EXPLORING THE EFFECT OF DESIGN TASKS ON CONCEPTUAL DESIGN ACTIVITIES

A DESIGN PROTOCOL STUDY BASED ON THE FBS ONTOLOGY

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ABSTRACT

This paper reports an experimental study comparing the cognitive processes during conceptual design of two different classes of design requirements for the same groups of industrial design students. Using a task-independent approach based on the FBS design ontology, this study transformed the observations of designing processes into sequences of design issues using the FBS coding scheme. The examination of design issue distributions showed that no significant differences observed between the two sets of sessions in the beginning of designing processes, but significant differences occurred following that. Results suggested that the nature of design requirements may influence how ID students generate and develop solutions. In particular, the designing with open-ended requirements is more concerned with the purpose of designs being produced.

Keywords: Designerly thinking; design protocol study; the FBS ontology.

INTRODUCTION

Conceptual design, i.e., the activity of generating new design concepts, is considered as one of the most creative parts of designing. It typically occurs in the initial stage of a designing process, defining fundamental characteristics of the designed outcome and setting the goals for subsequent phases to implement (French, 1999; Keinonen, 2006; Kroll, Condoor, & Jansson, 2001). Revealing the cognitive process of conceptual design activities can help to elucidate the nature of designerly thinking (Cross, 1992, 2008). However, little is known about the cognition of how designers think during this key period of designing.

RESEARCH QUESTION

In industrial design (ID) education, conceptual design exercises are usually part of a design studio project, a learning-by-doing pedagogical approach (Oxman, 1999, 2001). During studio a generic designing process and related knowledge and skills are taught through a series of guided conceptual design exercises, usually moving from simple to complex. Students are expected to develop a repertoire of design methods/approaches, and gradually gain their independence through these guided projects.

The ID program in National University of Singapore (NUS) provides such a curriculum that has a lower emphasis on "taught" modules (e.g., lectures) but more heavily relies on an immersive hands-on doing and experimenting (NUSDID, 2011). Students are expected to develop by initially following the taught approaches and then moving to a task-based and/or strategy-based thinking (Lawson & Dorst, 2009). In the latter approaches, students learn to appreciate the uniqueness of a specific problem and adjust their design process accordingly (Schön, 1991). Therefore, a research question is: do senior/final-year ID students design differently in response to different classes of design requirements? In other words, how does the nature of design tasks affect ID students' cognitive processes during conceptual design activities?

METHODS

RESEARCH DESIGN

In order to answer this question, an experimental study was carried out. Four teams of final-year ID students from NUS participated in this study voluntarily. Their average age was 23 years old. At the time of experiment, they had finished the taught courses and were involving the final year project. All participants had at least three years of experience of design studio projects and some had intern experience in design companies. According to the pre-test questionnaire and post-test interview, they all claimed they possessed above-average design expertise among their classmates, and five of them were award winners of international/regional design competitions.

The experiment was conducted in a design-studio-like setting, Figure 1. Two participants were paired up to work collaboratively for two different tasks. Two cameras were set up to observe, respectively, the overall designing activities and the drawing activities.

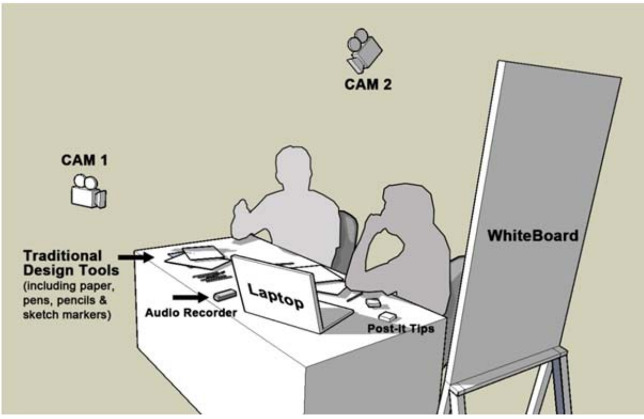

Figure 1. Experiment Setup (Jiang & Yen, 2010)

The assignments for this experiment were conceptual design under two different situations. One was to design a coffee maker for an existing market (Task CM), which was treated as a variant or adaptive design task (Pahl, Beitz, Feldhusen, & Grote, 2007), and the other was a visionary concept design, to design a next-generation personal entertainment system/ device for the year 2025 (Task PES). The latter task was beyond a normal new product development time frame, aiming to explore the future scenarios. Hence, Task PES was treated as a non-routine design task.

To replicate the flexible working environment of a real design studio, participants were allowed to choose traditional and/or digital design tools to work with. There were no strict time limits for this experiment.

After the completion of each task, the participants were asked to spend some time to organize their drawing or sketches and give a short verbal presentation of their designs. Some clarifications of their designs may be made at the experiment facilitator's request.

ONTOLOGICAL-BASED DESIGN PROTOCOL STUDY

Protocol analysis was used to analyze the observed conceptual design activities (Cross, Christiaans, & Dorst, 1996; Jiang & Yen, 2009; McDonnell & Lloyd, 2009). This method usually involves a pre-analysis treatment of experiment records, such as segmenting and coding the verbalizations during the designing process, i.e., protocol data (Purcell, Gero, Edwards, & McNeill, 1996; van Someren, Barnard, & Sandberg, 1994).

This study adopted a particular segmentation and coding technique based on the Function-Behavior-Structure (FBS) design ontology (Gero, 1990; Gero & Kannengiesser, 2004). The FBS ontology describes designing activities by three types of reasoning, i.e.,

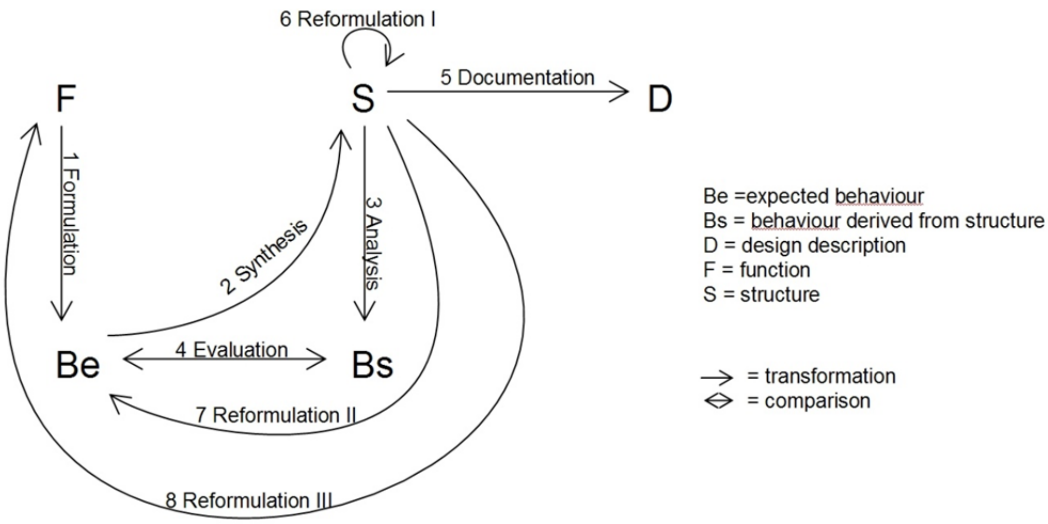

Figure 2. The FBS Ontology (after Gero and Kannengiesser 2004)

reasoning about function, behavior and structure. Figure 2 shows the relationships between these FBS variables. A domain-independent coding scheme is constructed by mapping these ontological variables onto design issues (Gero, Kan, & Pourmohamadi, 2011; Kan & Gero, 2009; Pourmohamadi & Gero, 2011). This coding scheme consists of six codes for issues, namely, function (F), expected behavior (Be), behavior derived from structure (Bs), structure (S), plus two additional codes, requirement (R) and design description (D). This coding scheme includes the intermediary documents (such as sketches, written notes) as indicators of cognitive processes, but it does not further distinguish the types of design documents.

This ontologically-based coding technique segments and codes protocol data concurrently using the "one-segment-with-one-code" principle. Each segment is strictly assigned with one of the six FBS codes. If an utterance is identified to contain more than one issue, it will be further segmented. Those utterances that do not fit in any of six the FBS categories are marked as others (O).

This approach is based on judgmental decisions. No rule-based inference can be automatically applied. This study then used the Delphi method to improve the reliability of judgments (Bilda, 2006; Gero & McNeill, 1998; McNeill, Gero, & Warren, 1998). The verbalization of each session was coded twice. The two separately coded protocols were then compared and arbitrated to produce a single protocol for further analysis.

The result of segmentation and coding is a sequence of design issues (FBS codes) for each design session, which represents cognitive processes for the observed conceptual design activities.

HYPOTHESIS

In the FBS ontology, the function issue represents the purpose of design. The structure issue refers to design proposals, ie elements and relationships in what is being designed. The behavior issue, which is a link between function and structure issues, representing the consequence of structure (Gero, Tham, & Lee, 1992). It includes "expected" consequence (Be), i.e., the expectations before a specific structure is proposed, and derived consequences for an existing structure (Bs). Therefore, design conceptualization mainly involves reasoning about function and expected behavior, while reasoning about structure and behavior derived from structure are related to artifacts as a solution to the design problem (Gero, 1990; Gero & McNeill, 1998).

The major difference between the experimental tasks is that the visionary task (Task PES) can accommodate major changes in technologies, markets and overall social-cultural environment, whereas the coffee maker task (Task CM) targets the existing market and contains more technical and feasibility issues that designers have to stay with. The large number of available precedents in the CM task may make students more concerned with design solutions. Meanwhile, the fewer "hard" constraints and precedents in the PES task may free students to spend more time on investigating broader context and the goals of the design.

It was thus hypothesized that ID students' cognitive activities (as measured by design issues) would be affected by the different nature of the design requirements. In particular, for Task PES, there would be more function and behavior issues (F and Be) and fewer structure issues (Bs and S), and an opposite pattern of design issue distributions would be found in Task CM.

This study did not assume the types of design problem could determine the type of designing process, like creative or routine designing (e.g., Chusilp, 2005; Kruger, 1999). The association or causal relation between these two variables is the objective for this study to determine.

STATISTICAL ANALYSIS

The results from coding used Pearson's Chi-Square test and related-samples Wilcoxon Signed Rank test (one-tailed) to test the hypothesis. Chi-square test measures are used to determine whether there is an association between design issue distributions and the type of design tasks. When an association is identified, related-samples Wilcoxon test, combined with qualitative inspection of cross tabulation, was used as a *post hoc* test to assess the difference for each issue.

The analysis was conducted at two levels. We first compared the overall distributions of design issues for the two tasks. Then, a fractioning technique

(Gero, et al., 2011) was applied to investigate the dynamic nature of issue distributions.

A preliminary qualitative analysis (Jiang & Yen, 2010) found the designing processes generally commence with a stage of understanding and formulating the design requirements followed by a stage of solution development. The duration of the first stage, in this study, lasted 1/3 to 3/5 of the total time. We can divide each session into two halves and use the first half of a protocol to examine the exploration and formulation of a design problem and the latter half for solution development.

RESULTS

In this section, we first report the general results of protocol segmentation and coding, and then report the comparisons of design issue distribution between the two tasks.

RESULTS OF SEGMENTATION AND CODING

By applying the Delphi method, a high level of agreement was achieved between arbitrated protocols and the two rounds of coding. As shown in Table 1, the coding consistency suggested the segmentation and coding of protocol data was reliable.

Team	Task	Coding1 vs Arbitrated (%)	Coding2 vs Arbitrated (%)
ID1	CM	85.1	89.3
	PES	81.5	87.9
ID2	CM	81.7	88.5
	PES	83.7	88.5
ID3	CM	77.6	89.6
	PES	81.4	87.4
ID4	CM	72.6	86.7
	PES	77.5	86.6
MEAN		80.1	88.1
SD		4.0	1.1

Table 1: Agreement between two rounds of coding and arbitration

Table 2 presents a summary of the segmentation and issues information from the design protocols. Participants normally took about one and half hours for each task (excluded briefing, warm-up and post-test interview sessions). Design issues represent around 72% of all the verbalization during the design sessions. This suggests that, during conceptual design activities, almost one quarter of the cognitive effort was used to plan/manage design process, and to coordinate work with other team member, etc., which are considered as extra-design activities.

Team	Task	Duration	Number of Total Segments	Number of Design Issue Segments	Design Issues /Total Segments (%)
ID1	CM	1:32:02	1101	782	71.0
	PES	0:57:13	599	418	69.8
ID2	CM	1:41:57	1082	731	67.6
	PES	2:01:36	1089	736	67.6
ID3	CM	1:31:02	987	707	71.6
	PES	1:01:06	679	502	73.9
ID4	CM	1:23:53	1088	829	76.2
	PES	1:32:51	1061	811	76.4
MEAN		1:27:43	960.8	689.5	71.8
SD		0:20:54	202.8	149.2	3.5

Table 2. Summary of segmentation and coding

Since the length of design exercises and number of design issues varied from one session to another (Table 2), we normalized the frequency distribution of design issues by converting them into percentages, as shown in Table 3.

The comparison of aggregated distribution for two tasks is illustrated by a box plot. The results in Figure 3 generally support our hypothesis. The percentages of function and expected behavior issues of Task PES are higher than those of Task CM,

Team	Task CM						Task PES					
	R (%)	F (%)	Be (%)	Bs (%)	S (%)	D (%)	R (%)	F (%)	Be (%)	Bs (%)	S (%)	D (%)
ID1	0.9	22.1	12.7	17.0	22.5	24.8	1.9	28.0	22.7	13.6	12.2	21.5
ID2	0.4	26.1	11.4	19.0	18.5	24.6	0.5	33.4	19.7	14.0	9.1	23.2
ID3	1.3	25.9	18.5	20.8	19.7	13.9	1.8	24.9	26.9	16.3	14.5	15.5
ID4	0.8	20.4	19.7	25.9	20.6	12.5	1.6	25.5	22.9	18.9	16.8	14.3
MEAN	0.9	23.6	15.6	20.7	20.3	19.0	1.5	28.0	23.1	15.7	13.2	18.7
SD	0.4	2.8	4.2	3.8	1.7	6.7	0.6	3.9	2.9	2.4	3.3	4.4

Table 3. Frequency distribution of design issues for each team

and the percentages of structure and behavior from structure issues are lower in Task PES than Task CM. The following presents the measurement of these differences statistically using Chi-Square tests.

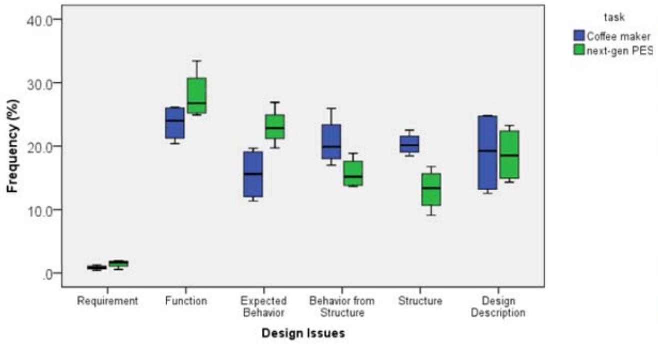

Figure 3: Frequency distributions of design issues for Task CM and Task PES

COMPARING THE DISTRIBUTIONS OF DESIGN ISSUES FOR THE WHOLE DESIGN SESSOIN

This analysis attempts to identify whether overall cognitive activities of the whole design session are subject to the different design situations that designers faced. A Pearson's Chi-square test indicated that the overall distributions of design issues were significantly different between the two tasks, X^2 (5, N=2) = 28.167, p<.001, Cramer's V = .143.

Design issue		Task ME	Task PES	Total
Requirement (R)	Count	7	9	16
	% within task	0.9	1.5	1.2
	Adjusted Residual	-.9	.9	
Function (F)	Count	180	172	352
	% within task	23.6	27.9	25.5
	Adjusted Residual	-1.8	1.8	
Expected Behavior (Be)	Count	119	142	261
	% within task	15.6	23.1	18.9
	Adjusted Residual	-3.5	3.5	
Behavior from Structure (Bs)	Count	158	97	255
	% within task	20.7	15.7	18.5
	Adjusted Residual	2.3	-2.3	
Structure (S)	Count	155	81	236
	% within task	20.3	13.1	17.1
	Adjusted Residual	3.5	-3.5	
Design Description (D)	Count	145	115	260
	% within task	19.0	18.7	18.8
	Adjusted Residual	.1	-.1	
Total	Count	764	616	1380
	% within task	100.0	100.0	100.0

*Table 4. Design issues * design task crosstabulation (overall)*

Table 4 presents the cross tabulation between design issues and tasks. Adjusted residuals in a cross tabulation provide an estimation of the differences between observed and expected values. Particular design issue or issues with a high absolute value of adjusted residuals (near or above two) suggest that these issues may be the major contributors to the overall differences of design issue distributions. These are highlighted.

The inspection of Table 4 and the one-tailed Wilcoxon test showed that, with a confidence level of 0.95, Task CM has a greater emphasis on structure (20.3% vs 13.1%) and behaviors from structure issues (20.7% vs 15.7%). More cognitive effort was expended on expected behavior in Task PES than Task CM (23.1% vs 15.6%). The results also indicate a tendency to focus more on function in Task PES than in Task CM (27.9% vs 23.6%), but it is not statistically significant (*p*=.072 >.05). There were no statistically significant differences found in terms of requirement and description issues.

Chi-Square tests were also conducted to compare the issue distributions of each team. Results in Table 5 indicated that all teams performed differently between the two tasks (*p* <.01). The distribution differences of each team were consistent with the overall pattern as hypothesized.

Team	Pearson's Chi-Square	df	Asymp. Sig. (2-sided)
ID1	41.704	5	.000
ID2	52.386	5	.000
ID3	18.010	5	.003
ID4	22.052	5	.001

*Table 5. Chi-Square tests (design issue * design task) for each team*

COMPARING THE DISTRIBUTIONS OF DESIGN ISSUES IN FIRST HALF OF DESIGN SESSION

The design session is divided into two halves to investigate the dynamic nature of design issue distributions. For the first half of the design protocols, no significant difference between tasks was found, X^2 (5, N=2) = 4.072, p>.05. Most teams, except ID2, had a similar distribution of design issues between the two tasks (p>.05). The differences between ID2's issue distributions did not comply with the overall pattern. Instead, ID2 had a higher percentage of behavior issues (both Be and Bs) and a lower percentage of function issue in the first half of Task PES.

In order to further explore the beginning of designing process, we changed the fractioning number to three. In the first one-third of designing protocols, the aggregated issue distributions were similar with those of the first half. No significant difference was identified between two tasks, X^2 (5, N=2) = 5.003, *p*>.05. However, Chi-Square tests for each team revealed more teams' issue distributions were significantly different, two in the level of 0.001 and one in level of 0.05, as shown in Table 6.

Team	Pearson Chi-Square	df	Asymp. Sig. (2-sided)
ID1	10.823	5	.055
ID2	29.656	5	.000
ID3	16.997	5	.005
ID4	28.876	5	.000

Table 6. Chi-square tests of the first one-third of the design process for each team

Table 6 presents the Chi-square statistics for within-team tests in terms of the first one-third of design protocols. Though many teams demonstrated significant differences regarding the design issue distributions (*p* <.05), the *post hoc* tests did not identify any consistent patterns for these beginning episodes of designing. No significant differences were observed in ID1's issue distributions (p >.05). Those of ID4 were consistent with the overall pattern that a higher percentage of S and Bs issues in Task CM. However, a opposite pattern was displayed by ID2 and ID3 teams. In the early stage of designing processes, students of these two teams were more focused on function issues in Task CM. ID3 was also involved with more reasoning about Bs in the early stage. These results may suggest that ID student's designing process commences with a "fuzzy" exploration of design situations.

COMPARING THE DISTRIBUTION OF DESIGN ISSUE FOR LATER PART OF THE DESIGNING PROCESS

For the second half of the design protocols, the differences of design issue distributions between the two tasks were statistically significant, X^2 (5, N=2) = 43.062, *p*<.001, Cramer's V = .250. A *post hoc* Wilcoxon test indicates the median of difference for F, Be, Bs and S issues were statistically different between the two tasks (*p*<.05).

The association between design issue distributions and tasks, Table 7, are consistent with our initial hypothesis, namely higher percentages of F and Be issues in Task PES, and higher percentages of S and Bs issues in Task CM. Similar results were confirmed by Chi-Square comparisons of each team.

The same tests were also applied to the latter two thirds of the design sessions. The result was consistent with the second half, X^2 (5, N=2) = 34.146, p<.001, Cramer's V = .193.

Design issue		Task		Total
		ME	PES	
Requirement (R)	Count	1	2	3
	% within task	0.3	0.6	0.4
	Adjusted Residual	-0.8	0.8	
Function (F)	Count	26	54	80
	% within task	6.8	17.5	11.6
	Adjusted Residual	-4.3	4.3	
Expected Behavior (Be)	Count	58	80	138
	% within task	15.2	25.9	20.0
	Adjusted Residual	-3.5	3.5	
Behavior from Structure (Bs)	Count	117	63	180
	% within task	30.7	20.4	26.1
	Adjusted Residual	3.1	-3.1	
Structure (S)	Count	111	55	166
	% within task	29.1	17.8	24.1
	Adjusted Residual	3.5	-3.5	
Design Description (D)	Count	68	55	123
	% within task	17.8	17.8	17.8
	Adjusted Residual	.0	.0	
Total	Count	381	309	690
	% within task	100.0	100.0	100.0

*Table 7. Design issues * design task crosstabulation for second half of the sessions*

DISCUSSION AND FURTHER STUDIES

The results of the protocol analyses demonstrated that there are no differences in terms of design issues in the beginning of the design sessions, but significant differences occur following that. The difference in the second half of the design sessions complied with the overall pattern with a greater difference in terms of Cramer's V (.250 vs .143). This translates into cognitive differences during ID students' designing activities in the latter stages of designing processes, rather than the beginning stages. It implies that ID students utilize similar strategies when analyzing/formulating design problems, but that they adjust their strategies to different design tasks when synthesizing and evaluating design solutions.

THE FORMULATION OF DESIGN PROBLEM

The design issue distributions of the first one-third of the design sessions (Figure 4) indicate a goal-oriented thinking style; the percentage of function issues is much higher than all other issues for both tasks. About half of the cognitive effort was spent on reasoning about the purpose of the design in both tasks. Meanwhile, little cognitive effort was expended on considering design outcomes, indicated by a low percentage of structure and behavior from structure issues, of which the averages are lower than ten percent for both tasks.

A qualitative examination of the coded protocols indicates function issues were related to discussions concerning target users and the broader context and structure issues were mostly concerned with the design precedents recalled to promote a further exploration of design contexts and to assist formulating the design goals.

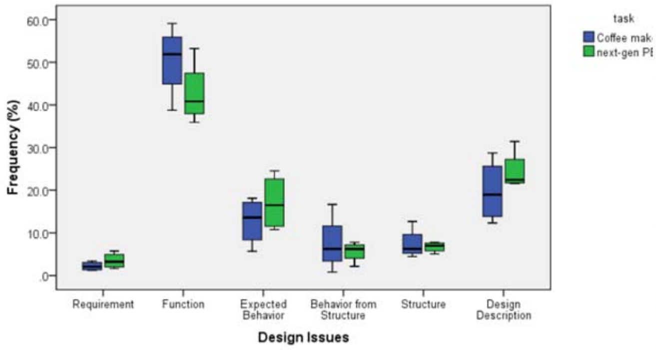

Figure 4. Frequency distributions of design issues for the first one-third of the design sessions

These results show that there are no significant differences of design issues distributions in this early stage. This implies that a user/context-centered thinking is dominant in the initial stage of ID conceptual design processes.

DEVELOPMENT OF DESIGN SOLUTIONS

The design issue distributions for the latter stage of the design sessions (Figure 5) indicate that the dominant issues concerned when designing for Task CM are changed to structure and behavior from structure issues (represented by dark hatching in Figure 5). Expectations of product behaviors (Be) are also frequently addressed (around one sixth of total issues) to draw comparisons with actual performance of products (Bs). However, the purpose of the design (as measured by function issue) was rarely revisited in this period. It implies students' thinking mainly goes back and forth between solution generation, analysis and evaluation in the latter stage of variant/ adaptive design tasks.

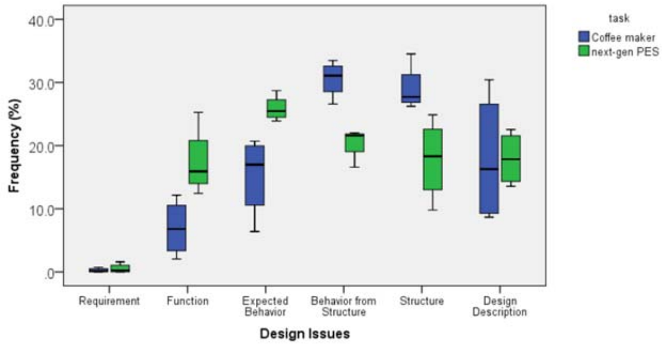

Figure 4. Frequency distributions of design issues for the second half of the design sessions

In contrast, the second half of Task PES protocols (represented by light hatching in Figure 5) shows a fairly balanced distribution of all issues (except requirement issues). A substantial proportion of function and expected behavior issues suggests conceptualization is still active in this period. Re-assessment of original design problems and re-articulation of design goals were frequently addressed along with the solution developments in visionary design tasks. This indicates that the visionary design process of ID students is a co-evolution between problem and solution domains (Dorst & Cross, 2001; Reymen, Dorst, & Smulders, 2009).

IMPLICATIONS OF DESCRIPTION ISSUE

In the FBS ontology, design description issues (D) are mainly concerned with the production of external representations of design solutions, like structures (Gero, 1990). The data from this study show that description issues were, to some extent, evenly distributed throughout the whole process, with a moderately high percentage, around one fifth (see Figures 3, 4 and 5). Even in the beginning of designing processes when there were few structure issues elaborated, the documentation activities were very active (see Figure 3). This provides evidence that sketching is consecutively employed as a mode of designing parallel with the verbal mode (Akin & Lin, 1995). It also supports the argument that designing as a constant reflective conversation with materials of a situation (Schön, 1991; Schön & Wiggins, 1992). A graphic way of working is not only important for elaborating design solution, it may also be essential for exploring and articulating the goals of design, although there is evidence to contrary (Bilda, Gero, & Purcell, 2006).

To conclude, based on this exploratory study, the cognitive activities of industrial design students are influenced by the nature of design tasks, and the differences mainly occur in the solution development period. For both tasks, participants initiated their designing process by investigating users' needs and the broader context for those needs. Concerns about purpose of design were primarily discussed in this stage.

For the remaining part, participants adjusted their strategies with respect to the particulars of the problem formulated in the earlier stage. Cyclic development between solution generation, analysis and evaluation were identified in the variant/ adaptive design task. In the visionary design tasks, re-assessment of original design problems and re-articulation of design goals were frequently addressed along with the solution development.

These conclusions need to be treated as tentative due to the limited sample size. Further studies with a larger sample size are required to generalize these findings.

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