between traditional and digital media for the 10 teams

Function	Behaviour		Structure	
Correlation	0.833	sig 0.003**	Correlation	0.985 sig 0.000**
Paired-T test	2.641	sig 0.027	Paired-T test	1.412 sig 0.192
			Paired-T test	0.000 sig 1.000

The correlation for structure was much lower than for function and behaviour. We can infer that the environments changed the way designers considered structural issues, but these were not significantly different. However, in terms of higher cognitive activities described by function and behaviour in FBS, the results showed high correlation in the numbers of segments of both function and behaviour in digital and traditional environments. Therefore, the environment influences a designer's approach to structural issues, but not behavioural and functional issues. Behavioural and functional issues represent high-level cognitive behaviours of designers.

### 3.4 Comparing the Transitions between Segments

After examining the differences of design processes in the two environments by comparison of the segment codes as design issues that designers were concerned with, this study continued to explore the differences between the design processes in two environments through an examination of the transitions between segments, in terms of FBS. There are nine types of transitions, comprising: F-F, F-B, F-S, B-F, B-B, B-S, S-F, S-B and S-S. The transitions between function-behavior-structure were based on the transitions between adjacent segments, and thus the total number of transitions was the total number of the segments minus one for each design session. The numbers of segments in each of the nine transitions of the 10 teams are shown in Table 8.

*Table 8. The numbers of transitions between FBS in the 10 teams, for both environments*

		<b>F-F</b>	<b>F-B</b>	<b>F-S</b>	<b>B-F</b>	<b>B-B</b>	<b>B-S</b>	<b>S-F</b>	<b>S-B</b>	<b>S-S</b>	Total
A	T	3	33	0	33	663	21	0	20	6	779
	D	1	34	0	34	602	14	0	14	2	701
B	T	4	28	0	27	437	8	0	8	1	513
	D	4	15	0	14	457	6	0	6	0	502
C	T	4	32	0	32	427	14	0	14	1	524
	D	4	22	0	22	442	18	0	18	3	529
D	T	3	15	0	14	164	9	1	8	1	215
	D	1	12	0	12	142	4	0	4	2	177
E	T	3	28	0	28	309	14	0	14	0	396
	D	2	24	1	24	338	6	1	6	0	402
F	T	5	12	1	13	392	9	0	10	2	444
	D	1	10	1	10	373	9	1	9	1	415
G	T	0	16	0	15	309	8	0	8	2	358
	D	0	14	0	14	316	13	0	13	1	371
H	T	1	10	0	10	298	7	0	7	1	334
	D	0	14	1	15	276	12	0	13	2	333

I	T	1	17	1	18	465	13	0	14	4	533
	D	1	12	0	11	425	24	1	23	3	500
J	T	2	17	0	17	314	12	0	12	0	374
	D	0	20	0	19	317	12	1	11	0	380
Mean	T	2.6	20.8	0.2	20.7	377.8	11.5	0.1	11.5	1.8	
SD	T	1.6	8.5	0.4	8.5	133.6	4.2	0.3	4.1	1.9	
Mean	D	1.8	18.5	0.3	18.3	364.5	11.5	0.3	11.4	1.6	
SD	D	1.5	7.4	0.5	7.4	123.5	6.1	0.5	5.9	1.2	

Figures 8 and 9 show the number of transitions for the ten teams combined for both the traditional and digital environments.

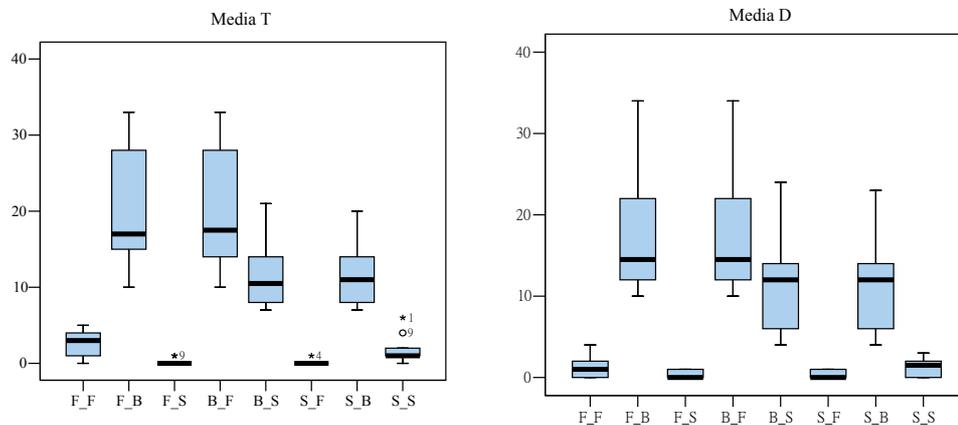


Figure 8. The box plots for the number of transitions of the ten teams combined excluding B-B, since the absolute values of the B-B transitions are one order higher than all the other values.

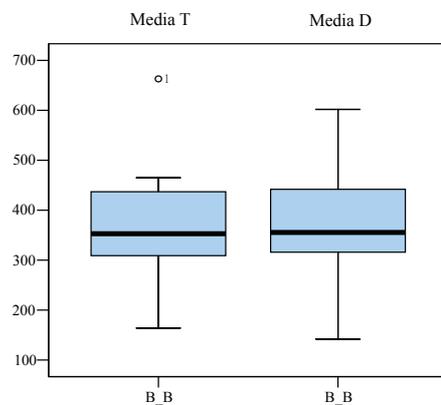


Figure 9. The box plots for the number of the B-B transitions for the ten teams combined

We assumed the transition between adjacent segments meant either a change of focus or one of the reasoning processes in FBS. These could be: synthesis, analysis, evaluation, formulation, and reformulation. Some transitions would be the result of a change of focus rather than an indication of a process. Some transitions have very few instances, for example: F-F, F-S, S-F, S-S. We listed the numbers of transitions in both environments for each team, to form a 2 x 9 table. The differences between the distributions in different environments were examined using the Pearson's Chi-Square test, as shown in Table 9.

*Table 9. Pearson Chi-Square values and significance for differences between the distributions of transitions between FBS of each of the 10 teams in terms of traditional and digital environments*

	A	B	C	D	E	F	G	H	I	J
Pearson Chi-Square	0.632	0.127	0.430	0.778	0.163	0.739	0.742	0.336	8.903	0.762
Sig	0.613	0.106	0.422	0.722	0.121	0.626	0.737	0.268	0.113	0.606

The results show that all the differences were not significant ( $p > .05$ ), meaning that the distributions of different transition numbers in both environments were similar. We further aggregated the numbers of each transition in the two environments for the 10 teams to form a 2 x 10 table, to examine the correlations between the numbers of each transition by Paired-T test. The transitions of F-F, F-S, S-F, S-S were not included because the number of segments was too small to run Paired-T tests. The results show that the transitions of B-B, B-F, B-S, F-B, S-B in the two environments were of no significant difference, while the transitions of B-B, B-F, F-B had significant correlations, as shown in Table 10.

*Table 10. Paired-T test values, correlations, and significance of relations in transition numbers between FBS in terms of traditional and digital media, for the 10 teams*

B-B	B-F	B-S	F-B	S-B
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Correlation	0.972	0.765	0.354	0.784	0.416
Sig	0.000**	0.010*	0.315	0.007**	0.232
Paired-T test	1.123	1.829	-0.157	1.835	-0.113
Sig	0.291	0.101	0.879	0.100	0.912

In this section, we compared the design processes of the 10 teams in digital and traditional environments in terms of the coded segment, and transitions between segments. The results show the codes of segments and the transitions between segments in the two environments were not statistically significantly different. The numbers of encoded segments were correlated in function and behavior in the two environments, while the numbers of transitions between B-B, B-F, F-B were correlated. In summary, the two environments did not create significant differences in the design processes in terms of FBS, and the segments and transitions that were related to function and behavior were highly correlated in the design processes in both environments.

## **4. Discussion**

### **4.1 Differences between the digital and traditional environments**

This study examined the differences between designing in digital and traditional environments based on the FBS coding of the protocols collected in order to explore the influence of this digital environment on the design process. Two design problems were of the same level of complexity evaluated by experts, and other variables were controlled by experimental settings, except for the media used and the locations of the members while collaborating. The production environment of different media was the main experimental variable. The digital environment was devised to emulate the traditional environment. The design processes in both environments were compared in terms of the design issues that designers concern themselves with and the transitions between design issues. These two aspects were studied by analysing the segment codes and transitions between segments. The transitions between segments represented a reasoning process of designing or a change of

focus. The results showed that in both environments there were no significant differences between the segment codes and transitions between segments in the two environments. These results indicate that this digital environment did not change the design process, and thus the settings of this digital environment were very similar to those of a traditional environment.

Moreover, the numbers of segments encoded as function and behavior in the two environments were highly correlated between environments in each team. The numbers of transitions between functional and behavioral segments and between behavioral segments were highly correlated between environments in each team. However, the numbers of segments encoded as structure and the numbers of the transitions related to structure were not highly correlated in two environments of the same team. We speculate that the different environments influenced the structure-related segments but produced no significant changes, and had no effect on the numbers of segments and transitions related to function and behavior. This means this digital environment had a small influence on low-level cognitive activities, and almost no influence on high-level cognitive activities because the function and behavior represent higher-level cognitive activities in the design process, and structure represented low-level cognitive activities. Therefore, this digital environment did affect the physical behaviors of designers to some extent, but this behavioral change did not consequently influence the thinking of designers, such as goal-setting, reasoning, and evaluation. They are represented by the function-related segments and the transitions between behavior-related segments.

## **4.2 Influence of media or other possible reasons**

Previous research that compared the influences of media on the design process has indicated that the design process using traditional medium is different from that using digital media. Bilda & Demirkan (2003) compared the design processes of interior designers and demonstrated that traditional media had advantages over digital media in supporting the perception of visuo-spatial features and organizational relations in the design, production of alternative solutions and better conception of the design. The two media were traditional pen-and-paper and the Design Apprentice software, where design proceeded with space elements instead of lines. Won (2001) utilized protocol analysis to compare the conceptual design processes of traditional media and Pro-E, which is a high-end CAD/CAM software used mostly for manufacture rather than design. The results showed that the user who used digital media produced fewer ideas, and showed more imaging activities than seeing and drawing. In 2001, Pro-E still targeted the manufacturing industry and its operations required many pull-down menus. It was not software suitable for conceptual design, because most of the forms being designed in the software had to be precise and unambiguous. The result of the research reported in this paper differs from theirs. Two possible reasons for the difference in results are discussed in the following sections: the type of media and collocation.

*The type of media:* One of the differences between this research and the two studies mentioned above was the choice of digital media. This research utilized software and hardware that were designed for conceptual design and the environment was set up to emulate the traditional sketching environment of collaboration.

Bilda & Demirkan's (2003) results showed that traditional media had advantages over digital media, such as supporting the perception of visuo-spatial features and functional relations of the design, production of alternative solutions, and better conceptions of the design problem. Suwa & Tversky (1997) demonstrated that sketches contribute not only to perceptions of

visuo-spatial relationships, but also to reasoning about the functional and conceptual issues of the design problem. Therefore, the digital media they used affected both the perceptual and the semantic aspects of cognitive activities. As discussed by Bilda & Demirkan (2003), the Design Apprentice software was not suitable for the conceptual design process, as it lacked support for designers' habitual activities such as doodling and sketching, activities they have developed throughout their education. The Pro-E software used in Won (2001) has similar problems. With the digital media software in our study, designers interacted with the digital media in a manner similar traditional media. Therefore, their habitual activities were not changed by the media they employed, and the systematic exchanges between conceptual and figural arguments were supported in the same way using both media (Goldschmidt, 1994). This contributes to the fact that the total number of cognitive actions was relatively similar in both media, in terms of function-behavior-structure.

Unlike Design Apprentice, Pro-E and similar software, CAD systems designed to support conceptual design processes, called computer-aided conceptual design (CACD) systems, aim at a different functionality. They have been an important topic for computer-aided design and design computing studies (Dijk, 1995). Many interesting CACD systems have been prototyped, to test their concepts (Gross & Do, 2004), and all of them have been based on a digital sketching environment that emulates traditional sketching environments. However, most of them do not have an equivalent visual resolution compared to pen-and-paper. This might reduce the benefits sketches could bring to designers, such as, perception of visual-spatial relationship, visual reasoning about functions, and potential creativity provoked by the situatedness of the sketcher in relation to the sketches. Despite the knowledge derived from

such research, there has been little empirical examination of the usability and validity of these CACD systems, nor has there been research comparing their use with the traditional environments. The digital sketching environment in this study is similar to traditional media in terms of visual resolution, therefore, all the benefits produced by fuzzy, ambiguous sketches could be preserved in the digital media.

*Collocation versus remote collaboration:* The second difference between traditional and digital environments in this research is collocated collaboration versus remote collaboration. The results seem to suggest that distance does not matter in the settings of our digital environment where two collaborators worked remotely. Two studies claimed that being collocated at least assisted in the productivity gain, based on their study of seven groups of people who were maximally collated (Covi et al., 1998; Olson et al., 1998). However, in our experimental settings, the result of remote work was not significantly different to that produced when the team was collocated. We speculate that our settings provided equivalent advantages of face-to-face situation.

There is potentially a third and equally significant reason for the lack of difference between using the digital and traditional media in this study and it has to do with the digital background of the participants. The average age of all the participants is 20.35 with a standard deviation of 0.73. Participants in this age group can be labelled “digital natives” (Prensky, 2001a), ie, individuals who were born, have grown up and developed within a digital culture rather than having it introduced at a later stage in their cognitive development. Digital natives have been shown to treat digital tools differently than digital immigrants (Prensky, 2001b). This is a confounding variable that needs to be tested.

## **5. Conclusions**

This study examined the design processes in a traditional sketching environment and in a digital sketching environment that had been devised to emulate free-hand sketching. It can support the designers' drawing activities with good resolution, and remote communication with a face-to-face connection. The digital and traditional environments were empirically compared through protocol analysis of the design processes in these environments. The coding scheme was the function-behavior-structure ontology. Both the content of the segments and transitions between segments were examined. The results showed that the design processes of the digital and traditional environments were similar in terms of the speed of the design process, design issues concerned in the design processes, and the transitional activities. Moreover, the digital environment seems to influence low-level cognitive activities only slightly and to have no influence on high-level cognitive activities. Therefore, this digital sketching environment is similar to free-hand sketching in all significant aspects of the design process.

The results have implications for CAD and design practice. For CAD systems, the setting might be a foundation to establish future computer-aided collaborative conceptual design systems that can fulfil the needs of designers. It demonstrates the essential elements needed for remotely collaborative conceptual design that requires a high level of freedom and visual representation. For design practice, remote collaboration is feasible in the preliminary design process.

Olson & Olson (2000) proposed that groups with high common ground and loosely coupled work, with readiness both for collaboration and collaboration technology, have a greater chance at succeeding with remote work.

*Common ground* refers to that knowledge that the participants have in common. In our study, all the subjects are from the same classroom, and they have had some common ground established during the class. According to the levels of effort for people to obtain common ground (Clark & Brennan, 1991), our video-conferencing setting had almost the same factors that can contribute to the establishment and maintenance of common ground with face-to face, except for co-presence. Therefore, our results seem to suggest the remote collaboration digital sketching environment with video-conferencing and the background of our subjects helped them to establish common ground, and the results of remote collaboration work were similar to that of collocated work. The concept of *coupling* refers to the extent and kind of communication required by the work. Many design tasks are tightly coupled because they strongly depend on the talents of collections of designers and are non-routine, even ambiguous. The influence of degree of coupling embedded in different phases of the design process is still unclear. Further studies could explore the relationship between the degree of coupling in design collaboration and the choice of CAD tools. In terms of *collaboration readiness*, our participants were required to share. However, the attitudes toward cooperation and skills to collaborate were likely different in each team. How this collaboration readiness affects the design process and results are important issues to study. Finally, *technology readiness* indicates that people who have not adopted e-mail, for example, will not be ready adopters of NetMeeting. According to the speculative order of difficulty of technology (Olson & Olson, 2000), our experimental setting was listed in the hardest category with its simultaneous collaboration with NetMeeting and shared drawing board. Our subjects were all categorized as digital natives, and thus technology readiness seemed not to be an obstacle in the remote collaboration setting. The differences between digital natives and immigrants for remote design collaboration still remains unknown. The research reported here opens up new areas to be explored in future studies. The results of those studies can influence how designers work remotely in the digital and globalized future.

Future study would aim to explore the entangled variables of this study, digital natives or immigrants and the choice of computer-aided conceptual design software. Disentangling these two variables would further improve our understanding of why the design processes in traditional and digital environments in this study are similar in terms of function-behavior-structure. It might be difficult to examine the influence caused by the differences between digital natives and immigrants since it involves age and experience. It is reasonable that most of digital immigrants in design practice should be experienced designers. Therefore, their design experience might compensate the deficiency of digital immigrants. Another possible future study would be to compare the design processes of digital natives using software of this study and CAD systems examined by previous studies, for example Pro E. If there is no difference between the design processes of using our CAD system and other CAD system, we can speculate that digital natives could utilize CAD systems as their accustomed tools as readily as pen-and-paper for digital immigrants. This would open up a new direction for CAD developers to design a new generation of CAD systems to fulfill the needs of digital natives

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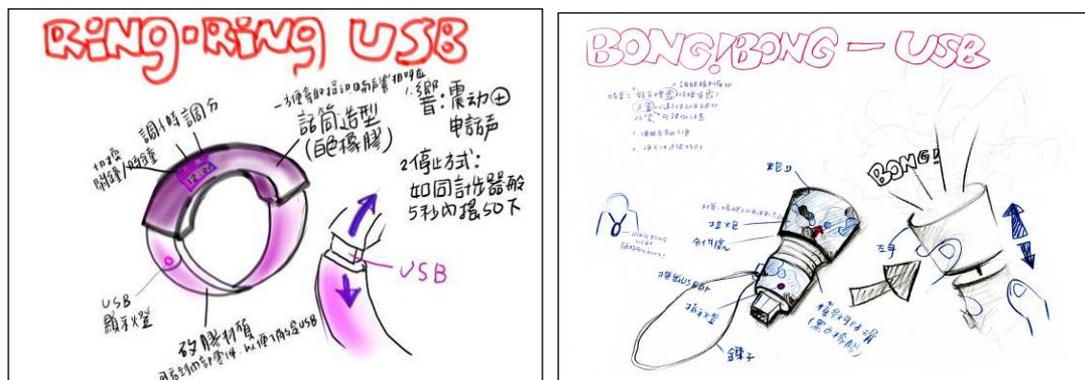
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## Appendix

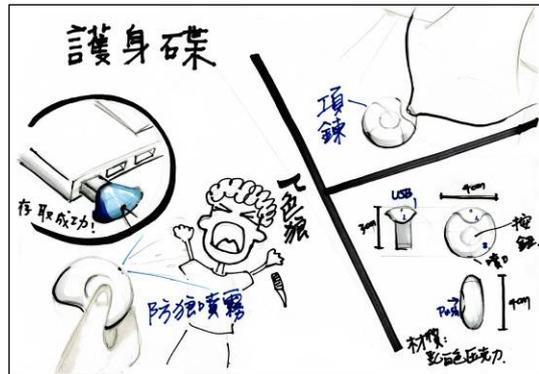
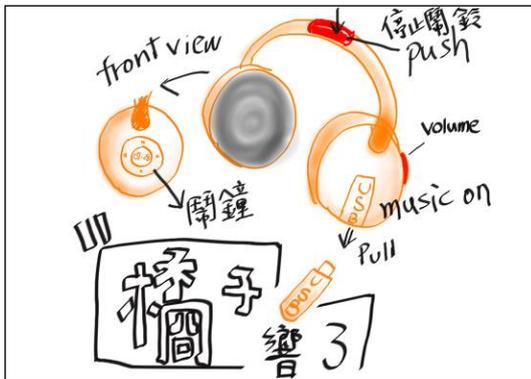
### Team A



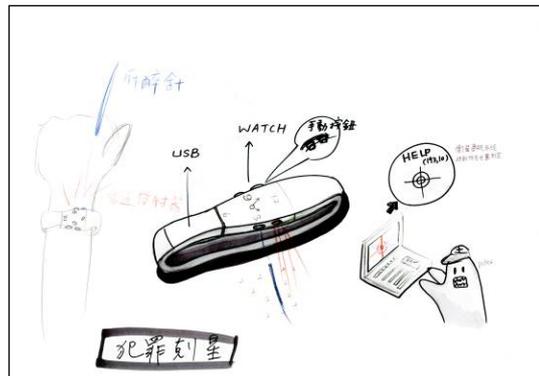
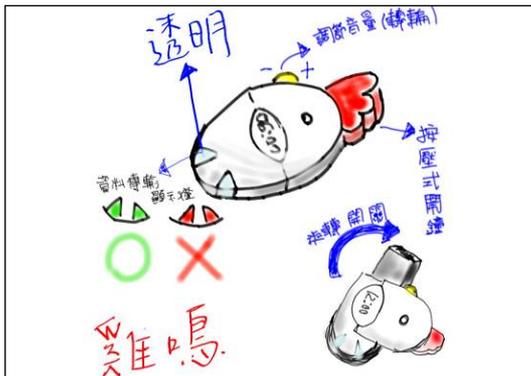
### Team B



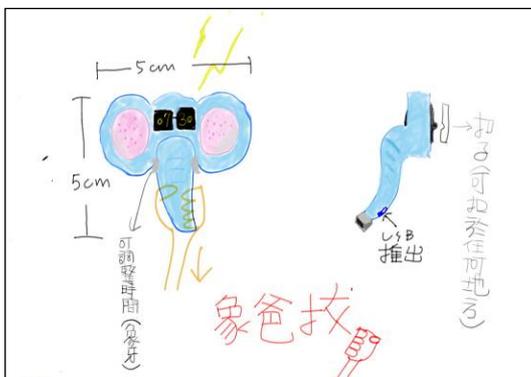
Team G



Team H



Team I



Team J

