Using Design Paradigms to Evaluate the Collaborative Design Process of Traditional and Digital Media

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This paper provides a quantitative examination of the collaborative design process of traditional and digital media in terms of design paradigms. The representative coding schemes are design prototype and reflection-in-action. 20 sets of protocols are analyzed as the statistical basis. The major result is that the averaged position of Function-Behavior-Structure and the number of mature framing could be used as measurement for the quality of the collaborative design process, opening a new direction for protocol research.

Introduction

The last three decades have seen growing importance placed on protocol analysis in design research society since the first design research using protocol [1].

There has been a rapid growth of protocol studies in a wide range of design disciplines, such as architectural design, industrial design, engineering design, commercial design, and electronic design. A number of research topics have appeared to address different aspects of designing, such as sketching, perceiving, design media, design process. Most of these papers are qualitative research. The reasons are firstly it is hard to recruit a great number of good design subjects, and secondly, it is very time-consuming to conduct protocol analysis. With the increase of the complexity of coding scheme, the second problem worsens. Therefore, very little protocol analysis has been re-examined, and very few coding scheme has been re-applied. These establish the beginning of this paper.

Applying previous important protocol analyses, we are interested in examining the quality of the collaborative design process in an attempt to produce quantitative evaluation criteria. They could provide a bridge

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connecting design research and design practice. Hopefully, the results of protocol analysis could guide the application of collaborative designing in design practice.

The research problem of this paper is how we could quantitatively measure the quality of the collaborative design process using protocol data. The aim of this paper is utilizing design paradigms to measure the quality of the collaborative design process using traditional and digital media.

The objectives are three. First, we conduct 20 sets of collaborative design experiments, so we have enough number of data sets to run quantitative tests. Second, we re-applied previous successful coding scheme to form a solid foundation. It forms the theoretical base to compare the differences of these design processes. Two design paradigms were applied using design prototype and reflection-in-action coding scheme as representatives. Third, we use the quantitative results of encoded protocol to generate the criteria. They can measure the quality of the collaborative design process.

The reason of focusing on collaborative design process is that we could apply concurrent protocol without further labors on reminding subjects to think aloud, avoiding the possible deficiency of think-alod.

Literature Review

After the first design protocol study, protocol analysis has been widely applied in design community [2]. The delft design conference further established its methodological position [3]. Currently, protocol analysis has become the standard experimental technique for exploring the process and the cognitive activities of designing [4][5]. Two types of protocol approaches have been developed: concurrent and retrospective [6]. In concurrent protocols, the subjects are required to design and verbalize thoughts simultaneously. In contrast, in retrospective protocols, subjects are asked to design first and then retrospectively report the design processes with or without visual aids.

In general, concurrent protocols have been utilized in the process-oriented aspect of designing, which is largely based on the information processing view proposed by Simon [7]. Comparatively, retrospective protocols have been utilized in the cognitive content aspect, which is largely based on the notion of reflection-in-action proposed by Schön [8]. Normally, design researchers choose one or the other methodology according to their research purposes.

In terms of collaborative design, think aloud is the common technique in design studies because members of collaborative design have to communicate verbally to carry on the design process. The think-aloud occurs naturally in the process.

Design Paradigms

In design studies, there have been two design paradigms: information-processing [7] and reflection-in-action [8]. Studies based on information tend to explore the issues of the design process, such as the content of design process or the foci of design reasoning. Studies based on reflection-in-action tend to explore the cognitive behaviors of designers, such as drawing, perceiving, and related cognitive activities.

The representative coding scheme of information-processing is design prototype [9]. It has been applied in several process-oriented protocol studies [10][11]. This coding scheme provides a simple but solid analysis for the reasoning of the design process, including function, behavior, and structure. The term, design prototype, is given in the original paper, and its content is actually an ontology of the design process.

Comparatively, the representative coding scheme of reflection-in-action is produced by Valkenburg and Dorst [12]. It similarly provides a simple descriptive method for understanding the reflective aspects of the design process, consisting of naming, reflection, framing, and moving. The microscopic coding scheme of Suwa, Purcell and Gero [13] is also based on reflection-in-action, but its structure and details focus more on designers' cognitive activities. Since our research topic is the collaborative design process, we apply the coding schemes of design prototype and reflection-in-action by Valkenburg and Dorst [12].

Method

This is a typical protocol studies. Data were collected using think-aloud procedures of protocol analysis in which subjects conducted collaborative design. The experimental procedure is first announcing the instruction and design brief, warming-up, running main experiment, presenting design results by subjects for 5 minutes, and an interview in the end. The 5 minutes presentation and corresponding drawings were used as materials for expert judgment of the design results.

A design competition devised for this research was held to recruit subjects from the third year industrial design students in Taiwan. A group of two students were qualified to join the competition, and they are free to select their partners from their classmates. 10 groups of students, two third of the class, participated in the design competition, and each team has to finish two design tasks respectively using traditional and digital media in about 60 minutes. Two design tasks were design a USB flash drive that can protect you and a USB flash drive that can wake you up. The levels of difficulties were regarded as similar by two design experts. 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.

Environmental settings of experiments are shown in the follows. Figure 1 illustrates the collaborative design using traditional media where two subjects, marked (1), face to face. The experiment instruction and design briefs, marked (3), were provided. Two cameras, marked (5), and a digital camera, marked (4), were utilized to record the design process with the experimenter, marked (2), taking memos for observational findings.

Figure 2 illustrates the collaborative design using digital media where two subjects, marked (1), were located separately in two rooms. The experiment instruction and design briefs, marked (3), were provided. Four cameras, marked (5), and two digital cameras, marked (4), were utilized to record the design process with two experimenters, marked (2), taking memos for observational findings respectively in two rooms. The digital media included WACOM digitizer and ALIAS sketchbook pro, to establish a digital sketching environment. A LCD monitor and web cam with MSN software in each room provided face to face video image, namely being virtually co-located.

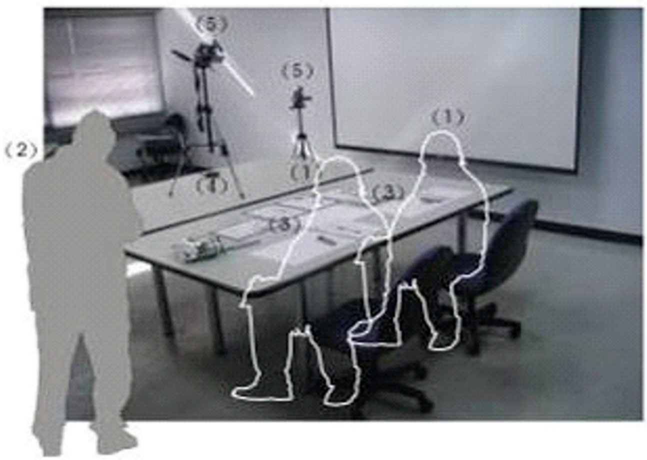

Fig. 1. The experimental setting using traditional media

The settings for digital media were devised in an attempt to provide a digital sketching environment that is almost no differences to the traditional sketching environment. That is pens and papers. With the help of the digitizer and the sketching software, subjects can easily adapt to the system with their own habits of using pens and papers. Most of design studies on media, however, utilized either too complicated CAD packages, such as Alias, or low-resolution software, such as MS Paint, to produce a fair comparison.

Fig. 2. Th

After conducting experiments, we began the analysis, including transcribing protocol, segmentation, encoding protocols, and producing qualitative descriptions and quantitative results to verify our hypotheses. The protocol was parsed by the intention of the subjects. The coding schemes were reflection-in-action and design prototype, respectively being the representatives of two design paradigms. Details of the coding schemes are described in the follow.

CODING SCHEMES

The verbal conversations between members during the collaborative design process were transcribed into protocols. They were then parsed by subjects' intention. Namely, if finding a coherent idea in the protocols, researchers separated it from the rest to form a single segment. It therefore consisted of several words or sentences, representing a single intention of the design team. Each design process produced different numbers of segment. The **segment number** is not necessarily related to the length of time but to indicate the amount of design intention shift. Each segment was categorized into one type of the coding scheme.

Two coding systems were selected from previous studies of protocol analysis. The first one is design prototype based on information processing theory. It consists of three categories: function, behavior, structure. Function corresponds to the users' need, the service the system will provide, the purpose of the artifact. Behavior corresponds to the system's documented and actual requirements, how the system and its sub-systems work. Structure corresponds to the design of the system and its physical form. Details of the system are shown at Figure 3, including the separation of behavior and documentation [14].

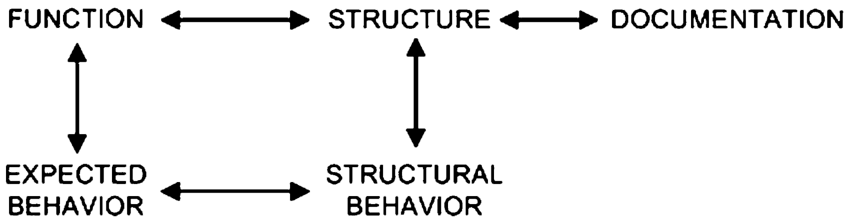

Fig. 3. The full structure of design prototype (Gero 1990)

The second coding scheme is reflection-in-action based on Schön's theory [15]. Valkenburg and Dorst [12] devise this coding scheme to describe the nature of team design, and their findings have them won the best paper of the year. The coding scheme 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 needed to focus on. During the framing–activity, the team is setting the context for the next activities or is framing a (sub) problem or (partial) solution to explore further. During the moving-activity, the team is trying to solve the problem, for example generating ideas, drawing, and comparing concepts. During the reflection-activity the team is evaluating earlier activities to know what to do next.

The four activities could visualize the design process, as shown in Figure 4. Valkenburg and Dorst [12] visualized two design teams attending The Philips Design Competition, and concluded that reflection-activity was the core for successful collaborative design process.

Results

The final results of each team with its 5-minutes presentation was used as material for expert judgment. 6 expert judges, 2 from industry and 4 from education, evaluated the participants' design results. Judges gave scores from 9 to 1 in terms of seven aspects: design concept, function, material, scenario, creativity, aesthetics, and completeness. The scores of each team using both media were listed in Table 1. Each team has two scores, one for design using digital media and one for traditional. The design teams were listed by the rank of the sum of both scores. If these two media do not cause the differences in the design results, the rank could represent the quality of the end products produced by a design team.

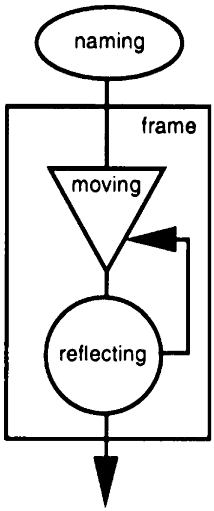

Fig. 4. Visualizing the design process using Reflection-in-action

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

Design Team	Digital Media	Traditional Media	Sum	Rank
A	301	253	554	1
D	272	280	552	2
C	305	235	540	3
F	245	275	520	4
G	219	294	511	5
H	221	290	494	6

E	248	246	494	7
I	213	251	464	8
B	222	201	423	9
J	216	196	412	10

The scores across different judges were examined for their reliability. Cronbach's alpha value, being 0.833, indicated that the external consistency of the scores provided by 6 judges was reliable.

The segment number and its relation to the design results

The results showed the segment number of design process was not related to the design results, as shown in Table 2. This implies that the number of design intention shift is not related to the performance of the design process. The number of design intentions in a design team does not affect its design results. This result complements previous study.

Table 2 The segment number and its corresponding rank in each team

Rank	Team	Media	Score	Segment Number
1	A	Traditional	253	779
		Digital	301	702
2	D	Traditional	280	216
		Digital	272	178
3	C	Traditional	235	525
		Digital	305	530
4	F	Traditional	275	445
		Digital	245	416
5	G	Traditional	294	359
		Digital	219	372
6	H	Traditional	290	335
		Digital	221	334
7	E	Traditional	246	397
		Digital	248	403
8	I	Traditional	251	534
		Digital	213	501
9	B	Traditional	201	516
		Digital	222	506
10	J	Traditional	196	375
		Digital	216	381

Tang [16] demonstrated the experienced designers have more segment number than a novice, meaning that a design expert handles more design issues than a student due to a bigger chunk of knowledge. However, we demonstrate that this phenomenon is not significant amongst students, even though they perform differently. The differences between students do not exceed that between experts and novices.

The encoded protocol using design prototype

The raw protocol was encoded by two coders. The proportion of encoded protocol using design prototype is shown in Table 3. The results of design process using traditional (T) and digital (D) media was presented separately in terms of function, behavior, and structure.

The results showed the distribution of function-behavior-structure was not related to the rank of design results. This implies that the proportion of design prototype is not related to the performance of the design process. This idea is not examined in previous studies using design prototype [10][11].

Table 3 Proportion of encoded protocol using design prototype for each team

Team	Rank	Media	Function	Behavior	Structure
A	1	T	5%	92%	3%
		D	5%	93%	2%
D	2	T	9%	86%	5%
		D	7%	90%	3%
C	3	T	7%	90%	3%
		D	5%	91%	4%
F	4	T	4%	93%	3%
		D	3%	94%	3%
G	5	T	3%	93%	4%
		D	4%	92%	4%
H	6	T	3%	95%	2%
		D	4%	92%	4%
E	7	T	8%	88%	4%
		D	7%	91%	2%
I	8	T	4%	93%	3%
		D	3%	92%	5%
B	9	T	2%	92%	6%
		D	4%	95%	1%
J	10	T	5%	92%	3%
		D	5%	92%	3%

In terms of Function-Behavior-Structure, the difference of design process between media in one team was measured using Chi-Square. If the difference between media is significant, our following discussion should be divided into two parts, presenting the findings of collaborative design using traditional and digital media separately.

Table 4 The Chi-Square value of different media in terms of design prototype

Team	Rank	Media	Observation Value	Chi-Square Value	d.f
A	1	Traditional	0.91	χ^2 =1.92<5.99	2
		Digital	1.01		
D	2	Traditional	0.33	χ^2 =0.73< 5.99	2
		Digital	0.40		
C	3	Traditional	1.34	χ^2 =2.67<5.99	2
		Digital	1.33		
F	4	Traditional	0.42	χ^2 =0.87<5.99	2
		Digital	0.45		
G	5	Traditional	0.38	χ^2 =0.75< 5.99	2
		Digital	0.37		
H	6	Traditional	1.49	χ^2=2.98< 5.99	2
		Digital	1.49		
E	7	Traditional	1.49	χ^2 =2.97< 5.99	2
		Digital	1.47		
I	8	Traditional	1.42	χ^2 =2.93< 5.99	2
		Digital	1.52		
B	9	Traditional	1.89	χ^2 =3.82<5.99	2
		Digital	1.93		
J	10	Traditional	0.7	χ^2=0.14< 5.99	2
		Digital	0.6		

As shown in Table 4, the differences between media in each team are not statistically significant. The environments of different media did not cause differences in the encoded protocol of the design process. We can assume that the two design processes of each team are the same in terms of design prototype.

The encoded protocol using reflection-in-action

The raw protocol was encoded by two coders again using reflection-in-action. The proportion of encoded protocol using reflection-in-action is shown in Table 5. The results of design process using traditional (T) and digital (D) media was presented separately in terms of naming, framing, moving, and reflection.

The results showed the distribution of naming-framing-moving-reflection. was not related to the rank of design results. This implies that the proportion of reflection-in-action is not related to the performance of the design process. This is actually inconsistent with the results of Valkenburg and Dorst [12] in which the number of reflection was related to the design performance.

Table 5 Proportion of encoded protocol using reflection-in-action for each team

Team	Rank	Media	Naming	Moving	Framing	Reflection
A	1	T	5%	81%	2%	12%
		D	5%	78%	3%	14%
D	2	T	9%	74%	3%	14%
		D	7%	71%	5%	17%
C	3	T	7%	82%	2%	9%
		D	5%	85%	2%	8%
F	4	T	4%	77%	3%	16%
		D	3%	80%	3%	14%
G	5	T	4%	79%	4%	13%
		D	4%	79%	4%	13%
H	6	T	3%	80%	4%	13%
		D	3%	80%	4%	13%
E	7	T	8%	76%	3%	13%
		D	7%	77%	5%	11%
I	8	T	3%	84%	3%	10%
		D	3%	87%	2%	8%
B	9	T	6%	76%	3%	15%
		D	4%	80%	2%	14%
J	10	T	5%	78%	6%	11%
		D	3%	86%	3%	8%

In terms of reflection-in-action, the difference of design process between media in one team was measured using Chi-Square. If the difference between media is significant, our following discussion should be divided into two parts, presenting the findings of collaborative design using traditional and digital media separately.

As shown in Table 6, the differences between media in each team are not statistically significant. The environments of different media did not cause differences in the encoded protocol of the design process. We can assume that the two design processes of each team are the same in terms of reflection-in-action.

Table 6 The Chi-Square value of different media in terms of reflection-in-action

Team	**Rank**	**Media**	**Observation Value**	**Chi-Square Value** χ^2	**d.f**
A	1	T	1.66	(χ^2 =3.49< 7.82)	3
		D	1.84		
D	2	T	0.62	(χ^2 =1.36< 7.82)	3
		D	0.75		
C	3	T	1.75	(χ^2 =3.48< 7.82)	3
		D	1.73		
F	4	T	0.75	(χ^2 =1.55< 7.82)	3
		D	0.80		
G	5	T	0.73	(χ^2 =1.43< 7.82)	3
		D	0.70		
H	6	T	0.13	(χ^2=0.25< 7.82)	3
		D	0.13		
E	7	T	1.19	(χ^2 =2.36< 7.82)	3
		D	1.17		
I	8	T	0.49	(χ^2 =0.96< 7.82)	3
		D	0.46		
B	9	T	1.97	(χ^2 =3.97< 7.82)	3
		D	2.00		
J	10	T	3.01	(χ^2=5.98< 7.82)	3
		D	2.97		

To summarize, we find that the number of segment, proportion of design prototype and reflection-in-action, as the measurement of performance of the design process, are not related to the design results in terms of the rank of their scores. Next section, we look into the encoded protocol using the essential meaning of design prototype and reflection-in-action in an attempt to relate rank of the design results to the encoded protocol of the design process.

Discussion

The segment number, the proportion of design prototype, and the proportion of reflection-in-action establish a macroscopic view toward the quality of the collaborative design process. However, there is no relationship between these factors and the rank of the design results. This research continues to explore this issue from a microscopic view consisting of the essential ideas of design prototype and reflection-in-action.

The position of design prototype

McNeill, Gero and Warren [11] generalizes that a designer begins a conceptual design session by analyzing the functional aspects of the problem, continues by focusing on the three aspects of function, behavior, structure, and ends by focusing on synthesizing structure and evaluating the structure's behavior. This implies a standard of sequential order of time as shown in Figure 5. In the theoretical situation, we assume that the averaged position of function is located in the 25th percentile, the averaged position of behavior is located in the 50th percentile, and the averaged position of structure is located in the 75th percentile. They are the hypothetically ideal location of function-behavior-structure.

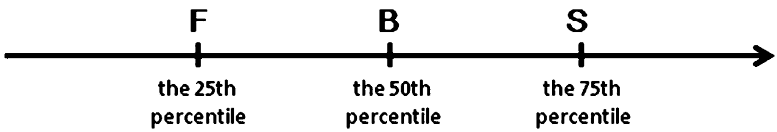

Fig. 5. The hypothetically ideal location of function-behavior-structure

We calculated the deviation of the function-behavior-structure from their hypothetically ideal location in terms of averaged segment number. The Δ equals to the sum of D1, D2, and D3. The hypothesis is that a better design process produces a smaller Δ value.

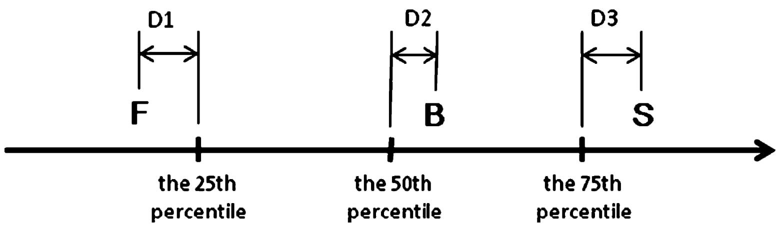

Fig. 6. The calculation of deviation from the idea location

For example, the location of function-behavior-structure of the first team using traditional media is the 17th, the 51st, and the 73rd percentiles, and the total segment number is 779. The Δ value is about 85, and the calculation is ((0.25 - 0.17) + (0.51 – 0.5) + (0.75 - 0.73))*779.

Table 7 The sum of deviation values of 10 design teams

Team	Rank	Media	Deviation	Sum of D
A	1	T	85.17	99.95
		D	14.78	
D	2	T	10.51	43.91
		D	33.40	
C	3	T	134.09	319.49
		D	185.40	
F	4	T	231.62	439.20
		D	207.58	
G	5	T	15.68	53.09
		D	37.41	
H	6	T	29.06	132.59
		D	103.53	
E	7	T	64.12	166.03
		D	101.91	
I	8	T	70.09	241.13
		D	171.04	
B	9	T	41.29	127.61
		D	86.31	
J	10	T	58.11	179.20
		D	121.09	

We sum up the Δ values of both media of each team, correlating the sum of Δ to the corresponding rank of the team, as shown in Table 7. Findings were the top five teams had smaller Δ values than the last 5, except C and F. The reason why team C and team F had larger Δ values was their spending more time on drawing than other top 5 teams. Therefore, their averaged S positions moved toward the center of time line, increasing the Δ values.

This finding is consistent with McNeill, Gero and Warren [11]. They conclude there is no significant negative slop for the structure category, but the center of gravity for function is significantly before the center of gravity for structure. Although the trend is conceivable, the Δ value is not significantly related to the rank of the design performance.

The number of mature framing activities

Valkenburg and Dorst [12] demonstrated that the number of reflection is related to the design performance, but this phenomenon is not obvious in our data sets. We examined the reflection in our data, finding that the activities triggered by reflection did not always contribute to the design process. Some reflections were not followed properly to form a new direction for the design process. It would be beneficial for the design process that a reflection triggers a series of actions to form a partial solution or a sub-goal. This is named framing in the coding scheme of reflection-in-action. However, the number of framing is not related to the rank of the design results.

This study further examined the framing activity that contains at least 10 segments, and had it named **mature framing**. This kind of reflection really changes the design process in terms of solutions or problems. The proportion of mature framing to the total number of framing in each design process is calculated, shown in Table 8.

Table 8 The proportion of mature framing to the total number of framing for each team

Team	Rank	Media	The number of mature framing
A	1	T	87.5%
		D	82.6%
D	2	T	71.4%
		D	87.5%
C	3	T	90.0%
		D	87.5%
F	4	T	71.4%
		D	71.4%
G	5	T	75.0%
		D	73.3%
H	6	T	58.3%
		D	53.9%
E	7	T	66.7%
		D	50.0%
I	8	T	57.1%
		D	60.0%
B	9	T	33.3%
		D	53.3%
J	10	T	40.9%
		D	45.4%

The results demonstrated a clear separation between the top 5 teams and the last 5. In our cases, a design process consisting of more than 70% of mature framing was among the top 5 ranking teams. The more the number of mature framing the better the final rank. This result is consistent with the visualization of the results in Valkenburg and Dorst [12]. The winner, Team Tecc, had 3 mature framing, while the loser, The Delft Pitchbulls, had only one mature framing. Their research divided the protocol into episodes in which the same activity occurs, and this research distinguished episodes by the objects the teams attend to. Therefore, the number of segments needed to form a mature framing is different.

Conclusions

We can conclude with certainty that this paper provides a beginning for quantitative protocol studies. Our goal is not only to generate statistical results, but also to provide different angels for exploring the collaborative design process. Four of these findings are worth summarizing: first, the segment number, the segment proportion of design prototype, the segment proportion of design reflection-in-action are not related to the rank of the design results. Second, the averaged position of function-behavior-structure is related to the rank of the design results. Third, the number of mature framing is related to the design results. Fourth, the digital environment for conceptual design in this study is no different to the traditional environment of pens and papers in terms of segment number and proportion of our coding schemes.

The results fulfill our purpose of using design paradigms to evaluate the collaborative design process of traditional and digital media, but more issues remains to be resolved in the future research. First, this study should complete all the statistical examination of the results, for example, the relation between the segment number and the rank. Another important issue is re-examining the differences between two media using the averaged position of function-behavior-structure and the number of mature framing. Second, the original score of expert judgment could be utilized instead of the rank of the result. Third and most importantly, we would explore the reason why the relationship of the second and the third findings exist to have better understanding of the quality of the collaborative design process.

This work has potential contributions to design computing and cognition. For design computing, this paper demonstrates that it is possible to produce an almost identical digital environment compared to traditional pens and papers. Therefore, the trend for CAD development should be connecting this environment to the current CAD/CAM system to form a holistic supplementary environment for designers from concept design to manufacture. Moreover, some excellent works on computational sketching software systems [17] could further incorporate our digital sketching environment to their proof-of-concept software to have better design cognition support. For design cognition, we can start to verify our findings in previous studies of design cognition to form a better scientific base for design computing to continue. Hopefully, the results of this paper can contribute to the connections between design cognition and design computing.

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