

Understanding Senior Design Students' Product Conceptual

Design Activities:

A comparison between industrial and engineering design students

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Abstract

This paper reports an experimental study with a purpose to investigate and compare the design thinking processes between final-year industrial design (ID) and mechanical engineering design (ME) students. Two types of conceptual design activities were observed and analyzed. One was to solve a realistic problem for the current market and the other was to generate “blue-sky” visionary concepts for the future. A qualitative method, derived from design protocol analysis, was proposed to explore the structure of observed design processes. The preliminary result demonstrated the disciplinary difference, between ID and ME students, on formulating and approaching design problems. In contrast with the previous perception that ID process is more solution-led while that of ME is more analysis-oriented, ID students were observed to spend much more time on systematically analyzing target-users and possible contexts of usage, in order to establish new design goals and requirements with regards to the above analyses. Whereas ME students were more dedicated in solving the problems identified from the given design brief and conducted little analytic work before concept development.

Keywords

Variations of design thinking; design protocol study; structure of design processes.

Design thinking is one of the most important issues in design research. During past three decades, design researchers constantly sought to identify the shared core features across all design professions, in order to generalize the cognitive mechanism of designers into a distinguished way of thinking and knowing from sciences and humanities (Archer, 1979; Cross, 1999, 2008; Goel & Pirolli, 1992; Owen, 2006). The term “design”, however, does not refer to a homogeneous activity; instead, it includes an extraordinarily broad spectrum of activities, with one end linking to engineering and the other end to fine arts (Lawson, 2004). Normative studies (Akin, 2001; Lloyd & Scott, 1994, 1995; Roozenburg & Cross, 1991) have also identified that significant differences existed in the design models between industrial design and engineering design, which implies there are many variations within the general design approach. This study therefore attempted to analyze empirical evidences from design process to evaluate or refute these pluralism arguments

of design thinking. Insights on similarities and differences between different design disciplines are also expected to contribute to the generalization of design cognitive patterns during various design processes.

Conceptual Framework

Our explorative approaches for the variations of design thinking were: (1) to select several related design disciplines within a specific design field and (2) to observe and compare their design cognitive processes.

Product design is the focused area of this study. Two related design disciplines were selected, i.e. Industrial Design (ID) and Engineering Design in particular Mechanical Engineering Design (ME), which are believed to respectively represent the synthetic- and analytic-oriented aspects of product design (Owen, 1998, 2006). It is thus hypothesized that, given the same design problems, these two design disciplines will show distinguished differences between how they approach the problems and synthesize the concepts and solutions.

One way of investigating design thinking is to portray the structure of design cognitive mechanism while performing a particular design task. Dorst (2003) argued that design cognitive processes were nested; analysis, synthesis and evaluation activities were not proceeded in a spiral sequence or simple iterations, but rather in a form of complex nested network of “cycles within cycles”. Our pilot study confirmed this argument. This paper aims to empirically explore the detailed cognitive structure between both ID and ME students’ conceptual design processes and compare the ways of how design activities (i.e. problem analysis, idea generation, etc) were organized within conceptual design processes.

Another concern of our study is the nature of design tasks. The purpose of design tasks and the amount of constraints linked to task type may also alter designer’s cognitive strategies and thus produce different patterns on design processes.

Research Methodology

Design protocol study (an observational, experimental research method, see Cross, Christiaans, & Dorst, 1996; Jiang & Yen, 2009) was adopted as the primary method in this research.

Factorial Research Design

A 2X3 factorial experimental design (shown in Table 1) was applied to this study. Two factors, i.e. major independent variables, are design disciplines and types of design tasks.

Table 1 Comparative Dimensions of Design Experiment

	ID teams	ME teams	Mixed teams
Task A: realistic problem solving for the present (with hard & unalterable constraints)	4 teams	4 teams	4 teams
Task B: visionary concept design for the future (allowing wild imagination)	4 teams	4 teams	4 teams

Final-year ID and ME students from National University of Singapore were recruited voluntarily as the research participants. The unit of participation was a design team consisting of two persons. Three participation categories were designed in this study: ID teams (both participants come from ID), ME teams (both from ME) and Mixed teams (one from ID and the other from ME). A total of twelve teams were observed and analyzed.

This study focused on design conceptualization phase, which is considered as the most creative element of design activities. Two different types of design tasks were assigned to each team. Task A is to design a coffee maker for a Singaporean start-up company. Based on the context of current market, the purpose of this assignment is to create realistic commercial problems with several hard and unalterable requirements. Task B is a visionary concept design, i.e. to design a next-generation personal entertainment system/device for a world leading electronic corporation. Compared with the former task, task B allows much more space for wild imagination and subjective interpretation.

Experiment Procedure & Setup

Each experiment session was conducted as the procedure shown in Figure 1. A pre-test questionnaire was designed to recruit voluntary participants. Their demographic information, basic understanding of design and perception of design process were also collected. All participants were asked to execute both task A and B and a lunch break was provided between these two tasks. In order to balance the sequence effect, half of the teams in each category performed task A first and the other teams performed task B first. After the completion of each task, the participants were allowed to make a short presentation within 5 minutes to explain their ideas.

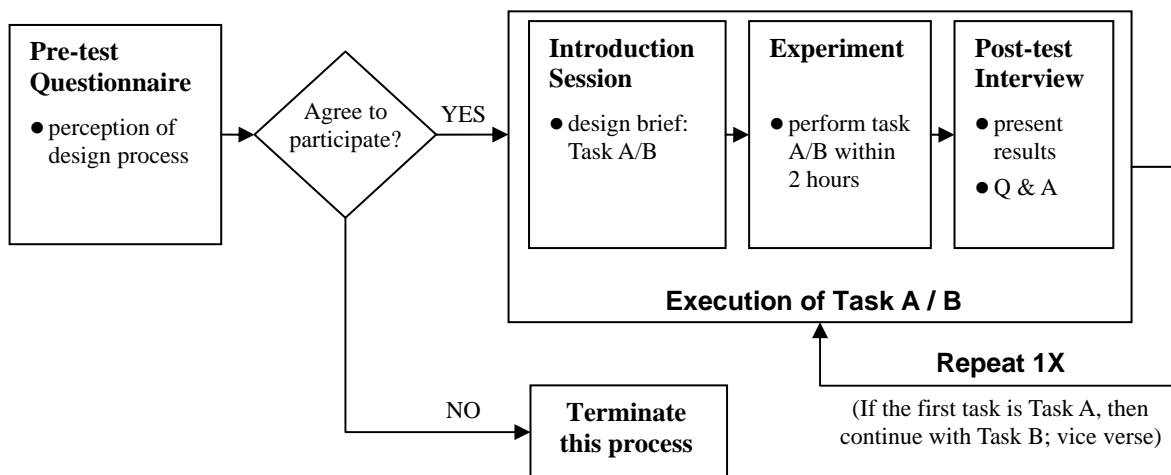


Figure 1 Experiment Procedure

The experiments were conducted in a design-studio-like setting shown in Figure 2. Both traditional design tools (e.g. pencils, pens, sketching markers, paper, etc.) and digital design tools (i.e. a laptop computer which was accessible to internet and pre-installed with CAD software packages) were provided. A white board nearby the workstation allowed designers to write, draw, and use post-it tips to share and collaboratively develop their design ideas.

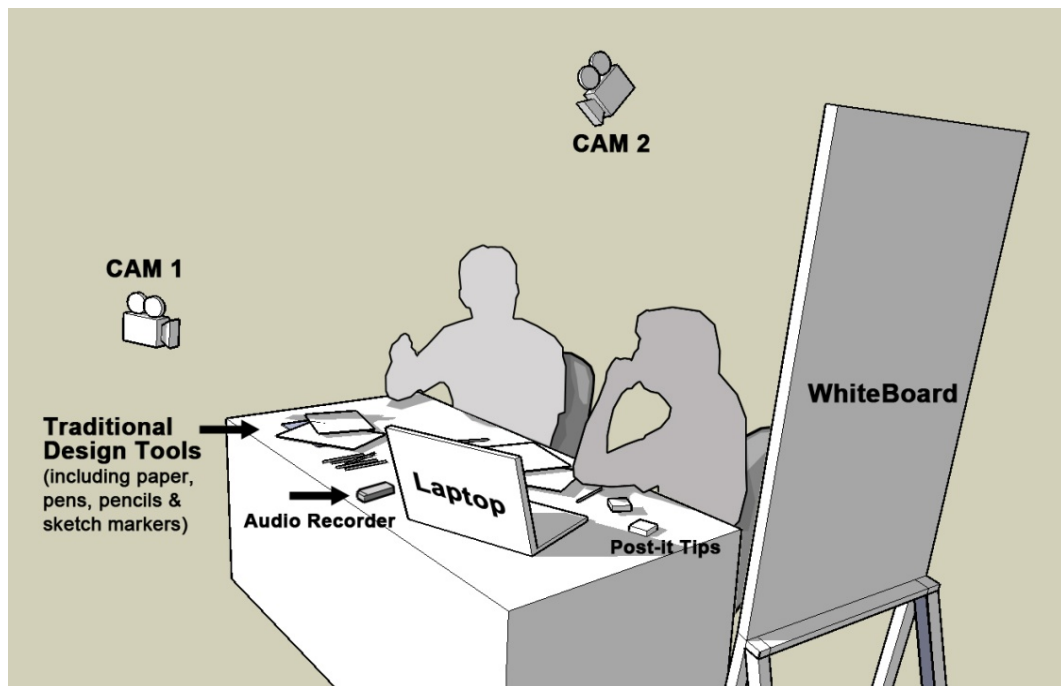


Figure 2 Experiment Setup

Two cameras and one high fidelity audio recorder, illustrated in Figure 2, were set up to capture the details of the observed design process. Thereof, CAM 1 took the overviews of designers' performance (lower part of Figure 3) while CAM 2 emphasized the specifics of designers' work, like sketching processes (upper-left part of Figure 3).

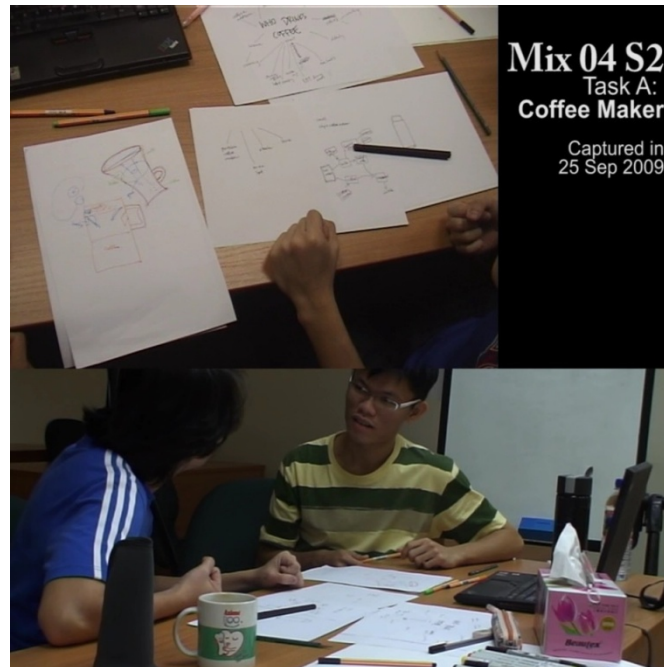


Figure 3 Snapshot of Multimedia file for analysis

After all session, the outputs of CAM 1 & 2 and audio recorder were synchronized into a combined multimedia document (exemplified by Figure 3). All conversation and utterances within the design activities were transcribed in textual form and non-verbal behaviors were recorded as the notes in the transcriptions. The sketches and drawings produced during design processes were collected and numbered with regards to the occurrence sequence. The multimedia

documents, text transcripts and sketches collectively constituted the tripartite design protocols for latter analysis, which were considered as the externalizations of cognitive processes of these observed collaborative design activities.

The data of pre-tests questionnaire and post-test interview served as extra references for making sense of design protocols.

Methods for Analysis

One of the most common techniques for design protocol analysis is to segment a protocol (i.e. the record of a complete process) into micro-actions of seconds, code them with a set of priori categories and then explore the coded segments qualitatively and/or quantitatively. This technique can identify the alternations of topics and designers' intentions within a design process, but the connections between micro-actions are severed (Dorst, 1997; Dorst & Dijkhuis, 1995). The observed design process was thus flattened into a simple sequence with iterations between several behavioural categories, rather than maintaining the nested structure of design activities.

"Linkography", on the other hand, is a technique proposed to analyze the interconnections of design actions within a process (Goldschmidt, 1995; Goldschmidt & Weil, 1998). But content of each protocol segment is omitted in this technique. All design actions are simplified as homogeneous design "moves" in a linkograph, i.e. a diagram visualizing the interconnected moves. It is hard to show patterns about major design phases (e.g. problem analysis, idea generation) and their structures.

In order to investigate the nested nature of design processes and relationship between major design phases, a revised version of design protocol analysis balancing the content and interconnection of micro-units of design activities was developed.

Rather than coded with a priori set of categories, we adopted a data-driven approach. A protocol was segmented according to its semantic meanings. The semantic transitions were adopted as the criterion of splitting protocols, like verbal hints that suggested designers were shifting their intentions, as well as silence situation lasting more than 5 seconds which indicated a process breakdown. These segments were usually clusters of several finer design actions. With regards to the dynamic nature of design activities, these segments varied from 1~2 seconds to several minutes.

After segmentation, each protocol segment was then coded based on its semantic meaning rather than a priori coding system. This allows a flexible coding process. New categories of code will be easy to generated and added into the coding scheme, and the existing codes are vulnerable to rearrangement. Table 2 summarized codes applied in our study. The organization of the applied codes resembled Purcell et al.'s (1996) coding scheme of design strategies. The immediate design actions could be mapped to three broader categories of analysis, synthesis and evaluation. Another set of actions, which we tentatively called "strategy", referred to the management of or reflection on design actions. They could be categorized as "meta-cognition", i.e., monitoring, evaluating and regulating people's own cognitive actions (Fayena Tawil, 2007; Jaušovec, 1994).

Table 2 Data-driven Coding Categories

Categories	Sub-categories	Interpretation	Example in transcripts
Problem Analysis	Info	Searching for external information	"Check the ice blend coffee (action: browsing WebPages)"
	Name	Identifying elements related to current design situation	"What factors are essential for entertainments? Audio... visual ... touch .. and? (action: drawing a mind map)"
	Analysis	Elaborating relevance of identified elements to design problem	"The interface is important for an entertainment device"
	Requirement	Establishing requirements or specifications	A: "So what do you want attributes of? ... What the ..." B: "Of course you must look trendy, sporty, professional..."
Solution Synthesis	Ideation	Proposing a new (partial) solution	"Playing music with heart beats, or mood of the day (action: brainstorming through post-it tips)"
	Revision	Modifying a proposed solution	"Yah, it must have some transparent thing here" "Maybe put it at the bottom, so it can be easily accessed"
	Synthesis	Combine several partial solution into one coherent solution	"I think these two ideas both"
Solution Evaluation	Interpretation	Interpreting and analyzing the proposed solution	"Because there is the ice, there is the coffee, there is the ... It sounds you need a lot of coordination" "Basically, when the water is boiled, the coffee is added here, the steam will eventually produce high enough pressure to force the boiling water up to here..."
	Evaluation	Making positive or negative judgments on proposed solution	"I like this idea, very ipod-ish ... cool, man" "This is really cute. I want to buy one when it's released"
Strategy	Management	Proposing a design global or local strategy on organizing design process	"Let's do some brainstorming, about 10 minutes ... hum, till 10:45, then we exchange ideas"
	Reflection	Evaluating and reflecting on current design strategy	"I think we move on too fast, let's focus on what is users really want at this moment." A: "Do we continue doing mind map?" B: "I think had better move on to concept generation"
Others	No code	The irrelevant verbalization for our study	"This color is quite cool" (comments on the marker we provided) "Wait me a second, I need go to toilet first"

Due to the explorative nature of this stage, the coding of protocol was conducted by a pencil-and-paper approach. No quantitative analysis was executed after coding process. Instead, we proposed a technique to visually manipulate coded protocol segments at a macroscopic view. Inspired by affinity diagram (Beyer & Holtzblatt, 1998), these coded segments were grouped and rearranged in a hierarchical structure, according to their similarity on design topics. Meanwhile, each segment's duration and position in timeline were still maintained. The structural pattern of design cognitive process was thus able to be read from the reconstructed sequence or the "flow" of design activities.

Findings and Discussion

Figure 4 exemplifies the visualization of coded segments. Generally, the top-level of protocol groups, which are not further grouped into another group as a component, could be seen as the phases in a stage-like designing process model. Most of such phases can be well aligned with three broad categories of coding scheme, i.e., problem analysis, solution synthesis and evaluation. Meanwhile, the actions of "strategy" was scattered along with a design process.

However, a closer examination of this visualization shows that the observed designing process was not a simple sequence of these three broad activities. Instead, a nested structure of design

cognitive process was found to emerge from the reconstructed sequence or the “flow” of design activities. Nearly all types of actions can be found within each phase. For example, in both sessions of Concept Generation 1 and 2 shown in Figure 4, these two “synthesis” phases include “requirement establishment” actions (that are attributed as “analysis” category) and actions of “evaluation of the generated design alternative” (that are a subcategory of “evaluation” activity) as their components. This finding is consistent with Dorst’s (2003) argument of the nested structure of design cognitive processes.

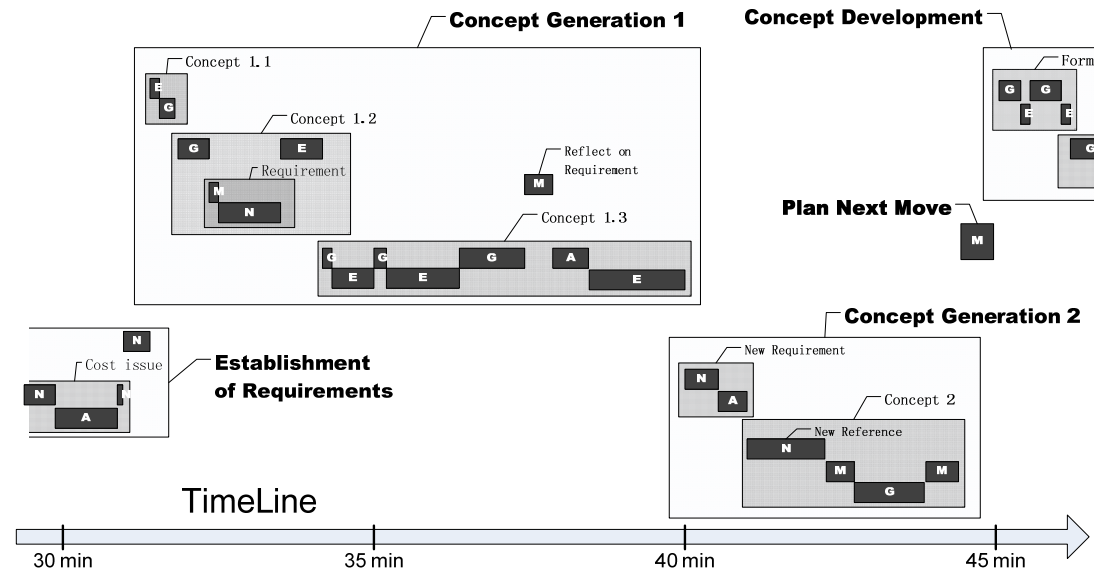


Figure 4 Nested Structure of a Design Process (an example based on a partial process)

Through examining both structural visualizations and the contents of protocol transcripts, some significant features of design processes in each factorial category were identified. Table 3 summarizes the preliminary findings based on qualitative examination at a macroscopic level. The results will be discussed in detail from two perspectives: the dissimilarities of process structure according design disciplines and experimental tasks.

Table 3 Preliminary findings of design protocol study

	ID teams	ME teams	Mixed teams
Task A	<ul style="list-style-type: none"> • Process: Analysis-Synthesis • Duration of Analysis: 1/3- 1/2 • Content of Analysis: Generic context; product features • Concept: 1 or 2 main concepts with several variations • Emphasis of concept: User experience 	<ul style="list-style-type: none"> • Process: Analysis-Synthesis • Duration of Analysis: 1/5- 1/4 • Content of Analysis: Understand existing products • Concept: 1workable concept • Emphasis of concept: Working mechanism 	<ul style="list-style-type: none"> • Process: Analysis-Synthesis • Duration of Analysis: 1/3- 1/2 • Content of Analysis: Generic context; design precedents • Concept: 1 main concept with several variations • Emphasis of concept: User experience
Task B	<ul style="list-style-type: none"> • Process: Analysis-Synthesis • Duration of Analysis: 1/3- 3/5 • Content of Analysis: Generic context; product features; design precedents • Concept: 1 major concept but initiated by several crude ideas • Emphasis of concept: User experience 	<ul style="list-style-type: none"> • Process: Synthesis • Duration of Analysis: < 1/5 • Content of Analysis: recognize problem from design brief; hardly found an explicit analysis phase • Concept: 1workable concept • Emphasis of concept: Functions 	<ul style="list-style-type: none"> • Process: Analysis-Synthesis or Analysis-Brainstorming-Evaluation-Synthesis • Duration of Analysis: 1/3- 1/2 • Content of Analysis: Generic context; design precedents • Concept: many crude ideas • Emphasis of concept: Functions

Design Processes: Analysis-oriented vs Synthesis-oriented

It was claimed that, within the comparison of ME and ID's designing process, the process of ME was more analysis-oriented, focusing on "finding" or discovering, whereas that of ID was more synthesis-oriented, emphasizing "making" or invention (Owen, 2006). But the empirical findings of this study appear to demonstrate a reverse phenomenon.

In the observed design sessions, ID participants dedicated a considerable amount of time (more than one third of total time) into problem analysis or design context analysis. Their process was usually initiated by a general exploration of broader design context without consideration of any expected design outcomes. When an unfulfilled need or a more promising potential was identified, the focus of design discussion was relocated to the features of product concepts, or design requirements. Design brief like statements were explicitly made before they went into generating design concepts.

ME participants, conversely, showed a very solution-led strategy. They were observed to spend little time (usually less than 10 minutes) on problem analysis and quickly jumped into the details of design solution. Their analytical work was also closely related to particular aspects of solutions, e.g., understanding existing products' working mechanism.

The general contexts (usually not explicitly concerned with specific product concepts) that were discussed in detail by ID students were seldom observed in ME processes. Only 2 out of 8 ME sessions explicitly, though very briefly, considered their target-user, usage context and design requirements before approaching possible product concepts. Other sessions either stated the abovementioned considerations as hindsight, or simply omitted them.

Moreover, ME sessions spent much less time on problem analysis. Their process thus seemed more "efficient"; the average time of ME sessions was 33 minutes shorter than that of ID sessions, which lasted about 91 minutes on average per session.

The processes of Mixed teams stood somewhere in the middle, depending on which participant was more actively involved in the process.

The above results demonstrate significant dissimilarities between ID and ME students' design strategies. These structural differences of designing processes seem to be correlated to the very different understanding of design held by ID and ME students.

According to the pre-test questionnaires, ME students treated design as a particular type of problem-solving activities. For them, the problem situations were already given or prescribed in design brief; a designer's job is to gather them and identify one or two feasible ways to solve them accordingly. ID students, however, apprehended design from the perspective of its ultimate purpose, i.e., a means of "improving human lives" (excerpted from an ID student's response to pre-test questionnaire).

It is likely that, guided by the different views of design, ME students spend very little time on the problem analysis and tend to consider the designed product as a system. The interactions of

subsystems or product components are thus their specific concerns. For example, issues, like proposing a scheme to breakdown components or “functional modules”, were frequently discussed in ME protocols.

In contrast, ID students valued the role of human much more than that of a product. They are thus willing to spend more time to systematically go through the analysis of potential user’s profile and possible usage contexts, and to explore the potential opportunities to create something new and more appropriate. The product concepts, most of time, are discussed under a broader user-product-context framework while the internal structures of designed product are less important. Human-centred values are their major concern. For instance, during the design process, “experience”, “fun”, “feeling” and “interaction” were the terms most mentioned by ID students.

Influences of the Nature of Design Tasks

The structure of designing process seems not only to be influenced by the constituting members of design teams, but is also subjected to the type of design tasks (Table 3); the abovementioned disciplinary differences were more significant in visionary concept design task.

In task A, the processes of all three categories followed an “analysis- synthesis” sequence in general. Most sessions generated one or two design concepts based on their initial analysis. ID students usually experimented with several variations on form or ways of how people could interact with designed product, whereas ME students appeared to be more committed to a single workable solution. The evaluative actions intermediately followed actions of synthesis, thus no extensive evaluation stages came up.

Situations changed in task B, i.e., future-oriented visionary concept design task. ID teams followed a similar “analysis-synthesis” strategy; ideas of expected product were triggered by the analysis and then naturally evolved. ME teams, instead, proposed the possible solutions in the very beginning, and the final outcome seemed to be a simple assembly of everything they had thought of. Both ID and ME sessions, for task B, adhered to the development of a single concept; very little variation of product concept was considered.

The Mixed sessions in task B showed a very different story. Two Mixed teams’ processes resembled those of ID teams, i.e., synthesis stages followed analysis of problems. However, the other two Mixed teams were stuck at the analysis stage, without emerging a promising direction to pursue. Participants resorted to a formal brainstorming for idea generation. The consequence of brainstorming was that designers had to face a variety of solutions (7 and 22 in two sessions respectively); an explicit “evaluation” phase was thus required to perform in order to identify which idea, or an integration of several ideas, was appropriate for further development. These two teams adopted an “analysis-synthesis-evaluation- synthesis” strategy in visionary conceptual design.

In our original conception, task A and B represents two design problems of different nature. According to theory of problem finding (Dillon, 1982; Getzels & Csikszentmihalyi, 1976; Runco, 1994; Starko, 1999), there is a distinction among presented problems, discovered problems and created problems in terms of whether or not there are explicit problems, standard solving methods

and/or possible solutions known to solver and/or others. Compared with task A, task B contains more potential and implicit elements requiring designers to identify and actively formulate. It is supposed that task B will involve a longer problem analysis and formulation phase. ID and Mixed sessions confirmed with this hypothesis, but ME sessions did not. This phenomenon is difficult to be accounted for by the traditional view of problem solving, which frames the design processes by analysis, synthesis and evaluation activities, but it can be possibly explained from the view of problem finding and formulating. One probable explanation is that ID and ME students held very different problem formulating strategies.

According to Thomas and Carroll (1979), design is not necessarily associated with a particular type of problem. More precisely, design is rather “a (particular) way of looking at a problem” (p. 5) and any problem can be viewed as a design problem if the solver treats it as ill-defined. In our experiments, a longer problem analysis phase in task B suggests ID students made a greater endeavour to understand the problem situation and create a workable problem when they encountered a visionary design task. On the other hand, the very short phase of ME problem analysis may be explained by ME students’ “convenient” but passive strategy in which they tended to frame the problem situation as well-defined and simply select an available problem representations according to their experience. Retained from reconstructing the problem situations by other possible problem representations, ME students were thus easier to follow an adaptive or variant designing process, rather than conducting an original designing process (Pahl, Beitz, Feldhusen, & Grote, 2007). The examination of designed outcomes also showed a strong fixation effects in ME sessions.

The different strategies concerning with design problems were consistent with Harfield’s (2007, 2008) two different design “problematization”, i.e., “problem as given” and created problem “as design goal”. They also indirectly refute the argument of design as a particular way of looking at a problem (Thomas & Carroll, 1979). Various ways of looking at a problem may co-exist within design activities.

Experiment Effects

All participants reported the experiment setting was similar to their design studio. They did not feel anything uncomfortable when working in this controlled environment. The observed design activities could represent their daily design processes.

However, a sequence effect (sequence of performing task A or B) was found in our study. No matter which task was performed first, the second task took less time to complete. The total experiment time was reduced almost 1/3 for ID teams and 1/5 for Mixed teams. The proportion of analyzing the second problem also decreased significantly in ID and Mixed sessions. The decrease of total experiment time in ME sessions was less obvious, but their second tasks were also found to last for a slightly shorter time. The latter effect, i.e. the alternation of ratio of analysis to synthesis, however, was not found in ME sessions, as ME students hardly explored the problems while performing task B.

Conclusion

The qualitative examination of design protocols shows significant dissimilarities between ID and ME design processes. This finding reflects different attitudes of ID and ME students to the tasks provided in this study, i.e., treating design brief as a given problem or as an impetus to formulate actual design problems to solve. This conclusion provides evidences for variations within design thinking and cognition.

Due to the explorative nature of this study, it actually raises more questions than it has solved. This study suggests that ID and ME students differ in their problem finding activities. A more detailed analysis will be conducted to investigate their problem finding processes and how problem finding actions are related to synthesis of design outcome.

The current analysis is a qualitative examination of design process structure at a macroscopic view. Further studies will include creating a sophisticated coding scheme and quantitatively analyzing both content and process aspects of design thinking (Goldschmidt & Weil, 1998).

In addition, the design strategies (including problem finding and solving) and understanding of design were taught, directly or indirectly, in the educational programs. Further study should include the discussion of the curricula of ID and ME programs in the National University of Singapore and identify the differences between these design trainings.

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