THE EFFECTS OF FUNCTIONAL DECOMPOSITION (FD) INTERVENTION ON STUDENT INVENTIVENESS

Norkhairolizah Hamzah

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Declaration

I declare that this thesis has not been submitted in whole or in part to this or any other University for the award of a degree.

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Functional Decomposition helps to see what I can do, see what extra bits I can have, and helps to organize my thoughts…

~ Participant 8, Segment 8, Post Intervention Phase.

Summary

The Effects of Functional Decomposition (FD) Intervention on Student Inventiveness

The purpose of the current investigation is to find evidence on how FD as a design method affects problem solving in inventive design tasks in three separate studies (Experiment 1, Experiment 2, and Case Study). The purposive sampling technique was used to sample only 30 post-graduate students of similar background engineering knowledge with experience in designing who were then grouped under three separate design methods, which were: “FDI”, “CPS” (Creative Problem Solving) and “FDII” (10 each), while conducting inventive problem solving tasks. This is done with the provision that implementing those methods may affect the subsequent knowledge recall and thus, the resultant problem representations. The experiments were only conducted on a specific group of participants, so the results only apply to this limited pool. The scale of the experiment was limited to testing the skill of decomposing complex problems based on functionality during the preliminary design stage only. Therefore, the findings are not generalizable to actual design processes in the field. Further investigations need to be conducted to prove the applicability of FD in actual design problem solving which takes a longer time (even months) to complete.

The findings show that there is a significant effect of FD intervention on participants’ cognitive ‘processes’, specifically on the kinds of design aspects they used during problem solving. The transition analyses revealed that the training significantly changed the way problems are represented by the participants in the current studies. Transition analysis is different from quantifying the design aspects (i.e.: the function, behaviour, structure, people, purpose, and resource aspects). It is found that the Function-to-Function transitions in the FDI group has significantly increased after the intervention, in parallel with the significant increase in the quantity of utterance of function aspects. However, the Function-to-Function transitions in the FDII group showed no significant difference after the FDII intervention, even though the function aspect has increased significantly.

This means that, even though there is a significantly low utterance of function statements during the pre-intervention phase, the function aspect has been closely followed by other function aspects among the FDII participants. Therefore, it causes no difference to the function-to-function transitions after the intervention. This shows that the transition analysis measures a different aspect of the participants' representations. Furthermore, the findings on the 'product' inventiveness have shown no clear trend across all groups and all phases.

Finally, the qualitative Case Study indicated that the processes of 'control' (functional knowledge) and 'goal' definition (the decomposition operators) across the selected participants had changed after the FDI and FDII interventions only, unlike the CPS. Even though participants started at around the same rate of recall of information based on the conceptual maps depicted, this pattern has changed due to the method they used, showing an effect of the FD intervention. The Case Study explored the nature of the conceptual change following the intervention, in terms of the qualitative aspects of function including the concept formation in each problem solver (based on the protocols and retrospective debriefing reports) and the use of different kinds of function-based operators that were used.

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CHAPTER 1

Introduction

1.1 Overview

The cognitive processes of invention and design have been extensively studied since the last four decades (Ball et al., 1997, 2004; Cross, 2004; Goel & Pirolli, 1989, 1992; Kruger & Cross, 2006; Mehalik & Schunn, 2006; Vermaas et al., 2011). Systematic research to study the processes of design and inventiveness and how to enhance these processes have a great potential for future empirical studies. As Weber (2006) put it:

> …invention in the context of real expertise may include mental processes that are not typically studied in the laboratory. These processes must first be adduced from important case studies. But once they are identified in real world invention, some of them may then be abstracted and find their way back to laboratory investigation and the more limited time span of minutes, hours, and days. And some of them, once made explicit, may then find use in the more limited intellectual capabilities of most of us because they **can be deliberately taught** (p.2)

This implies that design strategies, if made explicit, can be deliberately taught to students (Ball & Forzani, 2007; Dufresne et al., 1992; Mourtos, 2011; Weber, 2006). In line with this, it is found that there is high awareness (80%) that innovation in engineering education is needed. Unfortunately, the actual implementation and adoption of new skills by educators in the field was only 47% (Borrego et al., 2010). In addition, the study by Ahmed, Wallace and Blessing (2003) suggested that the teaching of specific design strategies to novices is important since they are unmindful of their usage in solving design problems as compared to more experienced designers.

The current work is intended for promoting one of those design strategies explicitly to engineering design students. During the design, the conceptualisation of an intended technology takes place (Vermaas et al., 2011). As Dasgupta (1996) put it:

> The powerful part of modern design is the explicit addition of purpose, requirement, and constraint at the beginning of the process – that is to say a planning and symbolic representation that is separate from the act of construction (p.61).

Thus, design instruction centres around promoting learners with various design methods and symbolic representation acts through which students could fulfil the clients' needs as an outcome of such acts. "Necessity is the mother of invention"—as the saying goes—tells us that a separated analysis of human needs (the necessity) prior to the actual design implementation is paramount to a successful design. Designs should focus on analysing and solving human problems as an end, so that an engineering design can be the means for achieving that end. This approach is also known as a human-centred design (Dreyfuss, 1995; Giacomin, 2014; Zachry & Spyridakis, 2016).

The current work is about the teaching of a design method that fits the philosophy of a human-centred design. There are factors that encourage the development of this study, that is mainly for supporting the design instruction. This is explained next.

1.2 Background and Motive

There are a lot of competitive designs from time to time, and this has to do with change to the environmental constraints as well as human needs. The notion of human-centred design suggests that designers should propose technologies that are designed to function, that is to satisfy their needs (Giacomin, 2014). To produce good designs, inventive designers set the state of future affairs by changing clients' current needs. The technology they develop should function for fulfilling these newly identified needs. Furthermore, functions underpin subsequent design construction processes so that solution development becomes more manageable.

In the same vein, Mehalik and Schunn (2006) emphasise on the importance of functional decomposition in their meta-analytical study about what constitutes a good design. The study yields important outcomes, particularly on the desirable design methods according to the literature. It is shown that Tier-1 and Tier-2 design skills are primary methods, including 'explore problem representation', and 'use functional decomposition'. They are methods that are reported in high frequency across the selected 40 design studies. Design methods related to solution development such as 'build normative model' (Tier 4) and 'explore engineering facts' (Tier 5, lowest reporting) are found to be less profound methods.

This calls for a specific study that fills in the gap on the teaching of functional decomposition as a design method in the contexts of improving the current understanding of the method itself, and in return, enhance the method for future implementation. If functional decomposition is a good method, it should not just be widely used as reported by Mehalik and Schunn (2006). Rather, how and to what extent the method can enhance design processes. This is by testing the method empirically, through execution and followed by the explanation. The current work is going to fill the gap in our knowledge.

So far, the general impression towards functional training is that it largely stands outside of the tools, software and methods that designers normally use during design synthesis such as CAD (Eckert, 2013). The modelling such as FMEA21 (Failure Mode and Effect Analysis; US Dept. of Defence, 1949); TRIZ (Tsai, 2008); C & C (Contact and Channel) (Grauberger, et al., 2020); FAD (Functional Analysis Diagram) and many more are stand-alone functional methods that have been used as generic thinking tools in the designing process. Eckert (2013) posited that:

> Reading a definition of function at the beginning of a paper or a training session is not enough to change people's notions, they need systematic training to adopt a particular view, which than becomes hard to unlearn… Designers in industry are most likely to use functional modelling if it is part of established approaches, like QFD or FMEA, which are applied across their industry sector and are pushed through the formal processes in their organisations... (p.221).

The above tells us that adopting a specific functional approach is a considerable commitment and effort and needs organisational support and persistence. The current in-vitro study is different because we would like to isolate some properties of functionalities and explicate these properties to be taught to human subjects. Doing this involves integration of problem solving theories in the context of design~~,~~ as well as establishing training intervention suitable for human participants. Elements of such training is important for the continuous improvement of various levels of implementations, involving both the academia and industry, as many companies are still looking for ways to enhance creativity among their working teams.

1.3 Statement of Problem

The literature shows that there are studies on both functionalities in engineering, and the decomposition process in engineering. However, arguments put forward in these studies are not in a constant basis and not in concert with each other. Some studies have analysed components of decomposition but its functional properties are left implicit (Kruger & Cross, 2006; Cross, 2004). Problem decomposition, in general, is a heuristic identified to be used by problem-solvers in complex domains such as industrial design (Ho, 2001; Liikkanen and Pertulla, 2009). There are many other types of decomposition with different bases (e.g., functional, physical, informational) but in functional decomposition, the basis is to separate the distinct functionality into defined components that have well-defined interfaces (Melançon, 2008).

On the other hand, studies on functionality have generally addressed the decomposition of functions, even though there may not have been a direct address to multi-level functionalities organised to form a whole new concept of 'functional decomposition'. This study thus regards all research on 'engineering functionalities' and the cognitive study on 'decomposition' in engineering design as an overlap. For instance, Bradshaw (1992) has identified functionality as a factor of success in the invention of the first mechanical airplane where the decomposition of airplane functionalities into several parts are also mentioned. In electrical and computer engineering design, functionality has been introduced in classrooms with great success where functionalities are deliberately chunked into subcomponents in flow diagrams (Coulston & Ford, 2004), similar to systems engineering (Melançon, 2008) and management science (Volkemat, 1983).

Next, even though functional decomposition as a design method is regarded as effective especially among professional designers, the discussion and the empirical evidence regarding its effectiveness is still considered limited.

> Our argument for use of functional models for learning tasks is similar to the one for their use in memory tasks. While the literature on functional models for supporting problem solving and decision making is very rich, the literature on functional models for supporting learning is **quite sparse**. Nevertheless, each episode of conceptual design also engages learning, both during and after the episode (Goel, 2013, p.212).

The above entails studying functional decomposition as one gets to learn engineering concepts. Thus, there is a need to study functional decomposition in the context of enhancing students' ability to conduct design conceptualisation as a subject matter in its own right.

Further, design has long been regarded as a test-bed for analysing human cognition, in particular, because when people develop a new design, they seek human ingenuity to solve their problems and any dissatisfaction with current technologies (Goel & Pirolli, 1992). In a way, the teaching of functional decomposition to design students caters to the attempt to elevate their creativity and problem solving skills. Nevertheless, previous research through the literature shows that functional decomposition has never been regarded as a creative design method per se (Cross, 2004; Liikkanen & Perttula, 2009).

For instance, Liikkanen and Pertulla (2009) postulated that,

> Decomposition may have limited applicability in the design of radically new kind of products, because designers cannot possess an accurately fitting model for a novel artefact (p. 53).

This statement is highly arguable since in the study itself, there are no two similar decomposition of design ideas between the participants. Some schemes of decomposition (they are named as PDS or 'problem decomposition scheme', see Figure 1.1) showed better lists of more organised decomposition of one main function into solution types, and this is further broken into promising sub-functions. However, there is no analysis of HOW 'the better' decomposition is successfully done and WHAT are the characteristics of the functional principles that they included during design. As shown in the following figure, 'Plant Task' is decomposed into five sub-functions (water supply, regulation, transfer, mediator, energy source). The main function has a minimum of 6 sub-functions which carry many underlying engineering principles.

The Plant Task

Design an automatic watering device for home plants. The device should sustain a plant for at least one month, delivering one decilitre of water a week. Create as many different concepts as possible.

PDS for the Plant *task*

Main function	0. Plant watering device	
Solution type	1. Devices attached to pot 2. Independent devices	
Subfunctions	3. Water supply	4. Regulation
Principles	30. Separate tank 31. Water pipe 32. Rain wall 33. Condensation water 34. Ice 35. Bound water 36. Tank in soil 37. Tank in pot or in Plant board 38. Waterin can 39. Steamer 310. Closed system	40. Mechanical timer 41. Valve or choke 42. Humidity sensor 43. Pipe, hose, or string size 44. Mail man 45. Weight sensor 46. Surface permeability 47. Phone, PC, or electric timer 48. Tank decomposition 49. Controlled vaporization 410. Controlled by transfer SubF 411. Controlled by energy SubF 412. Liquid pressure difference 413. Liquid buffering
Subfunctions	5. Transfer	6. Mediator
Principles	50. Hose, pipe, or gutter 51. Capillar hose, stick, or string 52. Pouring system 53. Gravity; syphon or drain 54. Sprinkler 55. Pump, water gun, or pressure 56. Syphon 57. Diffusion 58. Absorption 59. Scooping or sprinkling	60. Plant mover 61. Soil changer 62. Robot 63. Rotating ground 64. Household air 65. Plant air 66. Humidity collector
Subfunctions	7. Energy source	
Principles	70. Mains 71. Sun 72. Battery 73. Wind 74. Rubber band drive 75. Candle or camping cooker 76. Explosive 77. Gravity	

Figure 1. 1: The Plant Task and the example of decomposition conducted by participants in Liikkanen's study (2009). PDS stands for 'problem decomposition scheme'.

The above work was conducted to explore the implicit decomposition processes among novice designers. In another study, Ho (2001) examined the distinction between the experts and novices in terms of decomposition processes. There are lessons that could be learned and explicitly adopted into our current work, and to support the design instruction in return. The 'relative' approach to the studying expertise assumes that expertise can be attained by a majority of the students through adequate exposure and training. As opposed to the absolute expertise approach (that expertise is categorical), the relative approach assumes that expertise is a level of proficiency that novices can achieve. As Chi (2006) put it:

> Thus, the goal of studying relative expertise is not merely to describe and identify the ways in which experts excel. Rather, the goal is to understand how experts became that way so that others can learn to become more skilled and knowledgeable (p.23).

Therefore, it is important to highlight that in such studies, elements of common weaknesses or errors as well as elements of improvement as an effect of intervention must be recognised. The purpose is to ensure that the transformation from a novice to an expert can be systematically conducted by focusing on specific elements at a time. However, this approach has not been implemented, particularly for promoting a specific method in the design instruction. Supposedly, the targeted design elements that need improvement can be explicitly promoted. After the intervention process, the elements, once underlined, can be re-formulated for future use or tested again in the context of improving the design instruction. A lot of design studies that investigate creativity depend only on the analysis of end products while neglecting the processes that make the production possible (e.g: Barak, 2006; Lewis, 2009).

Moreover, the Cognitive Science view on problem solving provides an explanatory power on why functional decomposition is a ‘creative’ method. The functional decomposition method refers to the use of a problem solving method that helps execute an engineering design activity based on functional heuristics. Functional decomposition has often been missed out from the list of creative methods. In this study, we challenge the view that the analytical process in functional decomposition method is ‘uncreative’. Directing the search towards functions is a way to mitigate design fixation that happens when the external aesthetical looks of an object inhibit the exploration of inherent and unobvious design intentions (Linsey et al., 2010; Bradshaw, 1992).

Furthermore, it is noticeable that even though the adoption of generic creativity methods as creative methods in the context of design may support creativity, this does not match what we already know about cognitive processes of design. There is a lot of characteristics in the human information system that inhibit divergent searches in real design tasks. The design process involves ‘satisficing’ manageable constraints while making iterative revision and reflectively act upon what is available in the environment to construct the intended design (Ball et al., 1998).

Design is a logical process that progresses through a lot of informed decision-making, rather than arbitrary search (Goel & Pirolli, 1992; Mehalik & Schunn, 2006). There are inconclusive findings on whether creative design methods such as the divergent thinking method that had been used in design classrooms, could promote inventiveness among design students. It is found that in a study involving 46 German inventors who were asked to apply the divergent thinking method to design using a computer-simulated microworld called FSYS 2.0, a divergence in terms of fluency of ideas does not lead to quality inventions (Wolf & Mieg, 2009). It is timely for the current study to make a direct comparison between the functional decomposition method and generic creative method that does not target functions in engineering.

The above has driven the current research objectives which are explained next.

1.4 Objectives

In Goel (2013), it is found that the approaches in previous studies on functional representations in design and their methodologies have catered to the following aspects: (i) to observe human behaviour as they address complex tasks such as the diagnosis and design using functions; (ii) to build knowledge-based intelligent agents based on functions for addressing design tasks; (iii) to use the knowledge-based methods such as hypotheses for explaining human reasoning on the tasks; and (iv) build interactive tools that use functional representations and knowledge-based methods for aiding humans in performing the tasks.

The current work is catered to the first aspect, that is observing human behaviour as they solve design problems using functional decomposition. Our study also contributes to the third and fourth aspects of studying functions. This is because as the outcomes of promoting functional decomposition, we would draw some conclusions about human reasoning during the design. We also develop offline materials for our functional decomposition intervention programme, instead of interactive tools in point (iv) mentioned above.

Functional decomposition is going to be promoted to design students whilst identifying the students' original condition before the intervention takes place, as well as how the method affects their design problem solving at a later phase. The significance of this is to advance the inventiveness of engineering design students, and to be able to explain how this may be a good method by showing the exact change in the way students approach problems.

There are four objectives for this study:

(1) To identify whether design students naturally use functional decomposition (FD) during the inventive problem solving before the ‘FDI’, ‘FDII’, and ‘CPS’ (the comparison group) interventions.

(2) To measure the degree of change in the process of inventive problem solving, and in terms of inventiveness of the products after the ‘FDI’ intervention, as compared to the other training methods (CPS).

(3) To measure the degree of change in the process of inventive problem solving, and in terms of inventiveness of the products after the ‘FDII’ intervention, as compared to the other training methods (CPS).

(4) To verify the characteristics of representational changes as the effects of FD interventions based on the qualitative analyses.

1.5 Questions

The following shows four research questions that will be answered throughout the study. Research Questions (RQ) number 1, 2 and RQ 3 consist of three sub-questions. They are followed by RQ 4 as follows:

Table 1. 1: Research Questions

RESEARCH QUESTION (RQ)	
RQ1 **Do design students naturally use FD during the process of inventive problem solving before the FDI, FDII, CPS interventions?**	1.1. What is the amount of ‘function’ search compared to the other main design aspects (‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) before the FDI, FDII, CPS interventions?
	1.2 What are the interactions that exist between all the main design aspects (‘function’, ‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) before the FDI, FDII, CPS interventions?
	1.3 Is there any difference among the students in terms of total inventiveness score of their products before the FDI, FDII and CPS interventions?
RQ2 **Is there a change in the process of inventive problem solving after the FDI intervention?**	2.1 What is the amount of ‘function’ search compared to the other main design aspects (‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) after the FDI intervention?
	2.2 What are the interactions that exist between all the main design aspects (‘function’, ‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) after the FDI intervention?
	2.3 Can design students invent inventive products after the FDI intervention?

RESEARCH QUESTION (RQ)	
RQ3 **Is there a change in the process of inventive problem solving after the FDII intervention?**	3.1 What is the amount of 'function' search compared to the other main design aspects ('behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDII intervention?
	3.2 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDII intervention?
	3.3 Can design students invent inventive products after the FDII intervention?
RQ4 **What is the nature of representational changes among the selected participants?**	4.1 How does FD change the control system from the arbitrary and shallow concepts to deeper conceptualisation of functions?
	4.2 How does FD change-the goal definition through decomposition and sub-goaling operators?

In short, this study seeks to find out about the ways functional decomposition affects or helps the process of invention (which can be seen in terms of their processes as well as the evaluation of their final inventions), and to derive a more complete picture about the nature of the function search before and after such a training programme. It will be compared against another generic design method originated from the creativity research called CPS (Creative Problem Solving).

1.6 Scope of the Study

This thesis will answer the stated research questions, with the following considerations. First, although creativity takes a lot more than cognition, other factors like motivation, personality and culture will not be considered. To enable rigorous analysis on a creativity training method, there is a need to single out only a cognitive process at a time (Frederickson, 1984; Scott et al., 2004). Developing creativity takes a lot of practice in the key design skills and thinking training apart from the subject matter knowledge, therefore training will not impact the designers in a single day all at once. In the case of our study, functional decomposition is compared to generic creative methods during the design which regards creativity as adequately defined as divergence or fluency in thinking.

Second, in order to capture the detailed cognitive processes, only a small number of participants are recruited for the study. The processes of design can best be captured by collecting protocol data from the participants (Ericsson, K. A.; Simon, 1993). Other methods in creativity studies such as psychometric tests or surveys involving hundreds of participants are more interested in measuring the end product of the activities, and also to see human creative potentials in a population (Hunsaker, 2005). Specifically, the current study is about exploring individual cognitive processes apart from the products. Protocol analysis as a tool to conduct an in-depth analysis of individual cognitive processes, nevertheless, enables exploration of the individual's representations in a greater detail. The trade out is that there are only a small number of products invented by a handful of participants during the experiments.

Third, this investigation only examines the conceptualisation phase of invention rather than the whole design processes such as the preliminary/conceptual design phase, refinement phase and detail design phases (Goel & Pirolli, 1992). The preliminary design phase marks as a cornerstone for other cognitive processes during the stages of refinement and detailing phases of design. Not all design constraints are considered in the current work because the focus of the current investigation is to see how FD is being used during the preliminary design phase only. Ergonomic constraints including aesthetical pleasure ('structure' space search), and user research ('people' space search) are more relevant during the later detail design phases (Goel & Pirolli, 1992).

Mehalik and Schunn (2006) conducted a meta-analytic study on 40 prominent design research and found out that the focus of each study is on different phases of design as shown in the following figure. Most design studies focus-on the preliminary design stage.

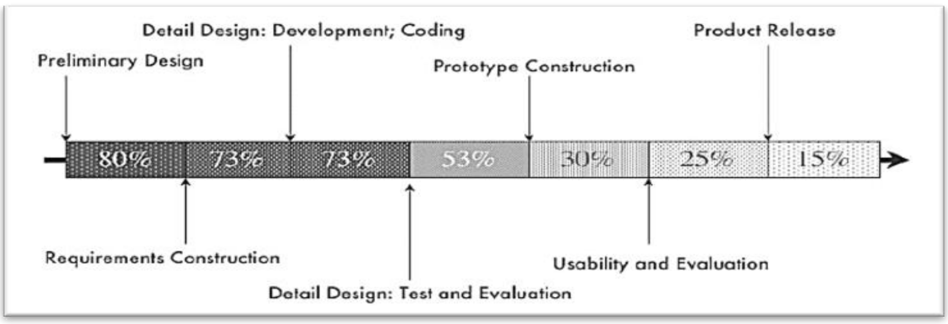


Figure 1. 2: Stages of the design cycle in the literature: 80% studies captured preliminary design phases (Mehalik & Schunn, 2006)

The tasks used in our investigation do not involve implementation and patenting processes in making a real invention. Invention-by-design, coined by Weber (1996), matches the approach taken in this study. Even though invention often involves both design as well as manufacture, this is rarely the case in our modern practical design profession. Dasgupta (1996) also characterised the whole field of design as an explicit planning of a design.

Last but not least, our emphasis is on the functional decomposition as the main design method that can improve designers' problem solving skills. Defining or modelling the cognitive processes of invention and design are not considered as design methods as they have been done elsewhere (e.g: (Ball, Evans & Dennis, 1994; Ball et al., 1997; Weber, 1996; 2006; Weber & Dixon, 1989; Weber & Perkins, 1989).

1.7 Significance of the Study

Practically, this study is in line with the international STEM (Science, Technology, Engineering and Mathematics) education agenda to produce more competitive students with inventive thinking. This, in the long term, will lead to a massive profit in product-making sectors.

Theoretically, in this study, the researcher presents functional decomposition in a special way by framing it against three different disparate areas in the literature. These three areas are:

(i) **Functional Decomposition as a Design Method.** The literature on functional representations in design shows a prevalent utilisation of this method among designers (Mehalik and Schunn, 2006).

(ii) **Human Problem Solving.** This study is backed up by the principles of the Problem Space Theory (Newell & Simon, 1972).

(iii) **Creativity Training.** Another field of research that has been of interest focused on enhancing creativity (Barak, 2006; Mumford et al., 1991, 1996; Scott et al., 2004; Sternberg, 1999).

The merging contributions served by the current studies are illustrated in the figure below.

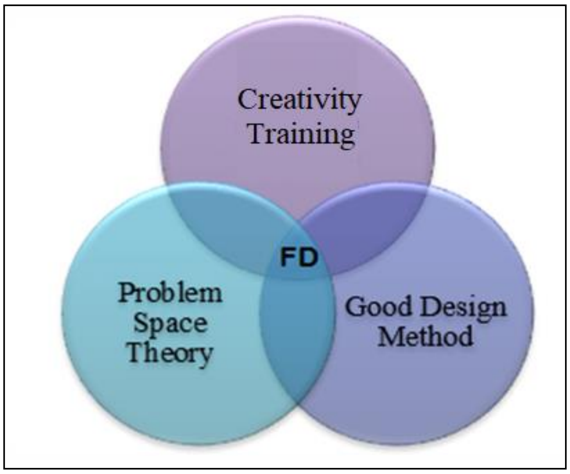


Figure 1. 3: The merging contributions served by the current study

The study furthers our current understanding on human problem solving in general. The theory of problem solving by Newell and Simon (1972) perceives that any problem solving action as an exploration of the problem space. The 'space' consists of all possible states (information), all methods (heuristics), and all possible passages to move the problem solver from the initial to the goal state. As FD is applied as a method by design students, there are aspects of their problem space that may change. This finding will then enrich the theory of human problem solving with new perspectives about problem solving.

Methodologically, this study is timely because there are limited sources on the effectiveness of functional decomposition as a design method in the design literature. This study also calls for further advancement on how creativity in design (or any other fields) should be promoted because we have deliberately addressed the methodology of this study to derive the findings on the training (the full methodology will be explained in Chapter 3).

Lastly, the overall organisation of this thesis will be explained in the next sub-heading.

1.8 Thesis Chapter Overview

The Introduction starts the thesis and is followed by the literature review in Chapter 2. Chapter 2 is allocated for the review on the notion of function in design and decomposition with regards to function. The literature review also outlines the requirements for conducting interventions to enhance creativity, and how to measure the process and product outcomes of such intervention programmes.

In Chapter 3, the methodology of the study will be presented. The study will explain the research design, sampling procedure, experimental procedures, and special materials for testing functional decomposition and the generic creative design method (for the comparison group). The data collection and the analysis methods will also be laid out.

Chapter 4 presents a report on the analysis and results of the students' processes of design and the product outcomes in Experiment 1, **before** the 'FDI' and 'CPS' interventions. The analysis will look into whether FD is naturally used among student designers.

In Chapter 5, the analysis and results of Experiment 1 **after** the 'FDI' and 'CPS' interventions will follow.

Another experiment (Experiment 2) on the teaching of FDII (i.e: the second type of FD material) in design problem solving will be elaborated in Chapter 6. The results of Experiment 2 **after** the 'FDII' intervention will be compared to the 'CPS' group.

Chapter 7 will present the Case Study which qualitatively explains how the participants conducted FD and what actual properties of the representations that are affected by the FD intervention based on the participants' protocols. The data are selected from Experiments 1 and 2.

Finally, Chapter 8 discusses the overall findings of the experiments and the qualitative study. Then, the chapter will suggest potential directions of future research in this area.

CHAPTER 2

Literature Review

2.1 Introduction

This chapter aims to provide the key arguments for developing the current research based on relevant and current findings in the literature. There are three parts in the literature section. First, the literature covers the definition of functional decomposition. Second, the steps for conducting creativity training in the context of the design instruction will follow. Finally, the methodology for analysing the processes and product outcomes based on prior works will be explained. The chapter ends after providing justifications for conducting the current study in order to answer the research questions put forth in the earlier chapter (Introduction).

2.2 The Definition of Functional Decomposition (FD)

Functional decomposition (FD) means to parse functions with their associated performances and quality to better characterise the desired system (Bechtel & Uttal, 2002; Langford, 2012). The purpose of this section is to select the necessary properties of function so that the properties are descriptive for the purpose of our design instruction (Carrara, et al., 2011). According to researchers, there are a number of approaches to define function. One is the "revisionary" strategy where researchers formalised the concept of function to replace the set of current concepts that contradict~~s~~ the upgraded concept of function. Another approach of defining function is the "overarching" strategy which introduces one formalised 'umbrella' concept of function that includes more current concepts of functions. However, Carrara, Garbacz and Vermaas (2011) postulated that the best approach is the first one which is the "descriptive" approach:

> Each meaning that is formalized on this (descriptive) strategy is analysed in detail, assessed for consistency, and if needed at points corrected. And if such corrections are not feasible, particular meanings may even be discarded

> as untenable ones on the descriptive strategy. Yet, after formalisation it still amounts to different concepts of function that co-exist in one formal system. By their co-existence in one formal system, these functional concepts may be compared and related, just as any other set of concepts can be compared and related (p. 152).

The above explains the plan for how the current work defines FD for the purpose of enhancing the method among design students.

Since the meaning of "decomposition" and "function" diverge into different fields of studies as mentioned in Chapter 1, our approach is to propose a framework on FD based on the literature. The theory is non-exhaustive, but rather contains sufficient details for explicating the properties of function. This framework narrows down and constricts the intervention programmes that are conducted in two separate experiments (see Chapter 3: Methodology). The framework is limited, but it dynamically provides room for further exploring instances of function under the given function themes within the context of the current study.

Knoblich, et al. (1999) said:

> Researchers have studied the formation of chunks … but there are no models of chunk decomposition in the cognitive literature (p. 1536).

The framework provides sufficient description of what function means. This has been the basis of our material development process for our FD intervention programmes with the aim of seeing the effects on the subjects' creativity and inventiveness.

Simon (1981) postulated that:

> As soon as we introduce "synthesis" as well as "artifice," we enter the realm of engineering. For "synthetic" is often used in the broader sense of "designed" or "composed." We speak of engineering as concerned with "synthesis," while science is concerned with "analysis." Synthetic or artificial objects and more specifically prospective artificial objects having desired properties are the central objective of engineering activity and skill. The engineer, and more generally the designer, is concerned with how things ought to be and how they ought to be in order to attain goals, and **to function** (p. 5).

The above quote explains that the role of engineers is to ensure that function is attained. It is clear that producing artificial objects with the desired properties are the central objective of engineering design (Vermaas et al., 2011). This means that function in the engineering domain provides a dynamic way for conceptualizing information to fit the current goals (Goel & Pirolli, 1989). Function is fundamental to communicate the properties of a product a designer has yet to form using formal engineering language. The causal structure is the final version of the product specifications. As Goel & Pirolli (1989) put it:

> …Conceptually, or logically, it is tempting to say that the transformation from goals to artefact specifications is **mediated** by functional specifications… one gets a story where the intentions are carried out by means of the functioning of the artefact, and the function is carried out by means of the causal structure of the artefact….In fact, the intentions constrain (underdetermine) function, and function constrains (underdetermines) causal structure (p.30).

The above quote highlighted the importance of function. Function is the central point in a design problem solving effort. As shown in Table 2.1, function is called a 'black box'. The black box needs to be examined and made transparent, and this would be impossible without the awareness of built-up sub-components of a seemingly single-box item (Karmiloff-Smith, 1992). Expert-like awareness of problem sub-functions in design involves identifying the component parts when potential intra-domain links that are remote concepts are accessible. This flexibility is an act of creativity; the blackness turns into explicit, viable conceptual solutions.

Table 2. 1: The literature on the notion of function as (i) the 'black-box' and (ii) the ontology of function

INPUT-BLACK BOX-OUTPUT	FUNCTIONAL ONTOLOGY
(i) Authors: Bogdanski & Best (2017) **Summary: They introduced a new structure for non-linear black box system identification using an extended Kalman filter.** **Domain: Automobile Engineering**	(i) Authors: Stjepandić et al. (2015) Summary: Ontology of function is introduced and is considered as a knowledge-based engineering. Domain: Concurrent Engineering
(ii) Authors: Killian, Mayer & Kozek (2015) **Summary: This study used fuzzy black box modelling to build heating dynamics.** **Domain: Building environment**	(ii) Authors: Tomiyama et al. (2013) Summary: Function modelling for AI enriched with practical examples using ontological approach. Domain: AI for Engineering Design

INPUT-BLACK BOX-OUTPUT	FUNCTIONAL ONTOLOGY
(iii) Authors: Hutcheson et al. (2007) **Summary: Function-Based Systems Engineering (FUSE) is a type of engineering system for eliciting functionality using input-black box-output approach.** **Domain: Systems Engineering**	(iii) Authors: Eisenbart et al. (2017) Summary: The authors developed A DSM-based framework for integrated function modelling. Domain: Engineering Design
(iv) Authors: Xue et al. (2019) **Summary: The authors exemplified inputs approximation for black box systems.** **Domain: Engineering of Computer Systems**	(iv)Authors: Carrara, Garbacz, Vermaas (2011) Summary: They maintained that engineering function is a family resemblance concept through a certain formalisation approach. Domain: Applied Ontology
(v) Authors: Pahl et al. (2013) **Summary: In conceptualisation process of design, input-black box-output modelling can be used, layer by layer.** **Domain: Engineering Design**	(v) Authors: Li et al. (2010) Summary: FMKC Representation (i.e.: The Functional Micro-Knowledge Cell) for conceptual design was introduced in their work. Domain: Engineering Applications of AI

The above notions of function as: (i) 'black box' and (ii) functional ontology propose that function in general is the *creation of activities or machine works* that have not yet existed before. Functional decomposition involves defining what is in the 'black box'. The word 'black box' comes from the design literature (e.g: Coulston & Ford, 2004; Pahl et al., 2013). Other lines of research in engineering function refer to this 'black box' as an ontology or the science of existence-technological existence in this regard (Cambridge Dictionary, n.d.) .Their works can be seen in the table above.

In the following figure (Figure 2.1), function is the 'brain' of a design activity, whereby (i) at the start of the design process, the client's intention is first translated into functional statements; (ii) the design brief is redefined based on the function analysis; (iii) the role of a designer is to redefine the design brief according to the derived functions; (iv) the exercise of control over the intended causal structure by the designer. Research shows that designers sometimes reverse the direction of the transformation function according to the constraints that they defined for themselves (Goel & Pirolli, 1992). This means there are aspects of the design brief that designers adjust to develop new design concepts or functionalities.

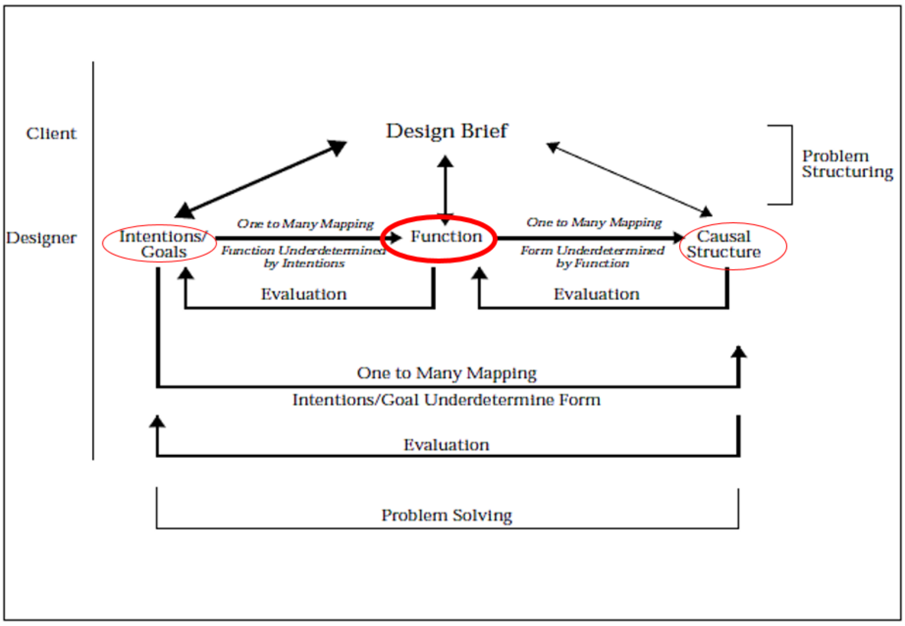


Figure 2. 1: Conceptual transformation of goals to artefact specifications (Goel & Pirolli, 1989)

Based on the figure above, the input to the design process is usually a set of goals or intentions. The output of the process is commonly a specification of an artefact. It is the designer's role to operationalise the functions and defining what would really work. This is supported by two other cognitive mechanisms of decomposition as follows:

(i) neglecting the unnecessary details or dropping 'slots' or 'values' (Weber & Perkins, 1989), and

(ii) systematically organising the then selected components to make things work (Bechtel & Richardson, 2010).

Gradually, the goals are refined as statements of function that designers want the artefact to support. Note that all of these constitute reasoning about artefact functions conceptually. A lot of the discussion on function revolves around the middle 'black box' where important decisions have to be made regarding *what will work*. Bechtel and Richardson (2010) posited that:

> The task of constructing an explanation for a phenomenon in a given scientific domain is one of finding a sufficient number of variables, the constraints on the values of those variables, and the dynamic laws that are functions on those variables, so that it is able to predict future states of affairs from descriptions of the universe at an earlier time…(p.12).

According to the quote above, predicting the future states of affairs denotes planning what variables to include in the current context.

During planning, bombastic solutions cannot be implemented, and are finally withdrawn. This is because the information-processing system in the first place is designed to solve limited sets of problems serially (Newell & Simon, 1972). There are constraints that define the value of certain variables. The less valuable variables are simply neglected. Here, we also emphasise on the act of neglecting the intimidating variables that only superficially supports the intention. This will be explained in the upcoming sections.

2.2.1 Defining what would work

Technology is meant for supporting humans at work (Vermaas et al., 2011). Technology speeds up our work, saves human energy, and even replaces some aspects of human intelligence, for instance with the advent of the field of artificial intelligence.

In the design of technology, there is no right or wrong answer, only better or worse ones (Goel & Pirolli, 1992; Rittel & Webber, 1984). Vermaas et al. (2011) suggested that technological knowledge is directed at usefulness, not at the truth. This was also highlighted earlier in the beginning of the chapter where engineering concerns itself with the synthesis of artefact, not for providing explanations on the natural phenomena. Even though invented artefacts around us are the 'truth' the moment they came into being, they can become obsolete and would need updating.

A biographical work on the invention of the airplane shows that less successful inventors varied the ready-made wing structures rather than defining a new problem for a 'heavier than air flying machine' (Bradshaw, 1992). Note that here, to define such a 'flying' function is the challenge before the Wright brothers decomposed the *flying* function into three sub-functions, which are, 'lift' 'yaw' and 'thrust'. The activities of problem solving could be directed towards channeling ready-made objects to solve new problems or venturing into unexplored unknown components of new problems or new functions the inventors define for themselves without worrying about the objects.

In the study of language, 'verbs' and 'nouns' are two distinctive categories for naming entities and activities around us. With respect to defining function, there are a number of researchers who seek to develop a functional 'ontology' where the emphasis is on verbal expressions (the work/activity) rather than the naming of technologies (see Table 2.1). In such cases, the designer builds an abstraction of the system that defines what the system does using an unambiguous notational language to explicate design concepts (Erden et al., 2008).

The following figure is a high-level functional decomposition of an automated pencil sharpening machine. Each different functional decomposition corresponds to a different conceptual design. As can be seen in Figure 2.2 the words “isolate”, “transfer”, and “remove” are transitive verbs that exert actions on objects.

Figure 2. 2: High-level functional decomposition of an automatic pencil sharpener.

No details of the sharpening device are provided in the figure above. If power is needed for such module, the use of the control system to turn power on and off to the sharpening device is one choice. An alternative design would keep the sharpening device powered-on at all times, which would require another sub-system to engage and disengage the pencil from the sharpening device, mechanically.

The level of detail in the figure above makes these additional design choices more obvious. Also, the act of sharpening involves removing the wooden material surrounding the graphite. The sharpening task is specified as "remove material", not "grind wood". Therefore, describing the task as "remove material" allows alternative methods such as grinding, cutting, or sanding, depending on the use case for the pencil sharpener, may be better solutions. Using verbs encounters the actual **work** the device is to perform (Bohm et al., 2017; Kitamura et al., 2004; Kitamura & Mizoguchi, 2013). The use of verbal expressions rather than objects to define function is also emphasised in other studies in design. The following is how function is presented in the ‘defixation group’ material in Linsey et al. (2010):

- *“Functions:*

  -Import natural or human energy to the system
  -Convert and transmit energy to peanut
  -Remove peanut shell (remove outer structure from inner material)
  -Separate removed shell (outer structure) from peanut (inner material)”

According to Linsey et al. (2010), their fixation material contains an exact sketch of a machine to crush peanut shells. The following is the actual material used for the fixation group in the same study:

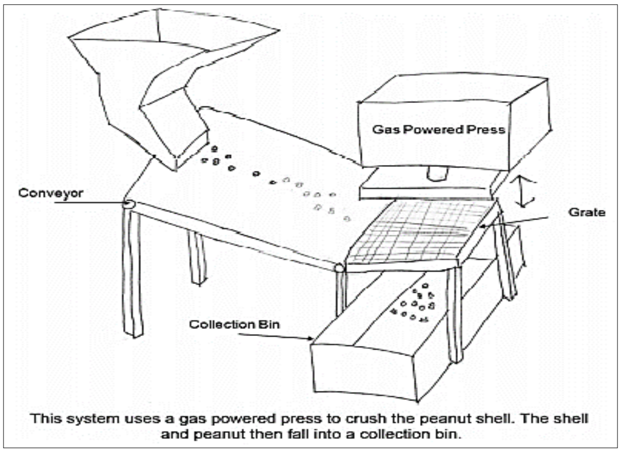


Figure 2. 3: Example solution provided to the participants in the fixation group (Linsey et. al., 2010)

The figure above was a ready-made peanut crushing machine shown to the fixation group. The image can be a hindrance for functional search because instead of searching for potential alternatives function, the design will be limited to solely adjusting the appearance of the same machine as confirmed by Linsey et al.'s study. In functional decomposition, problem solving is directed towards conceptualising an intended function. Later, designers find scientific laws ONLY where applicable to fulfil a selected new function. Apart from the natural law, technology also faces constraints that include mixed of aesthetical, social, cultural and economic determinants which could complement the stated functions (not to replace desired artefacts' functions) (Vermaas et al., 2011).

In fact, engineering is about the application of science. Engineering design offers 'discovery' not in terms of newly discovered science principles, but in the mechanisms of those principles that are implemented somewhere else, in order to make a particular new concept works. Design involves appreciating aspects of the scientific principles which are known and just discovered to be transferable to many technical situations, as in re-discovery and finding new instances of old scientific discoveries.

Function is achieved by deriving scientific principles and its specific mechanisms. Principles can also be drawn from nature, such as in studies on *biomimicry* (Benyus, 1997). If none of the current technology supplies direct and desired solution that matches the goal, nature may be a good source of scientific principles that can potentially fulfil the current design. This shows that function is conceptual, in that the derivation of concept is not a concern. Diverse functional definitions stick together under one umbrella concept of intended new designs. For instance, engineers in polymer engineering use the working principles of friction, adhesion, pressing and dragging using tiny material structures made of very stiff protein inspired from the gecko feet to invent adhesive pads (Mengüç et al., 2012).

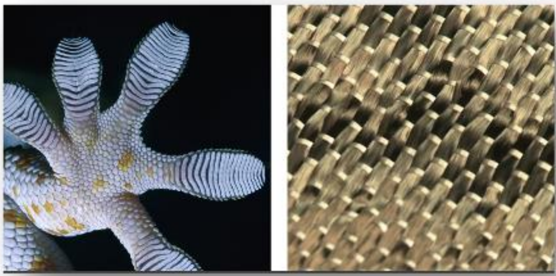


Figure 2. 4: Left photo: Gecko feet; Right photo: Polymer adhesive

In the figure above, geckos (a lizard-like species) have evolved fingertips which are covered in tiny structures. These structures make a comparatively vast area of contact with opposing surfaces, and, as a result, have strong attaching ability. The principles of friction, adhesion, pressing and dragging are taken from the context of a gecko and applied to the context of a polymer function. Extracted functions from the reptile enable the application of the same principle in another setting (the adhesive pads). The smallest unit of decomposition of the animal's function will enable the ungrouping of functional chunks. Later, using general functional statements, the chunked units extracted are integrated in a new design of adhesive pads. Such a definition allows the identification of new approaches to achieve the stated functions of an object by distinguishing it from its background of empirical experience.

Without a complete picture of the intended work which a technology is to accomplish, an engineer's conceptualisation is either patchy, too bulky, broken, less useful, or out-dated, but is never, and cannot be considered wrong (Goel & Pirolli, 1992; Rittel & Webber, 1984).

This is different from the work on misconceptions in science which is concerned with robustness of the Direct Schema, resulting in shallow narratives in explaining the natural phenomena (Chi et al., 2012). In engineering design, it is not about misconception. Instead, it is about muddled redundancies of the possible true design solutions (Fenesi et al., 2016). This is the result of recalling vast options of possible design solutions available in the market. Even though technology is external to the mind, note that the mechanisms of technology is **stored as symbol systems** in the human memory in order for the information-processing system to operate on the design solutions.

Newell and Simon (1972) lamented that:

> The relation between the designating symbol and the object it points to can have any degree of directness or indirectness. Thus, a symbol structure can point to a programme; but a symbol structure can also point to a symbol structure that points to a symbol structure that points to . . . a program. Because this book focuses on central processes, we will frequently be concerned with symbol structures that designate other structures in memory, and with structure that designate programs.
>
> We will be concerned less frequently with symbol structures that designate external stimuli or responses, for at that time we deal with them, stimuli and responses in the external environment will already be encoded internally – designated by symbol structures. Hence, we will almost always deal with these designations rather than with the external objects designated" (p. 21).

Based on the quote above, it can be analogized that designing as problem solving is purely conceptual. The later design construction phase follows the set function as a guideline. Goel and Pirolli (1989) argued that artefact-level decomposition includes physical, spatial, temporal and technological boundaries. Such physical components derive from a common category that may or may not be applicable in new situations. Design, on the other hand, is a conceptual process whereby the framing of problem elements is conducted in the representation-level decomposition (Goel & Pirolli, 1989).

Design is meant for improvisation of technology, that out-dated designs or damaged machines can be regarded as a junk. This makes it even more important to carefully define the functions during the preliminary design and to conduct the prototypical tests for specific functionalities since any defects in the invented technology will turn out to be costly (Goel & Pirolli, 1992). This is not the case with scientific knowledge that may be considered just as relevant or less relevant but remains true.

For things to work, design should be able to cope with the human life style and culture (Vermaas et al., 2011). Unlike natural sciences, 'knowledge' in the form of tangible technology is the end results. Designers should seek to identify the science for knowing what will work. The understanding of what will work implies an understanding about the man-machine interaction: the human factor psychology and ergonomics (e.g: Martinussen & Hunter, 2017). This requires certain adaptations to be made under the conditions where some engineering principles have to be retained while acknowledging the human physio-psychological needs (Elbert et al., 2018). Furthermore, the concept of miniaturization in technology, for instance, entails that in modern lifestyle items be simplified and small because handiness pleases human users (Tarbouch et al., 2016). Thus, functional solutions should ideally fulfil the ergonomic needs of their human users.

Unlike learning, problem solving in design involves iterative steps and recursive visits to partially known concepts because design develops incrementally (Goel & Pirolli, 1992). The end of this process is new knowledge in the form of technology (Perkins, 1986). The Emergent Schema proposed by Chi et al. (2012) is relevant as designers explain the nature of the process-like interaction (with properties such as uniformity, randomness, simultaneity, independence, and continuity) between the parts of the **finished** design (not at the start of the design process). In learning, there is only one explanation for a phenomenon. But in the case of technological design, if there are more than two 'correct' designs (each with properties of the Emergent Schema) the 'better' design goes to the one that can satisfy the client's aspirations at the maximum.

In short, one of the most important aspects of function is defining what will work. Thinking about technology is a purely conceptual endeavour based on recent findings that have found on the nature of cognitive processes in design (Ball, et al., 1994). The kind of concepts that will work should have bearings on the human factor psychology, apart from scientific principles that can be derived from the diverse fields of natural science. The work on functional ontology indicates that using verbal expressions are more effective in thinking about function compared to using nouns.

2.2.2 Neglecting the unnecessary parts

Goel and Pirolli (1992) pointed out that function works with other aspects of the design development to enable design. They stated that:

> The ones we employ are adopted from Wade (1977). Briefly, the intuition behind these terms is that *artefacts* (i.e.: *'structure'*) are designed to perform certain *functions*, which are calculated to support certain *behaviours*, which help in the realization of certain *purposes* held by *people*. This categorization provides a chain linking users to artefacts and recognizes that

> each intermittent step needs to be considered. To these categories we have added *resource* (e.g., time, money, manpower, etc.), (p 410).

The statement *"…a chain linking users to artefacts and recognizes that each intermittent step needs to be considered…"* implies the multiple spaces of search in design. Knowledge about available technology and functionality enable designers to make informed decisions on the clients' behalf, while integrating the 'people', 'purpose', 'behaviour', 'structure' and 'resource' constraints. Designers are found to reverse the direction of the transformation function because design goals are highly subjective unlike in science problems. As Goel and Pirolli (1992) put it:

> ..because rather than transforming initial problem states to a goal state, the designer can negotiate changes to the initial state and goal state that experience suggests are more easily achievable, or perhaps might lead to a more effective design solution, (p. 418).

Table 2. 2: Changing of Problem Goals and Initial States among Designers

Building Design (Goel & Pirolli, 1992):	**iPhone History** (Parikh, 2015):
SITUATION:	
Subject S-A was standing on a ninth floor balcony and had a bird's eye view of the small triangular site he had been given for the proposed post office. He was not content just to build a post office but wanted to redesign the whole area.	One day, Steve Jobs was called to oversee a prototype tablet that had two newly developed touch features by a genius user-interface engineer Bas Ording. Jobs stopped and explicitly try to formulate a new problem situation, so it ~~more~~ closely fits more with his expertise, knowledge, and new as well as old experience.
EXAMPLE EPISODE:	
S-A: So, given the fact we have that triangle over there as a limit. And I cannot exceed that I suppose?* *E**: Right, that, that.. .* *S-A: I have to take that for granted?* *E: I, I would think so.* *S-A: That's the boundary of. You do not allow me to, to exceed in, in my area of intervention?* *E: No, I think you should restrict it to that.* *S-A: So, I am constrained to it and there is no way I can take a more radical attitude. Say, well, look, you are giving me this, but I actually, I, I'd come back to the client and say well look, I really think that you should restructure actually the whole space, in between the building. I'd definitely do that, if that was the case. You come to me as a client, and come to me with a triangle alone, I will give you an answer back proposing the whole space… So, as to really make ah, this ah, a more communal facility. .*	*The first of the two features of the prototype tablet that had two newly developed touch features was called* ***inertial scrolling.*** *It allowed the user to swipe at a list on the screen, and in response the list would move based on how fast the swipe was, finally resting with a deceleration as if it had a real inertia.* *The second feature was called* ***the rubber-band effect.*** *It caused a list to rebound against the screen's wall when there are no more pages or icons to display. Jobs was so impressed by these two elements he exclaimed, 'My god, we can build a phone out of this.'*

Note: * S-A means Subject A ** E means Experimenter

Therefore, to some extent creativity does not only mean modifying or embracing the current idea with some changes. Creativity also implies ‘rejection’ of the current trend in totality, or in part, with concrete arguments (Sternberg, 1999). Decomposition allows due selection, where creators ignore irrelevant ideas or unnecessary constraints from the previous approaches by selecting only part of the desired function. However, a major step such as the rejection of old ideas must be based on rationality and careful reflection. Here it shows that the selection of the scope in a particular creative work is implied in the conduct of functional decomposition activities.

The rejection of the constraints can be seen in the design of the spacecraft as shown in Figure 2.5. The UI (user-interface) design evolution of the spacecraft is parallel with the advancements in computer technology. Here the concept of ‘button’ is dropped from the solutions over time. From the button touch whose details astronauts needed to memorise, and the meter-like analogue indicator lights in the ‘Apollo’ spacecraft, the UI changed to lighted buttons, screen and digital indicators in the ‘Shuttle’. Now, the touchscreen technology had dropped all previous features. Dragon (2019) is designed to make labelling things on the screen easier with just one touch, instead of, for example, having to remember Switches B13, B16, C9 and Dial A1 and up to 75 sequences.

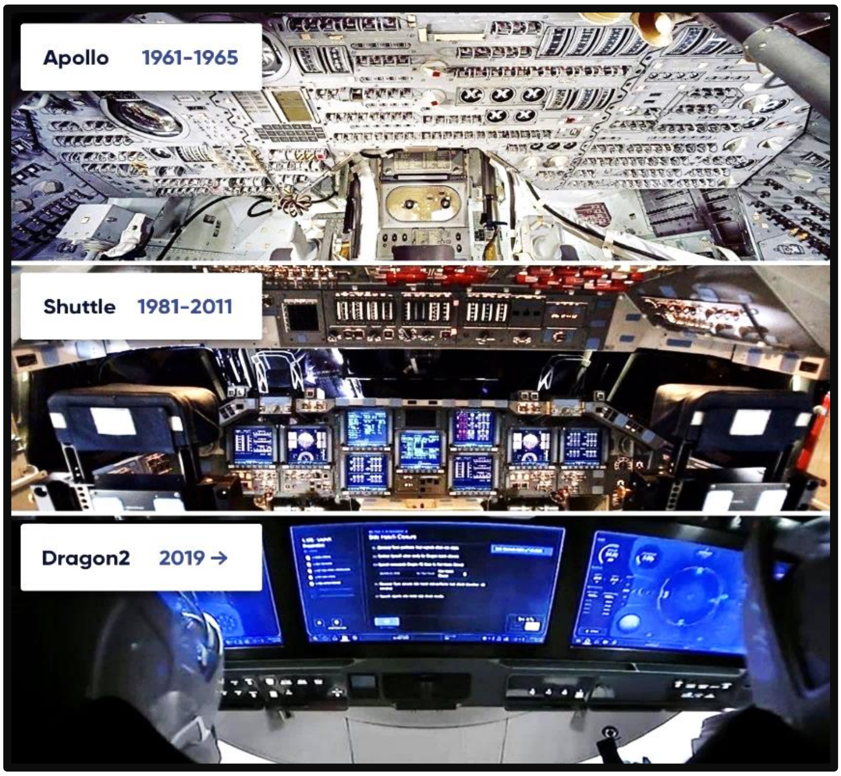


Figure 2. 5: The evolution of user-interface design in American Spacecraft (Malewicz, 2020)

In the same vein, Boden (1996) argues that the exploration of space is an act of creativity. Exploration is signified by the gradual omission of the previous composite entities. As she put it:

> Consider post-Renaissance Western music. This is based on the generative system of tonal harmony. Each composition has a "home key," from which it starts, in which it must finish, and from which—at first—it did not stray. Travelling along the path of the home key alone soon became boring. Modulations between keys then appeared. At first, only a few were tolerated, and these only between keys very closely related in harmonic space. With time, the modulations became more daring (distant) and more frequent. By the late nineteenth century, there might be many distant modulations within a single bar. Eventually, the notion of the home key was undermined (Boden, 1996, p 270-271).

The undermining of older modulations happened gradually, and depends largely on analysing the shortcomings of certain elements of the previous designs for current solutions. This is replaced with the convenience of the better options that are intentionally formulated, and do not randomly come into being.

In the discussions about engineering invention and design, scientists seek to draw upon methods of reducing and managing various incoming constraints, the science which Simon (1981) called the architecture of complexity. The nature of human information-processing system, in particular, the short-term memory, inhibits more than 5 to 7 items to be processed in one go. Therefore, the competing constraints, be it science-based, human-related, or environmental, are to be considered with a strategic mind. Designing, in part, is about acknowledging only the real constraints, and this can only be done by realising the aspects within the available solutions that must be tolerated or sacrificed altogether. This is because items must be reduced into manageable few, and possibly repeated actions for the next few items. Each set of items is taking up considerable amount of individual’s processing time. Including too many items makes processing unbearable, or in worst cases, impossible, as far as the short-term memory is concerned. This is why problem-solvers relax some constraints. Relaxation in problem solving involves sorting out the conceptual components and to reject the less important ones amongst the decomposed concepts (Knoblich, et al., 1999).

Further, the most important characteristics of expertise is the robustness of information, to the extent that experts experience over-glossing of information. As shown in studies on expertise, preceding knowledge may interfere with the search of new solutions during decision-making among experts (Chi, 2006). What about the 'knowledge' that resides in the environment in the name of technology? The same way, tangible technologies may hinder from searching for better designs. This fixates a designer to the only available mundane solutions, even among expert designers (Linsey et al., 2010). Therefore, the exploration of the space must still be done to avoid taking things (or alternatives) for granted due to the tendency to simply repeat the correct answer, instead of looking for a better one.

In the Representational Re-description or "RR" theory by Karmiloff-Smith (1992), the lower level knowledge is one that is not yet harmonised to fit new situations, which causes design fixation where designers experience the "representational adjunction" phenomenon. This leads to inflexibility as implied in the dependency on a big set of information.

> …information embedded in level-I[1] representations is therefore not available to other operators in the cognitive system…a procedure ***as a whole*** is available as data to other operators; however, its ***component parts*** are not. It takes developmental time and representational redescription (…E1) for component parts to become accessible to potential intra-domain links, a process which ultimately leads (see levels E2 and E3) to inter-representational flexibility and creative problem solving capacities (Karmiloff-Smith, 1992, p.20).

Creativity according to the RR theory refers to the ability to shift the main components of a class of representations with another group or class of representations to satisfy a current goal. In Karmiloff's experiment, children in various age groups were asked to produce drawings of objects (e.g. house, man or animal) that exist and do not exist. The reason these tasks were chosen was to study the normal and unconventional drawing procedures demonstrated according to age, such as whether children at different ages were able to perform changes such as deletion, insertion and change of position or orientation in their drawings.

A substantial difference was found in the drawings between the younger and older age groups. Older children often make cross-category changes from different domains in the middle of their drawing activity rather than at the end of the drawing procedure as commonly demonstrated by younger children. As shown in the following figure, older

[1] Level I- implicit knowledge
Level E1-E2-E3 –explicit knowledge levels 1 through to 3

children's drawing of a house that does not exist is composed of hands, with a mouth at the centre of the house. Older children tended to show *inter-representational whole-based changes,* which enabled them to integrate and access components from different categories of creatures that do not exist.

However, there is mere repetition of what a non-existent man will look like in the drawings of younger children. This condition is called *intra-representational element-based changes,* a condition where changes on the drawings occur within category.

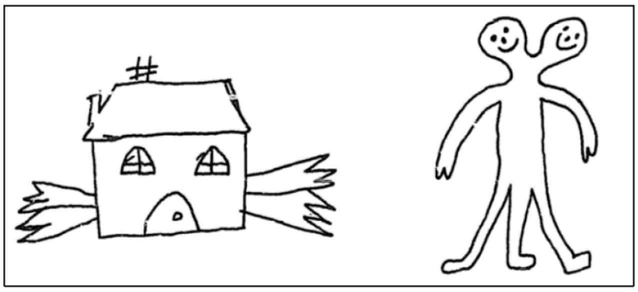


Figure 2. 6: Examples of older children's drawing~~s~~ (left), and younger children's drawing (right) (Karmiloff-Smith, 1990 p.68-70)

Therefore, it is not the amount of knowledge in its raw form that is counted in creativity processes. Rather, it is the flexibility in decomposing the relevant elements, to reject the unnecessary elements, and to fine-tune the needed elements at the face of new situations that allow creativity.

Bradshaw (1992) also indicates the success of the Wright brothers' airplanes as a success in terms of dropping constraints to fit the overall function of the heavier-than-air flight. On the contrary, early airplanes used other parameters and global measurements during the search processes. This is illustrated in the table below.

Table 2. 3: Some Design Parameters of Early Airplanes (Bradshaw, 1992)

Number of wings	**1 – 80**
Wing position	**1 – 3**
Placement	**stacked, tandem, staggered**
Lateral arrangement	**anhedral, flat, dihedral**
Camber of wings	**1 – 12, 1 – 6, etc.**
Wing span	**6′ - 104′**
Chord	**3' - 10'**
Shape of wings	**birdlike, rectangular, batlike, insectlike**
Tail placement	**forward (canard), rear, mid**

Inventors like Otto Lilienthal who searched in the design space (such as varying the forms of the wings and using global measurements like length of flight) had not succeeded in flying his airplanes. The search in the space of objects and external forms may cause failure in constructing the appropriate functions (McLellan & Nicholl, 2011). The size of the object-space search is large as shown in the above table. Thus, inventing becomes tedious, time-consuming and costly.

However, the Wright brothers relaxed the physical constraints. Conceptually, they broke down the problem of the flight into components such as providing lift through the wing configurations, providing thrust through using a powerplant and propeller combination, and providing stability and control using wing warping and movable control surfaces. No actual wing of an airplane was manufactured until, and unless, the details of the thrust and wing-warping functions were accurately estimated by them using scientific measures and principles.

Chi (1997) also explained that creativity is the capability to change the ontology flexibly. Interestingly, this shift to different ontology is also seen in poem-writing. Expressions such as, “anger is boiling” indicates humanly anger expressions, to give way to the word boiling from the domain of cooking and substance heating. This expression is comparable to heat, hence the use of the word ‘boiling’ making it deeply understandable. In addition, it was also indicated in the same study that students were facing difficulty in learning constraint-based interactions (CBI) in electricity due to the fixedness in conceptualising science concepts. By referring to the different ontological categories such as material substances, processes, and mental states, Chi demonstrated that a lot of the misconceptions can be avoided when concepts are correctly assigned to a different class of ontology. Chi showed that misconceptions are deep because associations of predicates have been built before formal science learning takes place since the mind compensates missing knowledge about the to-be-learned science concepts with daily direct concepts. Using predicates carried over from an appropriate ontology, students can eradicate misconceptions by replacing the older wrong predicates. Deep learning as in ontological training predicts better capabilities of science students in answering various phenomena in transfer problems (Chi et al., 2012). It cannot be done until the students become aware that the wrong concepts cannot stay and must first be *removed*.

In short, *“all problems are ill-defined in big and well-defined in small”* (Chase & Simon, 1973). The “small” elements denote the capability of detaching subcomponents from a super-ordinate category. This is to make the particular new problem more well-defined. Central to this is the process of rejection and elimination of redundancies. Redundancies can be traced only when elements are made explicit, and similar **functions** under the guise of different names of technological solutions can be flexibly dropped (i.e.: rejected).

Rejection allows focus towards necessary works. This channels the energy for the design conceptualisation, rather than testing physical parts of old artefacts. Of course this depends on the availability of solutions. Sometimes this is preceded by a new functional discovery (such as the case in prominent airplane inventions), thereby rejecting ready solutions. Other times, old solution is replaced with another ready available solution, but in a way that has never been done before, thereby rejecting its common usage, such with the case of the AMY software which uses available acrobatic drawings to sketch new acrobatic movements in drawings (Boden, 2004). The decision to discover new functionality altogether, or using available solutions to fulfil a set functionality takes logical explainable steps. “Only the thinkable is expressible,” (Simon, 1981). Thinking and expressing must be enhanced and supported via practice. Knowing if a standard has been achieved is another story: it is the role of a strong evaluation skill, which depends on the individual’s characteristics (Hayes, 1990).

2.2.3 Systematic placement

The word ‘how’ can be located at different places in a sentence as a function of English grammar. If one uses it to ask questions then the word ‘how’ is to be written at the beginning of a sentence, but not when one is explaining about how to make something. Function is also a matter of placement or localisation to make sure that messages can be delivered accurately to the receiver.

It is found that designers resort to using what is available to restore solutions into the limited scope and direction, a process called ‘satisficing’ (Ball et al., 1998). The key is in the skill of localising the components in a systematic manner. In this section, there are three mechanisms scientists found to help in the systematic organisation of previously fragmentary parts. First, there is the analogical reasoning where borrowing of external structures is done to make meaning of the current problems (Holyoak, et al., 2001). Second, it is the Geneplore Model on creativity which also indicates the ‘generate’ and ‘explore’ processes as intermediated by what is called the “pre-inventive structures” with properties such as ambiguity and incoherence (Finke, 1996). Thirdly is the studies on self-explanation which inform us how explanation enables mental-model repair so that a new uniform function can be developed conceptually (Hausmann & Vanlehn, 2007). To ensure the systematic localisation or placement, for instance, inventors develop hierarchical structures and frames as external assists even though there is no strong evidence that all inventors develop a particular standard diagram for thinking about function.

A biographical research on prominent inventors shows the use of function to give some structure to the subsequent processes of invention. Nersession (2008) examined one of the most significant problem solving episodes in the history of science, that is James Clerk Maxwell's first derivation of the field equations for electromagnetic phenomena. Nersession posited that:

> ..Maxwell used what might be considered analogical source domains not as providing for direct mappings between phenomena, but as sources for constraints. These constraints were incorporated into imaginary models that are hybrid representations of the source domain and target phenomena. **The model then becomes an analogical source itself** and isomorphic mappings are made between the models on their mechanical interpretation and the models on their electromagnetic interpretation (p. 28).

The above tells us that the machine and fluid mechanics functions were incorporated into Maxwell's imaginary models that together develop a whole new function of electromagnetism. Here, the machine and fluid mechanics functions are taken at a sufficient level of abstraction (not directly implemented). They are treated as the "pre-inventive structures" where further exploration and revisions are based upon (Finke, 1996). Research found out that functions give an immediate structure to a new problem, even if the initial functions, as with the case of Maxwell's model, is half-way through completion.

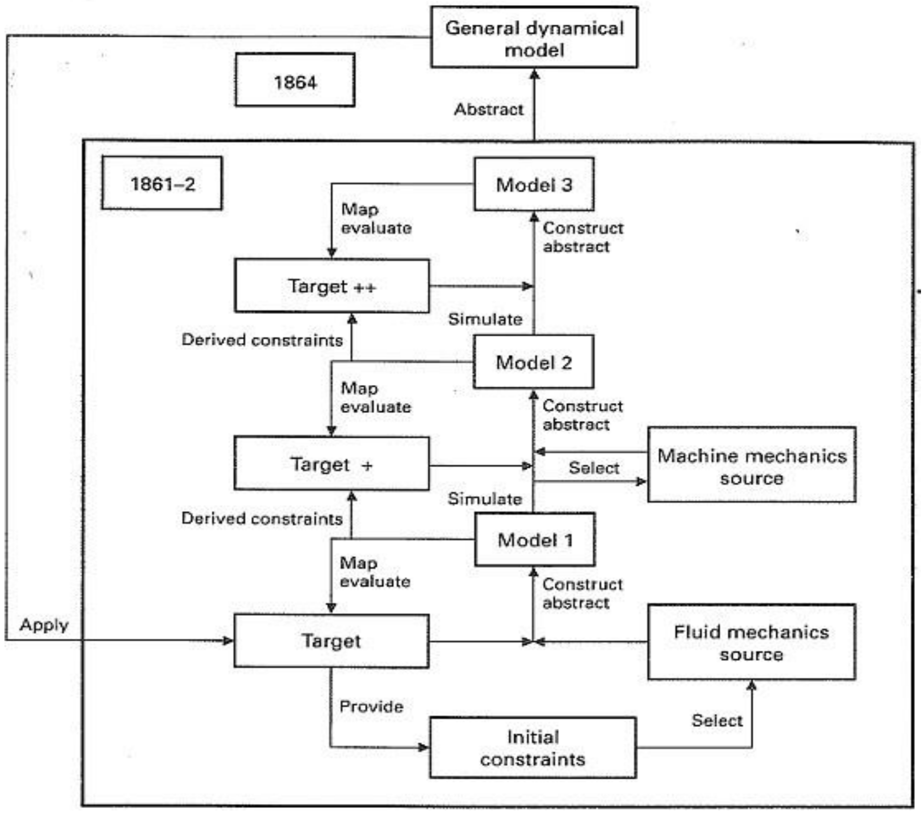


Figure 2. 7: Nersessian's (2008) depiction of Maxwell's modelling process.

In the figure above, the process progresses from Model 1, then Model 2, then Model 3. Each model can be considered as the 'pre-inventive forms' of Maxwell's representation, where the models recognise how the constraints apply and transfer to the final general dynamical model in the electromagnetic domain. However, they are subject to further incremental development as conceptualisations become more complex, i.e., multi-layered. Thinking about function results in a flexible system with respect to the levelling of the evaluation steps. However, the inflexible system is not decomposable, and this stops the search altogether, or diverts the evaluation to uncertain spaces (McLellan & Nicholl, 2011). Information and successive work reflected in the mind of a creator hold the entire "exploration of space" (Boden, 1996). Above all, the human cognition is administered by having a **structure** that holds initial elements together and act as the base model.

Creativity research also shows that thinking about function is found to **give structure** to intended solutions even in tasks involving imagination in drawing. In Ward's (1994) experiment, the subjects invented a new creature of a known category for an imaginary setting. This animal, even though non-existent, still composes of a head to contain a brain that controls actions in some sense, and sort of a deformed hand and a leg to serve the functions for the animal's food-hunting behaviour. It is not the physical head that is of concern. As living beings, organisms commit certain conducts like eating, moving for hunting, etc., to ensure functioning so that they can live in the first place.

Localisation in the literature refers to the manner in which a holistic structure of the whole artefact is developed (Bechtel & Richardson, 2010). Fragmentary parts make communication and delivery of the design impossible. The design task environment considers the design success also in terms of its clients' independence from the designer in operating the artefact (Goel & Pirolli, 1992). Seeing the holistic structure can be related to analogical reasoning that emphasises on structure that 'embodies' items as a larger unit. A **structure** is what gives a device its identity. This helps delivery of the device by the designer, as well as effective usage of the device by the clients.

Organising the design elements to develop a larger structure can be related to the elaboration processes in learning (Vanlehn, 1989). Elaboration bridges the gaps between decomposed elements. Elaboration needs to be initiated to make the developed structure meaningful. In studies on self-explanation, better students use self-explanation to repair their current mental models, identify gaps between the elements in the model by providing elaborations based on their experiences from outside of the domain (Fonseca & Chi, 2011; Hausmann & Vanlehn, 2007). The purpose is to fill in the gaps in their mental models so that they will reach cohesion. Elaboration and explanations are sought once the gaps are identified and considered. Copying an available design leaves no further gap upon which any explanation is needed, hence no novelty. It is found that apart from mechanical representations, the development of mental models are crucial during invention and design (Carlson & Gorman, 1992). This is a manifestation of explanations that are added and initiated based on the built representations.

In the domain of mechanical engineering, functional representations of experts are found to be more cohesive than their counterparts (Moss, et al., 2006). Cohesiveness of a representation requires 'systematicity' in analogical reasoning (Gentner, 1989). The overall representation is thus characterised by not only the content but also the structure of a representation. As Gentner (1989) put it:

> The central idea in structure-mapping is that an analogy is a mapping of knowledge from one domain (the base) into another (the target), which

> conveys that a system of relations that holds among the base objects also hold among the target objects….Objects are placed in correspondence by virtue of their like roles in the common relational structure: there does not need to be any resemblance between the target objects and their corresponding base objects. Central to the mapping process is the principle of systematicity: people prefer to map connected system of relations governed by higher order-relations with inferential import, rather than isolated predicates (p. 201).

The apparent isolated predicates may seem irrelevant at the first glance. Elaborating means borrowing inferences from the old model to be used in the current model. The presentation is simple, but the elaboration is detailed.

The following diagram displays the top-level macro-function, the relation, the sub-functions, the actual component (function carrier such as 'motor'), symptoms, and possible troubles that may happen as the result of such functional structure.

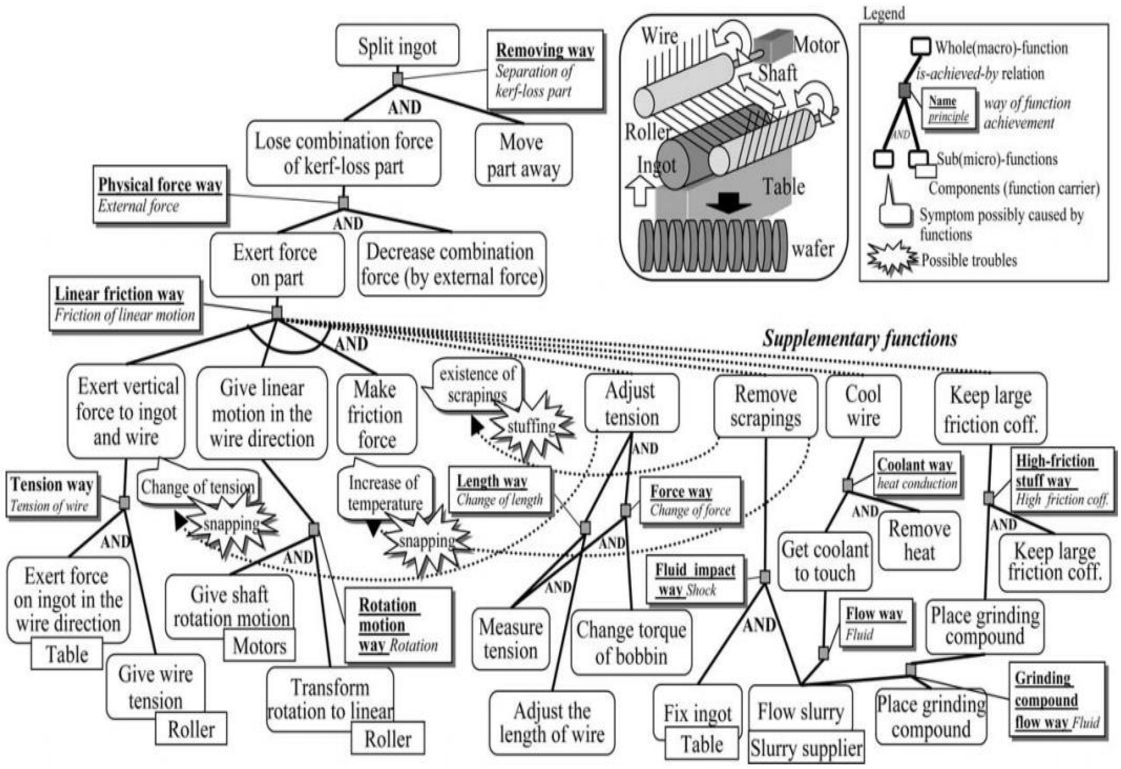


Figure 2. 8: Function decomposition tree of a wire-saw for slicing ingots (portion) (Kitamura et al., 2004)

Function requires providing explanations to resolve conflicts between elements that make a whole new function when sub-functions are re-grouped together (Erden et al., 2008).

As shown in the figure above, Kitamura and Mizoguchi (2013) developed a functional ontologies software and provided viewpoints and the vocabulary for capturing functional knowledge. This software has been used for tackling real problems in the industry. In the context of design instruction, exposure to functional ontology is still underestimated as compared to other skills such as animated design and material analysis (Kitamura et al., 2004). According to Coulston and Ford (2004), functional decomposition as a heuristic training can improve the design skills among undergraduate students over time and practice. The function ontology offers a maximum generality so that a lot of inferences can be drawn to connect the hierarchical structure meaningfully (Erden et al., 2008).

Table 2. 4: Frame structure for a common eating fork (Weber & Perkins, 1989)

Slot names have the initial letter capitalized and they are italicized; values are in lowercase.

Superordinate category: eating utensil.
General purpose/function: to avoid touching food with fingers for reasons of sanitation, to keep from getting burned or messy, manners in eating.
Physical principles: lever action for handle and grip; wedge action produces amplification of pressure at point of tines to slide under or to penetrate food.
Specializations: olive fork; fondue fork; salad fork.
Related inventions: spoon, table knife.

Function Analysis (slots along the top of the Table and values in the body)

Function	*Edge*	*Direction*	*Grip*	*AuxParts*
spear/stab	tines	down	precision bal/power	plate?
scoop	"cup"	lateral	precision bal	plate?
cut	side	down, lateral	forefinger	plate?
mash	back	down	forefinger	plate?
hold down	tines	down, op. hand	forefinger	plate & knife poke
holes	tines	down	precision bal	pie dish

Inverse: not part of tool; there is no inverse edge. But there is an inverse action. For example, pulling food off the tines with the teeth.
Need: high, for sanitation, manners, to avoid messiness, hot foods.
Global evaluation: effective for a wide range of eating requirements.

Parts Analysis (slots along the top of the Table and values in the body)

Part	*Material*	*Evaluation*
tines	metal	effective for stabbing and the prevention of twisting, but hard to clean.
"cup"	metal	not good for liquids.
edge of tines	metal	dull; for cutting soft food
handle	metal or wood	effective use of lever principle

Precursor inventions: hand & fingers, pointed stick, chop sticks, spoon?
Successor inventions: plastic fork for throw-away that will not have to be washed; spork (combination spoon and fork).

To build systematic structures, apart from using a hierarchy-like structure to construct sub-functions into a whole, visually, the literature proposes the use of frames for thinking about function (Weber & Perkins, 1989). Using frames involves interchanging of subcomponents and also omitting resultant redundancies among the ‘slot fillers.’ The above table (Table 2.4) is one example of the frame composed of slots on the invention of a fork.

Note that a frame structure is a general main heuristic. In the table, the slots are italicised words with the initial letters capitalised. As such, the definitions of frames and slots are as follows:

- Frames are defined as the entity with slots in which particular values, relations, procedures, or even other frames reside; as such, the frame is a framework or skeletal structure with places in which to put things.
- Slots are the generalisation of the idea of a variable. Slots are the instantiation of the variable, attribute, relation, or procedures specified by the frame.
- Values are used to tweak the slots. Values undergo flexible changes and extrapolations as well as interpolations.

The slots offer suggested solutions while the values define the category for each slot by bringing in the possible principles to satisfy the slots. The evaluation function, based on the inventor’s mechanical knowledge as a result of his niche and domain expertise, is needed to realistically develop the design further. As Weber and Perkins (1989) put it:

> Inventing things and ideas involve an extensive set of middle-range heuristic principles that are not domain specific, but evaluation function and criteria are likely to be highly domain specific and may become increasingly so with experience and development in some niche (p. 65)

Hayes (1990) indicated that experience in a field makes one more capable of making due revisions on their own creative outputs. This is still related to the notion of ‘self-explanation’, where the interpretation can be used to enrich, build linkages, or repair contradictions among the composite concepts (Hausmann & Vanlehn, 2007).

Here, it shows that design is also an ‘opportunistic’ process where progress or revision of previous designs can be utterly explained using ‘gain analysis’ (Weber & Dixon, 1989). Change in one respect of artefact is explainable since that particular change affects the entire artefact efficiency. This holistically increases the artefact’s gain factor. In their study about the invention of the sewing machine, factors including the development of progressively better interfaces between the needle and thread and the corresponding movements from the discrete to continuous sewing mode led to the invention of the sewing machine. In combination, these factors serve to minimise the psychological switching processes.

Explaining involves very delicate and precise "tuning" relations in addition to the basic idea in order to make an artefact works well. This is in line with the adaptation as the mapping processes take place during analogy according to Holyoak, et al. (2001):

> The resulting mapping allows analogical *inferences* to be made about the target analogue, thus creating new knowledge to fill gaps in understanding. These inferences need to be evaluated and possibly *adapted* to fit the unique requirements of the target. Finally, in the aftermath of analogical reasoning, *learning* can result in the generation of new categories and schemas, the addition of new instances to memory, and new understandings of old instances and schemas that allow them to be accessed better in the future (p. 9).

As presented in the findings about the analogical reasoning and the use of heuristics of invention, understanding the existence of 'slots' (or variabilization of knowledge) as well as 'frames' (or knowledge structure) leads to explanation of the intended new entity. Sometimes new slots necessitate some frame cancellations, extensions and adjustments. Carlson and Gorman (1992) said:

> Like frames, mental models can have slots or openings in which an inventor can try different arrangements or subassemblies. We suspect that a key skill for inventors is the ability to generate a mental model and then break it into slots that can be manipulated and studied…inventors create slots in response to their (problems) .. or "hands-on" knowledge (Carlson & Gorman, 1992, p 52).

Decomposition does not only mean to simply break chunks into components, it also means to efficiently separate, recognise or validate, and most importantly, to **regroup** these essential components to meet the specific requirement of the problem situation. For example, an experiment on chunk decomposition was conducted using matchsticks where participants had to transform the given Roman numbers wrongly arranged into correct equations (Knoblich, et al., 1999). To efficiently transform the inequation of 'XI = III + III', not only should the 'X' be decomposed into '\' and '/', but it should be consciously regrouped as 'V'. This involves the validation and recognition processes (Vanlehn, 1989). In design, validation involves prototype-building and testing, experimentation and expert reviews (Goel & Pirolli, 1992).

In short, inventors manipulate structures of knowledge with the help of relevant heuristics and vary the fillers of such structures with available stored information in memory. The elaboration process is crucial in order to organise sub-functions in an orderly manner. The capability of re-grouping elements involves the process of recognition and strong evaluation skill.

2.3 Effective Creativity Training

The above section discussed FD as it develops thinking abilities to equip engineering and technical students with the appropriate problem solving methods in design instruction (Duschl & Grandy, 2008). Apart from the content of the chosen intervention programme (FD, in our case), knowing the aspects of creativity and problem solving intervention is also important. This can be achieved by explicitly teaching students the chosen methods (Labudde et al., 1988).

There are four measures in the training components that have to be taken into account according to the literature: (i) The targeted cognitive process in the training; (ii) the training techniques (i.e., reading, lecture, visual stimulations, etc.); (iii) media (such as booklet, video tape); and (iv) the exercises given (Scott, Leritz and Mumford, 2004). Our investigations also expand on these components. We will also cover the evaluation and judgment methods used in the prior training programmes. Each component will be discussed in further detail next.

2.3.1 The targeted cognitive process during the training

There are trainings which promote the cognitive capabilities as demonstrated by the Process-Analytic Models of creative capacities (Mobley et al., 1992; Mumford et al., 1991). Other such processes include information encoding studied by Mumford, Baughman, Supinski, and Maherr (1996b), problem construction (Mumford et al., 1996a) and category combination (Mumford et al., 1997). Similarly, the use of visual analogy (Casakin, 2004), and design fixation and its mitigation (Linsey, et. al, 2010) all cater to fostering creativity through the teaching of cognitive components. Sternberg et al., (2005) purported that:

> By studying perception or memory, one would already be studying the bases of creativity; thus, the study of creativity would merely represent an extension, and perhaps not a very large one, of work that is already being done under another guise (p.356).

Therefore, any kind of cognitive-based training can help design students, provided that the processes are monitored. The processes need to be highly contextualised to suit the need of the designers. Training of a specific design method should coincide with the other prior, existing internal representations from a person, and not to interfere with it. Learning functional decomposition is an analytical approach of thinking about engineering constraints as well as what the designer has already experienced. The intervention on functional decomposition is going to enhance aspects of the analysis that may not be appreciated or only superficially done without any proper guidance.

2.3.2 The training techniques

Techniques represent the general instructional methods held to develop one or more processing skills (Scott et al., 2004). For the current studies, we adopt the self-explanation method. There are several reasons why the self-explanation method is adopted in the current intervention studies. It is a strategy of making self-generated explanations by making appropriate inferences and interpretations for the given learning materials (Chi et al., 1989; Taasoobshirazi & Glynn, 2009). Better self-explainers use interpretations across the domain and context such as making use of personal experiences and common sense in order to make meaning out of the learning material.

Further, SE is a widely tested technique among adult learners (Chi, 2000; Fonseca & Chi, 2011). It takes specific printed materials and form of exercises without external interferences because there is no instructor involved. It also provides elaborate data about which information problem-solvers are attending to at a particular SE session. The verbalisation of inner thoughts reveals thought patterns and brings subconscious thoughts to the consciousness, allowing problem-solvers to monitor their chain of reasoning and identify errors.

There are other techniques such as the Thinking Aloud Pair Problem Solving (TAPPS) that also used the same principle which is to make the individual's inner thoughts explicit. Johnson and Chung (1999) conducted a quasi-experimental study to examine the effectiveness of TAPPS in a supportive computerised practice environment. Working in pairs, problem-solvers exchange roles as a listener and an actor alternatively. It helps in directing the designing processes into a mature discussion based on a combination of different perspectives from two persons. However, we will proceed with the SE technique since individual units of inferences and interpretations are more manageable during this thesis' analyses phase.

2.3.3 The media

Media is a plural form of the word medium, and in the case of this study, it denotes the medium of instruction. The media of instruction are the materials used to convey the creative processes (through techniques of interest discussed earlier). A study by Pardamean (2014) used Logo programming in 16 sessions. A PC Logo for Windows version 6.5b 2002 was utilized in the class. Their module produced an introduction to the Logo programming through the turtle geometry. Students worked in pairs in order to cover the turtle activities on the computer. The teacher's role was to guide the students and teach the material.

Apart from the computerised media, there are also printed materials in the forms of images and diagrams used in prior studies. In the study of visual analogy (the targeted cognitive process) by Casakin (2004), visual displays were used to promote analogical reasoning among novices and experts.

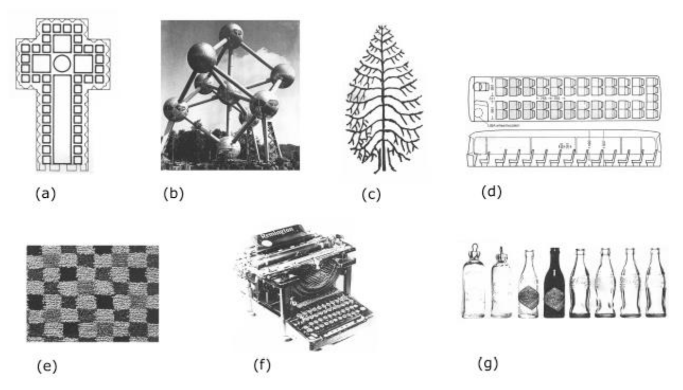


Figure 1 - Displays considered during the solving of the 'Dwelling' problem. a) Plan of a church; b) Atom and electrons; c) Tree; d) Plan of a bus; e) Textile fabric; f) Typewriter; g) Line of bottles

Figure 2. 9: Visual displays as media used in Casakin (2004)

As shown in the figure above, the visual displays were shown to both the novice and expert designer groups with the instruction to adopt the images in their sketches of designing dwellings.

Other studies used reading materials for training tutorials. Booklets are normally used to communicate the content of their trainings. For example, Nokes and Ohlsson (2005) used booklets to deliver the problem solving training for letter-sequence extrapolation task. To solve such a problem, the participant must first identify the pattern in the given sequence and then, use that pattern to generate the continuation of the sequence. As a simple example, to extrapolate the sequence ABMCDM to six places the participant would produce EFMGHM. The purpose of their study was to examine the learners' mastery of the extrapolation task through direct tutorial (using booklets) in comparison to the problem solving practice of the task (through spontaneous computer gaming) without explicit tutorials.

For the training group in Nokes and Ohlsson's study, there were two sequence extrapolation tutorial booklets, one for short instructions (12 p.) and one for long instructions (14 p.). Both tutorials consisted of general instructions on how to find pattern sequences as well as detailed descriptions of the component relations of patterns (e.g., forward, backward, repeat, and identity relations).

In short, media should be attuned to the assumptions about target cognitive components that a particular study is going to explore. The role of the media is to aid the chosen teaching techniques so that the training content is delivered in the most effective way. Media stimulates learning of problem solving strategies through human senses. Without the appropriate media, there will be unclear input about the target component of creativity skills, which, in turn, results in the failure of mastering the desired skills.

2.3.4 The exercises given

Exercise should be able to familiarise participants with the target cognitive components under study. Regardless of formats of exercises, two measures have to be observed, which are high validity and reliability of the exercises. These are obtained through replication of the exercises before implementation, or to conduct other related validity and reliability procedures. However, exercises do not become the measure of the study by itself. Exercises are transfer tasks that are given during the post-intervention phase (in cases where the experimental research design is adopted) and the post-test results which are considered to be the indicator for the training's success. Ma (2009) found out that with the exception of the training programs and age, no significance was found in the effect of the moderators such as dependent variables, duration of training, and experimental design. The duration of the training here also refers to the length and format of the exercises during the training phase. Even though the exercises outcomes are not taken as the study's measurements, the exercises are crucial for establishing the grounds for the worth of the training itself.

Exercises are important so that:

(i) the target cognitive component is mastered well;

(ii) other kinds of learning will not interfere, or will interfere only to a minimum degree; and

(iii) manageability of the task during transfer phase is under control. Exercises should be supplied with accuracy within adequate time and pace, so that participants can use the experience to solve later transfer tasks within the study.

Table 2. 5: Exercises given for letter-sequence tasks (Nokes & Ohlsson, 2005. pp. 776-777)

Problem Type	Given Letter/Number Sequence	Correct 8-Step Extrapolation
Problem 1		
Target	E F D G C O F G E H D P	G H F I E Q H I
Transfer	E G D I C O G I F K E P	I K H M G Q K M
Problem 2		
Target	A C Z D B Y Y D F X G E W W	G I V J H U U J
Transfer	A E Z G C X X G K V M I T T	M Q R S O P P S

Problem Type	Given Letter/Number Sequence	Correct 8-Step Extrapolation
Problem 1		
1	I J H K G S J K I L H T	K L J M I U L M
2	R S Q T P B S T R U Q C	T U S V R D U V
3	M N L O K W N O M P L X	O P N Q M Y P Q
Problem 2		
1	G I T J H S S J L R M K Q Q	M O P P N O O P
2	R T I U S H H U W G X V F F	X Z E A Y D D A
3	N P M Q O L L Q S K T R J J	T V I W U H H W

Note:
Above: Two sequence extrapolation problems and their associated transfer problems
Below: Three practice problems for each problem type

The table above shows the sample practice exercises used in Nokes and Ohlsson (2005). They explained their exercises as follows:

> The target tasks were two letter-sequence extrapolation problems. Problem 1 had a periodicity of 6 items and Problem 2 a periodicity of 7 items … To enable the participants to detect the embedded pattern, the given segment was 12 items long for Problem 1 and 14 items long for Problem 2. That is, the given segments covered two complete periods of the patterns… Each target problem was associated with a transfer problem… For Problem 1, the corresponding transfer problem was generated by quantitatively "stretching" particular relations of the pattern. For example, "forward 1 in the alphabet" was stretched to "forward 2 steps" … The second transfer problem was generated in a similar way from target Problem 2 (p.776).

The quotation above contains an explanation for the letter extrapolation tasks that are varied across Problem 1 and 2 where a longer list of letters was used in Problem 2. Later during the training, exercises were given to match each class of the problems respectively (see Table 2.11). There were a total of three practice problems for each target problem. The authors indicated that the three training problems followed the same pattern as the target problem.

Further, Scott, Leritz and Mumford (2004) conducted a meta-analytic study on the effectiveness of the creativity training. Eight major kinds of exercises were found (based on their meta-analytic coding of the prior work analyses) which are:

- Classroom Exercises
- Field Exercises
- Group Exercises
- Domain-Based Performance Exercises
- Computer Exercises
- Written Exercises
- Self-Paced Exercises
- Imaginative Exercises

The instructors' techniques rely on their beliefs in the best approaches to teaching as discussed before. The media as instructional aids as well as the formats of exercises however, is something that is varied according to the personal preferences and participants' background, material availability, and research constraints.

Usually, exercises should consider (i) the nature of participants or audience under study (e.g: level of expertise, age group, and socio-economic background); (ii) the target processes in question for a particular study (e.g: Nokes & Ohlsson (2005) wanted to compare paths to mastery between the theory and non-theory groups so both groups were given the respective forms of exercises); and (iii) availability of the exercise materials. Despite human factors such as intelligence, motivation, mood and participatory levels across samples, the general affordability and ability to successfully complete the exercises with passing rate can be used as the basis for including participants into a study.

In short, attention should be given to the type of exercise for the sake of helping participants of a study to understand the target cognitive component under study, failure of which can cause invalid results due to lack of control for the contravening factors and missing of the required skills.

2.3.5 Generic creativity trainings: what have been missed out?

One of the most cited creativity methods in designing ever known was the divergent-convergent thinking method (Creative Education Foundation, n.d.). This creative method was designed by Alex Osborn and Sidney Parnes in the 1940s and is still undergoing further theoretical development before the method can be implemented in various sectors.

There are basically two ways in which divergent thinking and convergent thinking support each other, and this is shown below.

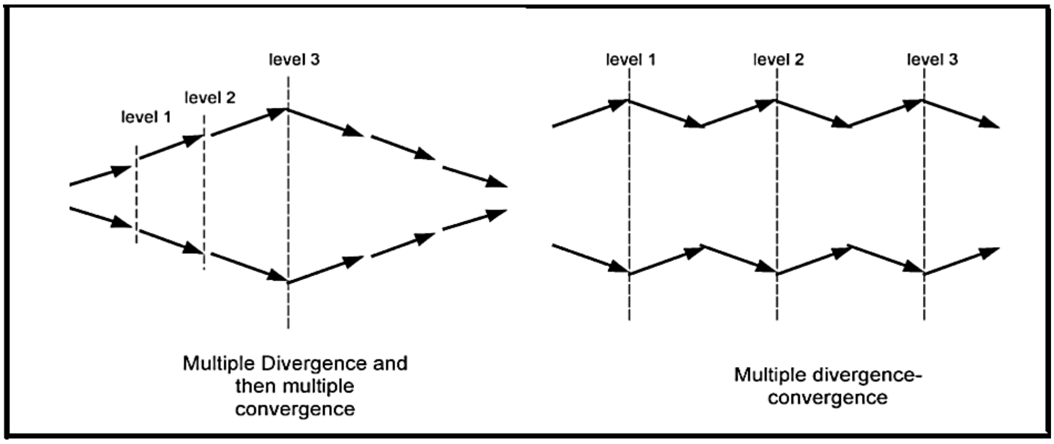


Figure 2. 10: The different divergent-convergent interaction approaches (Liu et al., 2003)

Along the course of divergence training, judgment is deferred until later in the process convergent thinking will take place. Some studies argued that the multiple divergence-convergence thinking (the right image) is more preferable compared to the multiple divergence followed by multiple convergence (Baer, 1988; Lin, 2011).

In Lin’s (2011) study, the attitudinal, behavioural and cognitive factors are all measured as cumulative outcomes of divergence-convergence training. The results show inconclusive findings especially when memory (prior learning) and task environment are not regarded. Psychometric measurements test one’s creativity potential only. However, it appears divergence-convergence thinking method has always been unduly used to define creativity in the absolute sense. Runco and Acar (2012) expressed this misleading trend as follows: “This has created one *problem*, namely that occasionally they are regarded as tests of creativity.”

In our study, taking problem solving as the background theory for defining creativity, only the cognitive variables are examined. Creativity should not be based on the product, as well as observed potentials, but rather the processing account should be examined in order to understand the whole account of creativity (Boden, 1996). “You can't understand the butterfly unless you (also) watch the caterpillar,” as suggested by Runco (2003). The cognitive change then gives implications to behavioural and attitudinal change (Hayes, 1990). In fact, cognitive research provides accounts with empirical evidence that eradicate ‘mysteries’ surrounding creativity. For instance, while ‘delaying judgement’ is viewed as an attitude, the cognitive approach viewed this as purely cognitive. Finke introduced the concept of “pre-inventive” structures with properties such as ambiguities and incoherence. Delaying judgement, in this case, refers to the cognitive mechanism where problem solvers search for solutions from other directions since the available solutions did not seem to work. It is also found that the designer’s pre-inventive structures (not pre-inventive structures in other people’s minds) are often re-visited after some gap in time and used as the baseline to thoughtfully construct the final full concept (Finke, 1996).

One example of the design research that tackles the divergent-convergent method in the engineering design domain was by Liu et al. (2003). The focus of the divergent thinking method in such studies is to delay premature decisions on design concepts through extensive search, so that designers can include a lot more possibilities for new designs (Basadur, et al., 2000). However, to regard deferring judgement and avoid premature convergence as the sole basis for judging creativity are too ambitious. As Basadur et al. put it:

> It is interesting that the active divergence attitude was associated only with the (avoiding) premature convergence attitude (HIA, .32), and not with any skills, contrary to the prediction of H2. Thus, although this research supported Basadur and Finkbeiner's (1985) suggestion that the ideational attitude of preference for (avoiding) premature convergence is necessary for the ideational attitude of preference for active divergence, the usefulness of including the divergence attitude in the overall causal model relationships is questionable," (p.93).

The divergence-convergence method is still useful in the context of design instruction to some extent since this method assesses creativity potential at the level of promoting generic divergence skill using universal criteria. As to the applicability of the method to specific target audience including designers requires further modifications and scientific testing. For instance, in the engineering design domain, designers conducted activities for divergence process by using heuristics such as "defer judgment" and "accept all solutions". The convergence process, on the other hand, is when the designers critically omit previously suggested alternatives if some of the suggested ideas fail to meet further design requirements or constraints (Liu et al., 2003).

However, the process could be overwhelming when learning about a particular concept is not taken as an agenda, especially as far as novices are concerned. In the case of the current work, the attempt to perceive FD as a problem solving way can never be complete without a proper agenda for learning it. In a current paper on functional representation in engineering design and AI, Goel (2013) posited that understanding 'function' should not be approached only as a problem solving tool but as an important aspect of learning about conceptualisation in engineering. As he put it:

> Principle 10: Functional modelling should support learning tasks in addition to memory and problem solving tasks. Learning tasks include learning of design cases and case indices, learning of abstract design patterns, and learning of abstraction hierarchies (p. 208).

In short, the teaching of divergence-convergence thinking as a creativity method is questionable due to the lack of theoretical basis for the definition of creativity. Also, the open-ended method could cause information overload among novices, which is discouraged to avoid 'cognitive load' (Sweller, 2011). Further, the measurement of divergence-convergence method depends largely on fluency and deferment of judgment, coupled with the judgment of the final design outcomes. However, the process is not made transparent, thereby leaving researchers with a lot of untraceable possibilities.

2.4 Measuring Creativity

Studies on design processes always stem from the need to understand both (i) the cognitive processes of creativity, including behavioural remarks as the indications of cognition such as 'fluency' (see Chapter 7 on Case Study); and also (ii) the final design output. This section presents the approaches for conducting both analyses in prior works. Afterwards, we will lay out the reasons why we adopt certain procedures for assessing the processes and products in the context of this study.

2.4.1 Assessing human cognitive processes using Verbal Protocol Analysis

To enable robust analyses, the most important aspect to consider when assessing cognitive processes is objectivity. One of the best objective approaches in the field of Cognitive Science and Social Sciences is the verbal protocol analysis method. We use this approach for our data collection and analyses. Ericsson and Simon (1993), who introduced protocol analysis approach, and Chi (1997), who proposed the verbal analysis approach, are among pioneers of the cognitive approach for conducting analysis on the thinking processes in objective ways.

The protocol analysis is a method that attempts to represent the use of ideal knowledge in a particular domain. A lot of cognitive processes can be captured through verbal protocol analyses. It is the analysis of spontaneous or heeded verbalization of an individual participants of 'think aloud' experiments to extract the kinds of information a problem-solver uses and their decision making-processes (Ericsson and Simon, 1993). This analysis involves the processing accounts such as the change of the speed of verbalization (i.e.: pauses) and whether there are different modes of expressions like writing, gestures and sketches that can inform something deeper about the person's cognitive processes in a minute-to-minute or second-to-second time span.

These are the basic assumptions about data obtained from problem solving protocol according to Ericsson and Simon (1993):

- The subjects' behaviour can be viewed as a search through a problem space, accumulating knowledge (not always correct) about the problem situation as they go.
- Each step in the search involves the application of an operator, selected from a relatively small set of task-relevant operators, to knowledge held by the subject in

STM (short-term memory). Application of the operators bring new knowledge into STM, moving the subject to a new point in the problem space.

- The verbalisations of the subjects correspond to some part of the information they are currently holding in STM, and usually to information that has recently been acquired.
- The information in STM, and reported by a subject, consists primarily of knowledge required as inputs to the operators, new knowledge produced by operators, and symbols representing active goals and sub-goals that are driving the activity. A goal may take the form of an intent to apply an operator, in which case the protocol may contain explicit evidence for the application of operators.

The above assumptions make concurrent verbal protocol as the most viable method available for analysing the processes of problem solving. In effect, the verbalisable cognitions can be described as states that correspond to the contents of STM-info that are in the focus of attention. Each information that is vocalised can be directly inferred as a verbal encoding of the information in STM. The verbalisation processes are initiated as a thought is heeded, and thus reflects the structure of thoughts. Further, units of articulation will correspond to integrated cognitive structure (hence the instantiation in forms of search trees/solution paths for encoding complete process).

With respect to how the assumptions affect the subsequent analyses, information in focal attention is vocalised directly after an initial encoding into oral verbal code. This necessitates the identification of verbalisation units (segments) that correspond to units of heeded information. Therefore, syntactic information is indicative of meanings, and verbalisation reflects internal representation. Pauses in articulation, phonemic intonation contours, and stress can uncover units of verbalisation. ‘Segmentation’ procedure can be conducted whereby each segment is parsing of a single unit of transcribed protocols based on syntactical information. It is assumed that segmented protocols are verbalised independently of those that precede and follow it, hence each can be encoded independently, without attention to context.

To cope with the activity well, warm up exercises that is simpler than the actual task but of the same nature should be given. In addition, the tasks should be novel and moderately difficult, so as to elicit conscious processing. Probes or comments by the researcher are necessary only if the problem-solver ceases to verbalise for more than 10-15 seconds. If prompts are required, researchers should take care not to cue behaviour or to prompt some desired behaviours. To minimise prompting effects, neutral and unobtrusive prompts such as "Keep talking," rather than “Explain what you are thinking?”, can be used (Ericsson & Simon, 1993).

2.4.2 Assessing creative products

Evaluating product inventiveness is one of the challenges for researchers interested in creativity training studies (Ritchhart & Perkins, 2005). Finding ‘perfect’, standardised evaluation criteria for evaluating creative products does not seem to be a useful solution to evaluate inventiveness. What is more critical is to be aware of how the selection of some particular criteria is made and how effective the criteria are for fulfilling specific research aims (Nickerson, 1999).

There are three important issues to cater to before materialising a judgment procedure, specifically for the current research. The issues are: (i) the criteria of inventiveness; (ii) the procedure and technique for conducting the judgment; and (iii) the characteristics of the judges.

When it comes to inventiveness criteria, there are several dimensions of creativity according to prior studies as follows:

Table 2. 6: Creativity criteria for product judgment

CREATIVITY CRITERIA	Authors
Novelty or Originality	Boden (2004), Charyton & Merrill (2009), Chiu & Salustri (2010), Ward et al. (1999), Torrance et al. (1974), Brown (2008), Shah et al. (2003), Thompson & Lordan (1999), Weisberg (1999), Genco et al. (2012), Mumford et al. (1997), etc.
Valuableness or Appropriateness or Usefulness/Functional/Correctness / Applicability/Quality/ Feasibility/	Boden (2004), Charyton & Merrill (2009), Chiu & Salustri (2010), de Bono (1992), Amabile (1983), Besemer & Treffinger (1981), Akin & Akin (1998), Larson et al. (1999), Shah et al. (2003), Thompson & Lordan (1999), Genko et al. (2012), Mumford, et al. (1997), etc.

Completeness/ Effectiveness	
Surprising or Interesting/Unexpectedness	Boden (2004), Chiu & Salustri (2010), Torrance et al. (1974), Brown (2008), Redmond (1993), etc.
Fluency or Divergence/Flexibility/ [the opposite for] Fixation & Conformity	Charyton & Merrill (2009), Genko et al. (2012), Torrance et al. (1974), etc.

Based on the table above, there are overlapping definitions for creativity regardless of domain, across age and background. The most important criteria are novelty, valuable, surprising and fluency (though some might refer to 'surprising' as a sub-criterion for 'originality'). Chiu and Salustri (2010) conducted invention competition and evaluated the outcome of the products in terms of originality and appropriateness. Apart from being 'new', an original product should also be 'useful'. This is because "ideas that are merely novel may be bizarre, strange or even incorrect."

The subsuming concepts are words of synonyms based on literal meanings of those main criteria. The next figure shows that the 'originality' criterion, for example, is composed of 'unexpectedness' while the 'quality' criterion is composed of 'completeness' and 'effectiveness' (Redmond, Mumford & Teach, 1993).

Note that no attempt is being made to go into further details of the full concept rubrics suggested by the different studies. This is because the meaning of creativity that has been covered in this thesis, in particular~~,~~ creativity as problem solving, is enough as a backdrop for the current work. Since majority of studies related to judgment of creative products agreed upon two main criteria, i.e.: novelty and valuableness/appropriateness, this study will also follow this trend to strengthen the construct validity of the materials. In the analyses of product judgment, we will present our attempt to see whether there are negative correlations between novelty and valuableness. Negative correlations indicate an increase or decrease in originality with the opposite for the appropriateness score. If the results turn out to be a negative correlation, then it can be inferred that originality and appropriateness are not redundant measures, indicating they measure different dimensions of creativity.

To get a total inventiveness score, both measurement criteria will be combined. The same approach is taken by Charyton and Merrill (2009). Using the creativity assessment tool called Creative Engineering Design Assessment (CEDA), they added up the fluency, flexibility, novelty and usefulness scores as the measurement of creativity for mechanical engineering undergraduates. In the same vein, participants' score in this study on both originality and appropriateness are summed up to get the total inventiveness score. This score will be included in the analysis to reflect the total inventiveness as a combination of both creativity criteria.

Further, the judgment technique for classifying outputs of creativity can also differ. Stemming from Boden's work (2004), there are two ways in which creative achievement can be perceived as successful: whether by the individual and on cultural level. She refers to the former as P-creativity, and the latter as H-creativity. P-creativity, according to Boden, refers to psychological creativity, which means the individual's best achievement regardless of whether anybody else has come up with the idea/invention. On the other hand, H-creativity refers to historical creativity, which means the individual's best achievement to come up with the idea/invention that coincidentally turns out to be the first of its kind in history.

Some judgment procedures set up certain rubrics beforehand and to be rated as original, a product should achieve standards set up by the rubric. This implies that there would normally be more than one person to be able to score the highest rate as long as they qualify to be in that position. This is akin to the P-creative approach mentioned by Boden (2004).

On the contrary, other judgment procedures compare creative outputs relative to what others from a similar class of output have produced. For example, if there are ten products, the judges will study each of them, and then, based on the incoming product criteria and characteristics, judges will decide whether the products contributed to the field in a significant way compared to the rest. It is more or less like a bottom-up process of decision-making. The advantage of this approach is no two products will have the tendency to come up with exactly the same outputs except if this appears to be the case. In this study, we will adopt both approaches.

The third issue concerns the judges' qualification and calibre as a judge. A judge's assessment and evaluation of creative products can differ according to the training they received as well as their experience. In the current study, the domain experts with adequate design experience in the work field are chosen to be our judges. This is because their definition of creativity is ruled by the “engineering definition of creativity” as opposed to “product development and retailing definition of creativity” by marketing bodies or industry (Chiu & Salustri, 2010). Therefore, this will give a fairer judgment because attention is given to the specific aspects of engineering knowledge students use while solving the inventive problems and not towards other external aspects such as product marketability, costs involved and also physical presentation. Although marketing and retail can become crucial at the later phases of product communication, designers usually focus on product concepts, essential components and functionality during the conceptual phase of design (Goel & Pirolli, 1992).

2.5 The implications to the current research

In conclusion, this review provides in-depth accounts for explicating functional decomposition as described in the framework at the beginning of the section. However, for the framework and theories on FD to be scientifically sound requires some empirical testing. The experimental materials, as implied, are developed based on the framework. The material details will be explained in Chapter 3. Data that are collected can be used as evidence for developing a theory of FD, and this requires a complementary study that separately analyses the same data qualitatively. The qualitative research done will be reported in Chapter 7.

The literature has also mentioned about the way prior works have promoted FD. One approach that is of interest is the crystallisation of the ‘black-box’ approach where functions are recalled and then organised analytically. The other approach is the ‘ontological approach’ where certain types of hierarchical relationships are explicitly introduced in the intervention, and using the ‘verb-operand’ phrases as the basis for defining functions. This brings the need to conduct two separate experiments that logically follow two different FD approaches, without demeaning other approaches that are available in the literature. However, these two approaches are considered sufficient for answering our questions.

There is also a need to find out more from the feedback that is collected from our field work. We suspect that FD is not an ‘all-or-none’ conceptual knowledge about engineering function. Some of the participants may have implemented this strategy even before the intervention. Engineering education has evolved to incorporate problem solving methods that are indirectly or directly highlighted in classrooms. Even students from outside of the engineering design domain understand the importance of problem solving as they are exposed to it since primary school. Therefore, there is a need to explore whether the extent of the participants' knowledge relating to the idea of FD during design problem solving.

Moreover, there are still questions regarding how functions are harmonised with other cultural constraints when they conduct decomposition of functions. This requires explicit analysis methods on the transitions between the function search with other kinds of search, such as the search in the spaces of 'structure', 'behaviour', 'people', 'purpose' and 'resource' (Goel & Pirolli, 1989). These other kinds of search are part and parcel of design since they are the constraints that determine the design goals (Goel & Pirolli, 1992). Engineering science concerns itself with the progress in learning or conceptualising about the science principles underlying a solution. As such, function, in this sense, is a substantial element. Nevertheless, it needed to be informed by non-functional constraints.

According to Chi (2006), like expertise, 'creativity' is a relative skill that can evolve as design students gain more experience. The manner in which creative expertise is measured is highly debatable since it involves subjective judgment involving cultural, ergonomic determinants and personal preferences. The study has taken an eclectic approach that is to take the acceptable creativity assessment criteria and judgment methods. However, this is not free from criticisms. There are possible issues regarding the nature of the end products of design which, according to Goel and Pirolli (1992) could only be judged as 'better' or 'worse' rather than 'right' or 'wrong'. This is also going to be explored in our experiments.

In addition, based on the literature, we look at direct comparisons between the divergence-convergence thinking method and the FD method. The former encourages open-ended search without specific intervention about conceptualising any aspect of the intended products, be it functionally, structurally, behaviourally, purposely, etc. The latter focused on the training of function search. Therefore, the variable is limited **only to the function** search among both groups as a factor.

To discriminate only the said factor, the training conditions provide the optimum learning setting (i.e.: the best material, technique, media and exercises) for all participants regardless of which group (experimental or comparison group) they belong to. This is explained further in Chapter 3.

CHAPTER 3

Methodology

3.1 Introduction

The previous chapter on literature on the study of FD method necessitates the testing of this design method in three different studies, which are: Experiment 1, Experiment 2 and the qualitative study. This chapter presents the (i) details of our research designs; (ii) participants for each study; (iii) materials used in all the studies; (iv) procedure for data collection; and (v) quantitative analysis procedures for assessing the process and product outcomes of the studies (with the chosen statistics) and general qualitative analysis procedures. This chapter explains only the mechanics of the field work and the research administration, while the results can be found in the upcoming chapters.

3.2 Design

The design of the current investigation is of a mixed method. Both quantitative and qualitative methods are used to answer the research questions. For the quantitative study, there are two Experiments (Experiment 1 and 2). Another method is the qualitative Case Study.

The experimental study is the most common method in Cognitive Science. Experiment 1 adopts the 2 by 2 experimental method where there are two types of training interventions (i.e.: FDI and CPS) by two phases (pre-intervention ‘vs’ post-intervention performance). The two interventions are “FDI” *(Functional Decomposition Version 1)* that implements the functional decomposition method and “CPS” *(Creative Problem Solving)* that implements the divergent-convergent method, as a ‘control’ group.

In Experiment 2, a different intervention material which is the FDII *(Functional Decomposition Version 2)* is compared against the same control group or what we call

'Comparison Group' in this study (because they also learned another design method-the CPS). The research designs are summarised in the following table.

Table 3. 1: The Research Design

<table>
<tr><th colspan="2">QUANTITATIVE DESIGN</th><th>QUALITATIVE DESIGN</th></tr>
<tr><th>Experiment 1</th><th>Experiment 2</th><th>Case Study</th></tr>
<tr><td>1) Two independent variables:
a. FDI Intervention
b. CPS Intervention

2) Four dependent variables:

a. Process of inventiveness in terms of aspects of design attended to and their frequencies
b. Process of inventiveness in terms of transition counts between all design aspects.
c. Judgment of the products</td><td>1) Two independent variables:
a. FDII Intervention
b. CPS Intervention

2) Four dependent variables:

a. Process of inventiveness in terms of aspects of design attended to and their frequencies
b. Process of inventiveness in terms of transition counts between all design aspects.
c. Judgment of the products</td><td>The Analysis of Aspect of Representation that has changed:

1)The control system:
Depiction of control using Conceptual Maps based on participants' protocols.

2)The decomposition operators:
Coding of function operators.</td></tr>
</table>

3.3 Participants

Thirty University of Sussex Masters students aged from 22 to 35 years old (21 males and 9 females) participated in the study. They were given GBP £20.00 as compensation. The sampling method was purposive sampling. Only students who had obtained their undergraduate degrees in Electrical Engineering and had completed at least one major design project could participate in the studies.

The advertisement to participate in this study was published in the Research Group email, as well as the University of Sussex website (job vacancy section). As shown in Table 3.2, students were randomly assigned into either of the FDI or CPS group in Experiment 1. In Experiment 2, all participants were assigned with the FDII materials.

Table 3. 2: The Participants

Group / Study	Experimental Groups (Total Participants)	Comparison Group (Total Participants)
Experiment 1	**FDI** (10 – 1* = 9) Participants' Identity: P1,P3, P4, P5, P6, P7, P8, P9, P10	**CPS** (10 – 3* = 7) Participants' Identity: P11,P12, P13, P14, P15, P16, P17
Experiment 2	**FDII** (10 – 1* = 9) Participants' Identity: P21,P22, P23, P24, P25, P26, P27, P28, P29	
Case Study	**FDI & FDII** (See Chapter 7 for the details.)	-

*Notes: The number of excluded participants

Five participants were later dropped from the analysis (1 from FDI group, 3 from CPS group, 1 from FDII group). This is due to the fact that these participants were found to be unrepresentative of the given methods during the post-intervention phase. This included participants who did not use the given strategies (even to a minimum degree). Their presence would contaminate the data because this training is about the impact of a particular creativity method on the students' inventiveness.

3.4 Materials

There were several steps for developing all the materials. The intervention session employed self-learning as the delivery method where participants would "self-explain" the materials (Fonseca & Chi, 2011). First, based on the study objectives, we browsed through the available materials of FD in the literature. During this initial search, a few of the collected materials were then short-listed for use.

After reviewing the materials, it was found that some of them were not suitable for human subjects. They were deemed not ready for use unless they were reorganised and simplified. Later, after considering factors and limitations with regards to our research constraints, only two materials were chosen at the final stage. These two materials were the "Input-Black Box-Output" functional representation and the "Ontological" FD material. They are materials for the most basic of the Functional Model (for FDI) and Ontology of Function, for FDII (see Table 3.3 below). The last material selected is the CPS material which corresponded to the Comparison Group explained in the 'Participant' section above. All the materials, regardless of their target users, are to fulfil Mayer's (1989) seven criteria of 'models for understanding'. Those criteria are: (i) complete; (ii) concise; (iii) coherent; (iv) concrete; (v) conceptual; and (vi) correct.

Table 3. 3: For conciseness, only a few principles were chosen based on Functional Modelling Studies (Goel, 2013)

ISSUES	PRINCIPLES
Basics of functional models	**Principle 1 (functional reasoning)** **Principle 2 (functional decomposition)** **Principle 3 (functional explanation)**
Basics of modeling Methodology	Principle 6 (experimental evaluation) Principle 15 (formalization)
Abstractions	Principle 4 (behavior) Principle 9 (patterns) Principle 13 (abstraction hierarchy)
Modality of Reasoning	Principle 11 (functional and visuospatial reasoning)
Ontology	**Principle 8 (ontology of states and functions)** **Principle 9 (ontology of patterns)**
Knowledge and memory organization	Principle 5 (functions as indices to behaviors) Principle 7 (functions as indices to design cases)
Analogy and learning	Principle 10 (learning cases, indices, patterns, abstractions) Principle 14 (analogical mapping and transfer in an abstraction hierarchy)
Perspectives	Principle 11 (system and environment centric views)

Note: The methodology of the current work is based on the Principles highlighted in bold.

All the main intervention materials (FDI, FDII and CPS materials) were *complete* and that they contained all of the explanations, worked examples, as well as exercises. The materials were *concise*, as in they were not lengthy. The research design of this intervention study involved three phases, and only 25 minutes were allocated for studying the materials. Synthesizing materials to make them more concise was challenging. We had to do a substantial amount of trimming since the literature offered too many kinds of representations with regards to engineering functions as shown in Table 3.3.

We also ensured that the materials were *coherent*. The flow of the process is logical and the operation is transparent, without diverting to irrelevant or unnecessary notes (Mayer et al., 2001) . This is especially so considering the experimenter was not in contact with the participants but with the materials. The intervention materials for both experimental and comparison groups were also *concrete*, that the cues including physical models or visual models were carefully selected. Functional definitions were clearly given using easy daily vocabularies. There was no new introduction of rare visuals, because familiarity helped to speed up learning.

Further, the materials we updated were *conceptual*. Participants could consolidate the materials easily with their current knowledge and store the FD or CPS concepts into long-term memory when they gauge the conceptual understanding right. Then, we ensured the materials were valid or *correct* by referring to established sources such as engineering design textbooks and indexed journals. The materials were also used in a Pilot Study and reviewed by a Professor of Cognitive Science from the School of Engineering and Informatics, University of Sussex. Finally, we were *considerate of the time constraints.* Since the duration of the intervention was only 25 minutes, the vocabulary and general organisation of materials had to be of sensible depth and they could be learned within the given time limit.

The 'intervention' materials are supported with 'administrative' and 'supplementary' materials. However, for brevity, this section will detail out only the Intervention Materials. This chapter first explains the findings from the Pilot Study before going into the details of the developed intervention materials.

3.4.1 Pilot Study

The Experiments were preceded with a Pilot Study. This was to ensure the validity and reliability of the materials. The pilot study involved six participants, where two were assigned for each kind of material (FDI, FDII and CPS). Useful feedbacks were taken.

Participants in the Pilot Study were generally able to follow the training session except for a few amendments. The suggested amendments, however, did not involve the content aspect of the main FDI, FDII and CPS interventions. Based on the Pilot Study, the participants were not verbose enough when giving any self-explanation. Consequently, we included a standard mark every two to three sentences to notify the participants to give their self-generated explanations. We put "sound" signs so that every time they see this mark () in the booklet for the intervention phase, they are required to 'self-explain' as a learning method.

The other purpose of conducting the Pilot Study was to ensure the procedure of the thinking aloud activity is followed during the problem solving session. In the Pilot Study, a simple calculation task that first appeared in Newell and Simon (1972) was used, but this did not help design students to solve design tasks. The pilot participants showed some difficulty in doing thinking aloud while giving annotations or sketching during the actual experiments without prior practice of verbalising their thoughts. This was due to the switch in the mode of verbal protocol from calculating to sketching and planning. We then changed the practice task into a painting-based problem so that participants could familiarise themselves with giving verbal protocols with a similar mode of problem solving activity.

Another important feedback was the pacing of the processes during the material learning (i.e.: the intervention) phase. It was found that the content of the intervention materials was of suitable depth and length inclusive of the exercises. This was an accomplishment because this proved the intervention materials were informative and learnable for them.

After the pilot study, we conducted another final revision. The material confirmation step was the final stage. Since this was a non-virtual training, all materials were printed out.

3.4.2 FDI Intervention Material

The first intervention material is the FDI Materials. A large part of the content of this material is adapted from Coulston and Ford (2004). The most important characteristic of the FDI intervention is the explication of function from the most abstract concept called ‘Step 1’, that is ‘general requirement’. Then, the ‘Step 2’, entails the ‘Level 0 functionality’ where the black box is specified. Unlike the general requirement, the input-black box-output diagrams require function specifications in the black box. In other words, the black box should be made transparent, so it is not considered as ‘black’. Then, in ‘Step 3’, the ‘Level 1 functionality’ is conducted where additions of other components into the main system architecture are made. The functionality specifications must be detached from the raw concept in Level 0, and then, explicated. In actual functional decomposition, designers can go through layers and layers of function search and explication process. However, this study looks into only the Level 1 Functionality to consider the limited training session (25 minutes).

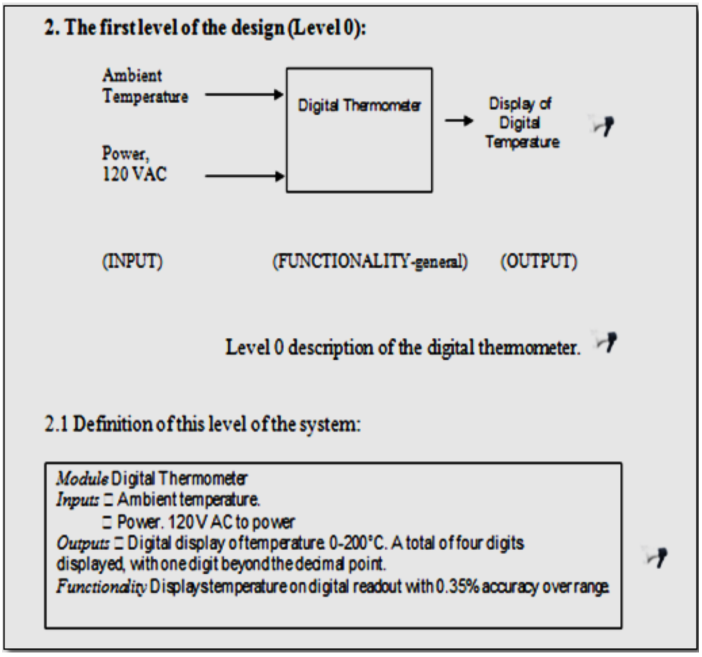


Figure 3. 1: The Input-Black Box-Output Functionality appeared in FDI Material (Level 0 Functionality)

Note that this FDI approach is also hierarchic, though not explicit in the diagrams used. This is because a lot of sub-gaoling processes happen in a step-wise fashion.

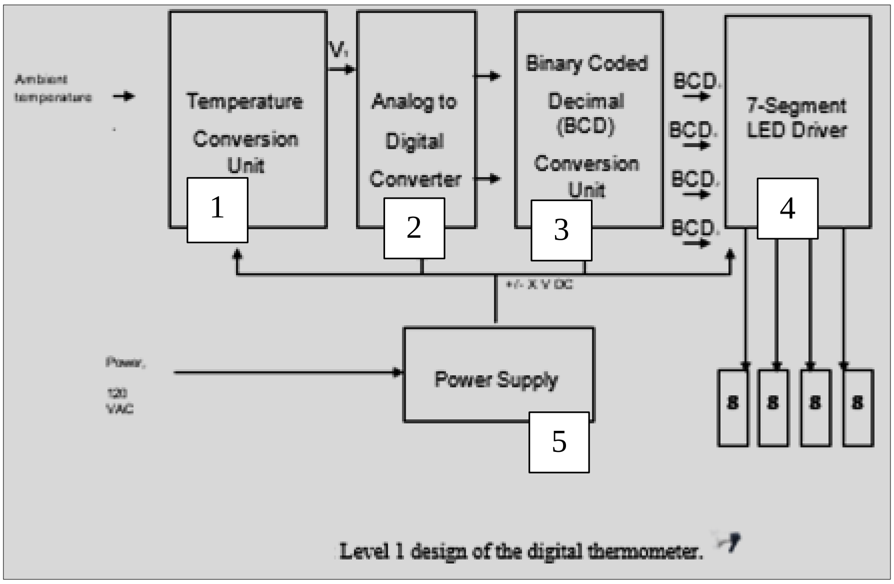


Figure 3. 2: 'Level 1 Functionality' in the FDI Material

The above shows the decomposition into Level 1 Functionality where 5 sub-functions were identified: i.e., temperature conversion unit, A/D converter, BCD converter, 7-segment LED driver and power. The following is the decomposition of the self-contained functionality (only sub-functions 1 and 2 are shown here as an example.)

Defining temperature conversion unit.

Module Temperature Conversion Unit
Inputs ⍰ Ambient temperature.
⍰ Power. __ V DC to power the electronics
Outputs ⍰ Temperature proportional voltage.
VT= αT, and ranges from __ to __ VDC.
Functionality Produces an output voltage that is linearly proportional to temperature. It must achieve an accuracy of ___ %.

Defining A/D Converter

Module A/D Converter
Inputs V_T = voltage proportional to temperature. __ V range.
Power. __ V DC.
Clock. System clock at frequency of__ Hz.
Outputs _ bit binary representation of V_T.
Functionality Converts analogue input to binary digital output.

Figure 3. 3 Some Excerpts from the FDI Material

In brief, the purpose of the FDI Intervention Material is to decompose functionalities into firstly, the general statement, then to Level 0, then finally to Level 1 functionality. The interface between the given sub-functions (e.g.: the output of this sub-function is an input to the next sub-function) are generally underlined by known technological solutions, but no real values are put so that the designer can explore the properties carefully without being restricted to the specific criterion, such as the exact voltage.

3.4.3 FDII Intervention Material

This material is adapted from the function ontology developed by Kitamura, Kashiwase, Fuse and Mizoguchi (2004). The differences between our version of the FD intervention and Kitamur et.al's (2004) are shown in the following table.

Table 3. 4: Amendments made in materials adapted from Kitamura, et. al (2004)

Features of Ontological Modelling Framework based on Kitamura et. al (2004)	FDII for the current research
An extended device ontology: Refined device ontology for capturing behaviours of components	Not included
A functional concept ontology: to provide generic functional concepts representing verbs of functions in is-a hierarchy	**Included**
Conceptualization of "ways of function achievement" and the is-achieved-by hierarchy for detaching them from functions	**Included**
Four types of functional knowledge and ontological modelling guidelines	Partially Included
Integration of information of unintended use for maintenance activity	Partially Included

Notes: Only the bolded texts are the element of ontology that is adopted for the current FDII material.

The 'Function as Intermediary (Black Box) Between Intention and Goal' (FDI) approach differs from the 'Function as Ontology' approach of FDII in that the former emphasises on the layer by layer reformulation of functionality. However, the latter pushes generality to even higher degree by using the VERB (an action which one would like the device to perform) and OPERAND (the object that the action is going to act on).

Examples of the verb-operand functional statements are 'remove material'; 'locate fastener'; and 'heat cylinder'. Our version of the ontology approach also uses hierarchical diagrams. The motive of both FDI and FDII approaches, however, is the same, that is to decompose meanings previously attached to a particular device solution by drawing the attention to the new formulation of device intentions in the current situations. This is because functional statements can be redefined from time to time.

These are some excerpts from the FDII Intervention material:

Table 3. 5: Vocabularies used for Ontological Training in FDII

STEPS	ACTIVITY	VOCABULARY	HIERARCHY
1	**Refine the question.**	verb-operand *e.g.: combine metal parts*	none
2	**Develop the *is-a* hierarchy of the ways of function achievement.**	verb + ..ing *e.g.:* *melting way; bolt and nut joining way*	*is-a* hierarchy (general to specific) ►
3	**Establish the *is-achieved-by* hierarchy of 'what functions'.**	verb-operand *e.g.: combine metal parts*	*is-achieved-by* hierarchy (a root function which composed of many sub-functions)
4	**Merge the information from all the previous steps to build a FD tree.**	verb-operand and verb + ..ing e.g.: see above	*is-achieved-by* hierarchy (a root function which composed of many sub-functions) ►

As shown in the table above, in the functional ontology training, specific vocabularies are introduced i.e.: **verb-operand** right from the start. Just like the FDI material, the material content here is presented in a step-wise fashion. The "verb-operand" statement consists of the work or the function, and an object. It is the first general design goal which refines the design task.

Next, the material presents a specific kind of hierarchies in the subsequent steps. The first hierarchy is the "way function" *is-a* hierarchy, to explore other means of fulfilling the upper level general intention. The *is-a* hierarchy induces designers to recall technical solutions. 'Way' means other technological approaches that function in a certain 'way' using the **verb+ing** expressions (e.g.: analogue-sensing way, temperature measuring way, etc.). The hierarchy of the "what function" comes later where the *is-achieved-by* hierarchy is used to explore the hidden functions using the **verb-operand** word combinations (e.g.: the supply power, sense temperature, code decimals, produce analogue, etc.).

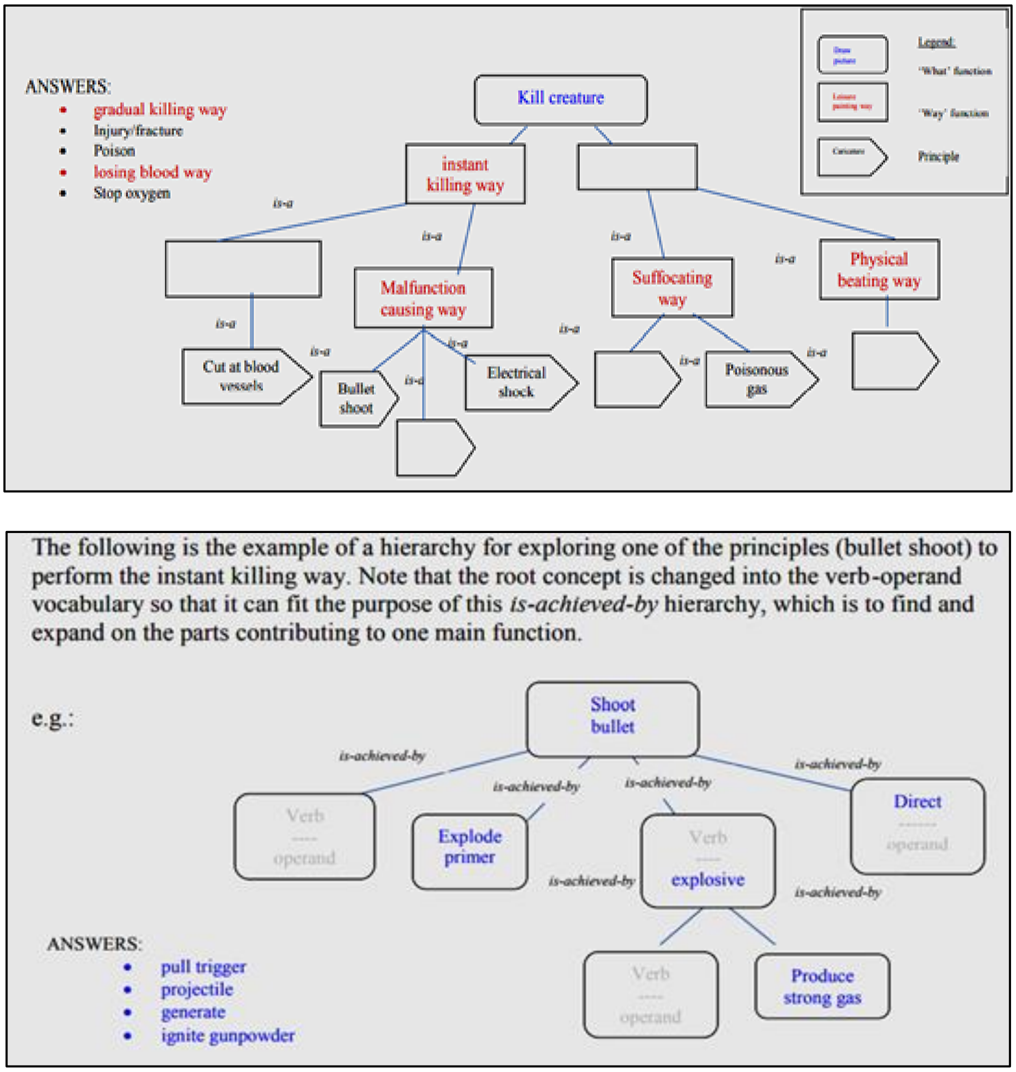


Figure 3. 4: Material excerpt showing the hierarchy of 'way function' (above) and hierarchy of 'what function' (below)

The figure above shows the worked examples provided in the FDII material. The developed materials are concise and complete for the purpose of the FDII training.

3.4.4 CPS Intervention Material

The CPS material is developed using the divergent and convergent thinking methods adopted from the literature (e.g: Baer, 1988; Creative Education Foundation, n.d.). The CPS materials follow the standard organisation format we set for all training materials, which are the Handout 1 for the definition of a particular method, and Handout 2 for the worked example, and Exercise sheets. The ground rules for CPS are as follows:

- For Effective Divergent Thinking:

  1. Defer Judgment
  2. Look for lots of Ideas
  3. Accept all Ideas
  4. Take Time to let Ideas Simmer
  5. Seek Combinations

- For Effective Convergent Thinking:

  1. Be Deliberate
  2. Be Explicit
  3. Look for Sneaky Spots
  4. Develop Affirmative Judgment
  5. Don't Lose Sight of Your Goals

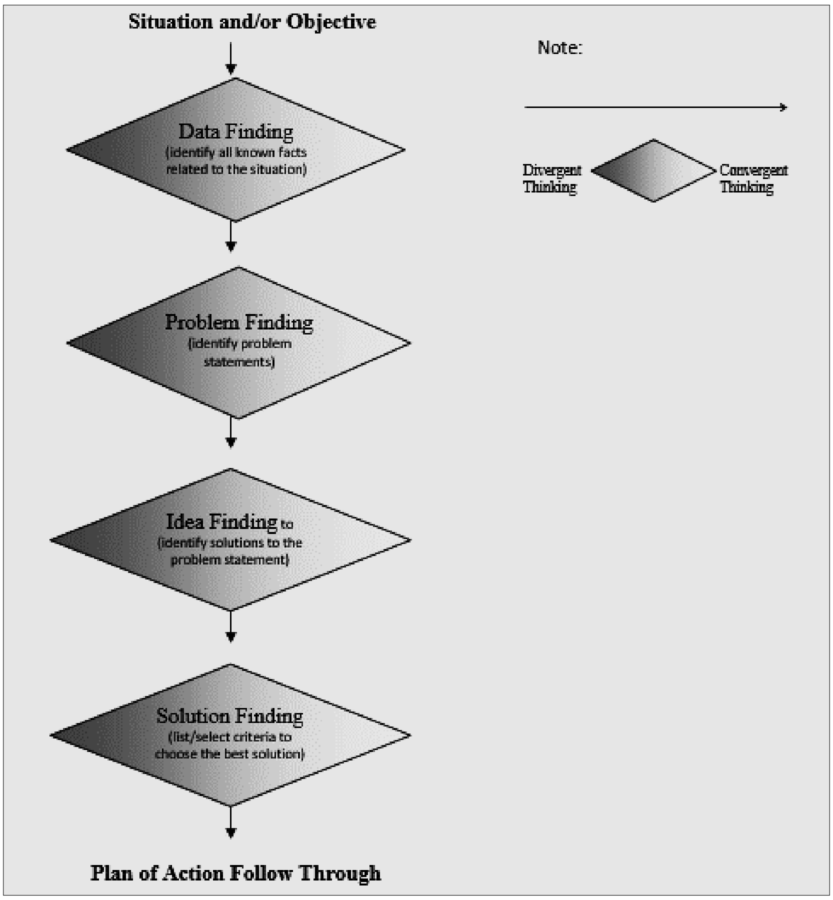


Figure 3. 5: CPS Materials

As shown in the figure above, there are four steps in the CPS methods which are: (i) data finding; (ii) problem finding; (iii) idea finding; and (iv) solution finding. For each step, the participant starts with divergent thinking. For example, 'data finding' should first be approached in an open-ended way. Then, as the data are all gathered, convergent thinking will follow where selections are made through the divergent thinking process conducted earlier. Moving to the second step, which is 'problem finding', participants move from divergence to convergence problem finding. A similar flow from divergent to convergent thinking takes place for 'idea finding' and 'solution finding' stages. The cues given to enhance divergent thinking is to initiate more and more questions such as: Ask yourself who is involved? What is involved? What are some examples of the problem? What causes the problem? When will it happen? Where does it happen? How does it happen? Why does it happen?

The CPS material provided clear examples for training purposes. The examples given are from the design domain, rather than the general daily problems. For example, in the 'data finding' stage, some questions and the worked examples given are as follows:

> **Who?** Everybody talks about the weather and seasonal changes. Scientists understand the interactions and changes of chemical substances by conducting experiments and measuring the change of temperature.
>
> **What?** Temperature keeps changing. Some means of detecting this change is available in the market. Weather can be told and generalized in terms of temperature.
>
> **How?** The change in temperature is caused by natural or artificial heating and cooling.

Participants using the CPS materials explored all classes of the design aspects without any specific attention to function, or structure and aesthetical aspects, or any other design aspects. Moreover, the biggest difference between the CPS material and its counterparts was that the CPS material called for recalling arbitrary information in most general connotations, while the FDI and FDII materials selected the function solution from the start. The next section explains the experimental procedures.

3.5 Data Collection Procedure

Each participant came individually for the experiments since they need to give their verbal protocols in Experiment 1 and 2. At the beginning of the experiment, they were asked to read and sign the Consent Form, which explained the brief purpose of the study, the request to cooperate with the experimenter, and the ethical consideration that their decision to participate or withdraw from the experiment was voluntary and not influenced by anybody. As shown in the next figure, the experiments were composed of three phases: the pre-intervention phase, intervention phase and post-intervention phase. Participants were occupied with the actual similar activities despite the different kinds of interventions given in the second phase. The duration of the experiment was approximately three hours with breaks in between the phases. The pre-intervention phase was preceded with a warming-up session for think-aloud protocols. This pre-intervention phase then resumed with participants solving the first inventive task. It was clearly communicated that we allow them to use any strategies they knew during this first phase.

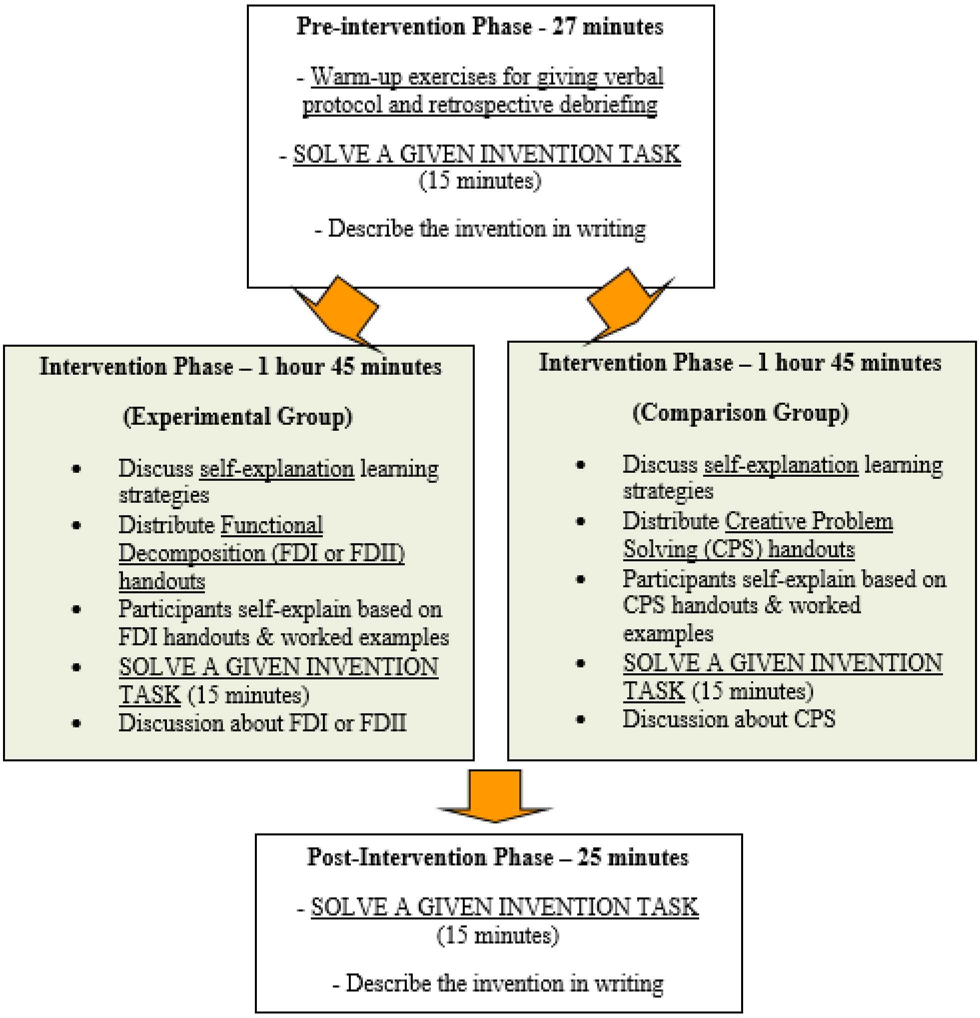


Figure 3. 6: Procedure of the experiments

To avoid the order effect, the Inventive Tasks[2] (TASKS A, B or C) were counterbalanced between the participants across the three phases. The Tasks were adapted from Finke et al. (1992). They were of relatively the same level of complexity and emphasised on the

2 The inventive problems used in this study are as follows:

TASK A: Invent an appliance that could catch a burglar.

TASK B: Invent a tool that a schoolteacher might use.

TASK C: Invent an item of furniture for the blind that can also be used for entertainment.

presentation of the question. The tasks were randomly given; and the participants were not restricted to solve problems chronologically (e.g.: Participant 1's order of tasks: Task B, then A, followed by C. For Participant 5, Task C, then B, followed by A).

Next, during the intervention phase, the participants were asked to self-explain while learning the given methods using The Intervention Materials (either FDI, FDII or CPS). Exercises and worked examples of how to use the given methods were given. Task 2 was given as a practice exercise for the given methods. Discussions between the experimenter and the participants were initiated after the completion of the second task to further rectify any misconceptions before moving to the post-intervention phase.

Finally, the third inventive task was given during the post-intervention phase. They were required to make use of the strategies they have learnt.

In short, the weighting of the activities was similar across groups. This was to make sure that the groups could engage in the tasks at all phases at the approximately similar level of depth. At the end, there were three design solutions given by the participants altogether. They were to drop written design descriptions in each phase (pre-intervention, intervention, or post-intervention). The design descriptions were treated as research data.

3.6 The Procedure for Analyses

The aim of the analyses is to answer the research questions. The analyses adopted both the quantitative and qualitative methods as described in the Design section and depicted in the following table. The quantitative analyses were less stringent due to the small number of participants. In addition, for this analysis, non-parametric statistics were used. The test represents only a small sample. Its results are thus not generalizable to other situations and are treated as rank-ordered data rather than interval.

Table 3. 6: The Research Questions are aligned with the Analysis Methods

RESEARCH QUESTION (RQ)	ANALYSIS METHOD
RQ1 **Do design students naturally use FD during the process of inventive problem solving before the FDI, FDII, CPS interventions?**	
1.1. What is the amount of 'function' search compared to the other main design aspects ('behaviour', 'structure', 'people', 'purpose' and 'resource') before the FDI, FDII, CPS interventions?	*Quantitative analysis:* (Analysis of occurrence of 'function' and other design aspects.) • Descriptive statistics • Kruskal Wallis test (non-parametric) (3 group difference, pre-intervention phase)
1.2 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') before the FDI, FDII, CPS interventions?	*Quantitative analysis:* (Analysis of interactions between design aspects.) • Descriptive statistics • Kruskal Wallis test (non-parametric) (3 group difference, pre-intervention phase)
1.3 Is there any difference among the students in terms of total inventiveness score of their products before the FDI, FDII and CPS interventions?	*Quantitative Analysis:* • **External Judges' Evaluation*** - Correlation Statistics (for material reliability) – Kruskal Wallis (3 group difference, pre-intervention phase).
RQ2 **Is there a change in the process of inventive problem solving after the FDI intervention?**	
2.1 What is the amount of 'function' search compared to the other main design aspects ('behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDI intervention?	*Quantitative Analysis:* (Analysis of design aspects irrespective of their order of appearance in the protocols.) • Descriptive statistics Mann-Whitney U Test (non-parametric) (between group, post-intervention change) Wilcoxon Signed Ranked Test (non-parametric) (within group, pre- to post-intervention change)
2.2 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDI intervention?	*Quantitative Analysis:* (Analysis of transition between the design aspects.) • Descriptive statistics • Mann-Whitney U Test (non-parametric) (between group, post-intervention change) • Wilcoxon Signed Ranked Test (non-parametric) (within group, pre- to post-intervention change)
2.3 Can design students invent inventive products after the FDI intervention?	*Quantitative Analysis:* • **External Judges' Evaluation*** - Correlation Statistics (material reliability) • ANOVA

RQ3 **Is there a change in the process of inventive problem solving after the FDII intervention?**	
3.1 What is the amount of 'function' search compared to the other main design aspects ('behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDII intervention?	*Quantitative Analysis:* (Analysis of design aspects irrespective of their order of appearance in the protocols.) •Descriptive statistics •Mann-Whitney U Test (non-parametric) (between group, post-intervention change) • Wilcoxon Signed Ranked Test (non-parametric) (within group, pre- to post-intervention change)
3.2 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDII intervention?	*Quantitative Analysis:* (Analysis of transition between the design aspects.) •Descriptive statistics •Mann-Whitney U Test (non-parametric) (between group, post-intervention change) • Wilcoxon Signed Ranked Test (non-parametric) (within group, pre- to post-intervention change)
3.3 Can design students design inventive products after the FDII intervention?	*Quantitative Analysis:* •**External Judges' Evaluation*** - Correlation Statistics (material reliability) and •ANOVA
RQ4 What is the nature of representational change among the selected participants? 4.1 How did FD change the control system from the arbitrary and shallow concepts to deeper conceptualisation of functions? 4.2 How did FD change the goal definition through decomposition and sub-goaling operators?	*Qualitative Analysis:* •Case Study

Notes: *Explained in separate section.

The analyses procedure above shows the plan on how to analyse our data to answer our research questions. The judging procedure is explained next.

3.6.1 Judging procedure

The procedure for product judgment started with the definition of the PRODUCT. Here, the evaluation involves all design descriptions collected from the pre-intervention and post-intervention phases. The tasks solved during the intervention phase are only regarded as practice tasks. At the end of both phases, after the protocol session ended, students gave written descriptions about the designed artefacts. The descriptions were transcribed for clarity. These descriptions were the products we were referring to. The diagrams that the participants sketched (if any) were included but left as they were. These product descriptions were identified with unique code names, for instance:

"B(ost)9".

The above code shows the descriptions' unique identification number. The first letter in the code indicates the task (e.g.,: B is for Task B). The letters in brackets indicate the phase when the invention takes place [either pre (re) or post-intervention (ost)]. The last number refers to the participant identity (e.g.,: 9 means participant P9).

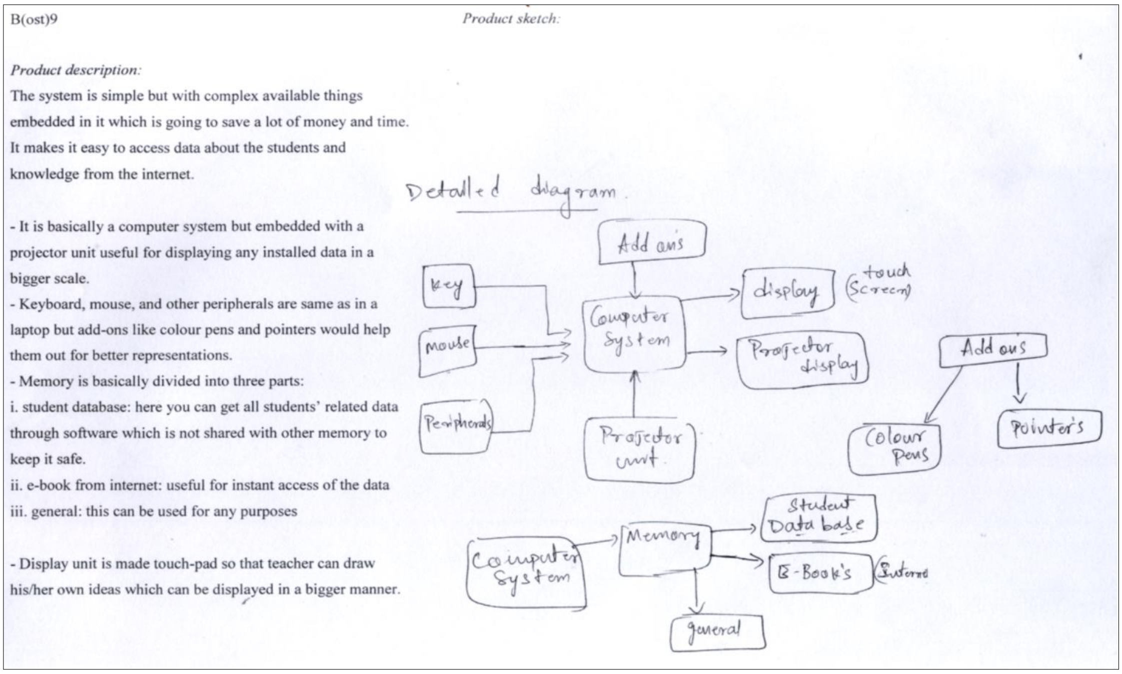


Figure 3. 7: A Sample of a Product Description (more samples in the Appendix section)

Next, we explain the JUDGE. The judges were experienced designers or university lecturers who have been in the field for more than seven years. The judges were compensated with GBP £ 20.00 after we advertised about the study in the job vacancy section in the University of Sussex website. Judges for Experiment 1 were different from those who judged the design outputs for Experiment 2. They were inexperienced in terms of research design as well as the condition under which specific tasks were given, so that there would be no room for biasness in judging.

MATERIAL and PROCEDURE for the product judgment are as follows. The reliability test was conducted to check the reliability and validity of the Judgment Materials. There were two methods of judging, and we chose only the method with the better reliability score as shown below.

Table 3. 7: The Judging Techniques, Procedure and Outcomes

Judgment technique	**Judges**	**Judging Material**	**Procedure and Reliability Measures**
Classifying (not reliable)	1. Senior Production Engineer 2. Senior Lecturer/ Ph.D students in Electrical Engineering, Univ. of Sussex	FOR EXPERIMENT 1: (i) 9 FDI participants + 7 CPS participants x two phases = 32 products written descriptions from all participants. (ii) Instruction to the Judges (iii) The Judging Scheme (iv) A form to be filled after the judgement. (v) 4 empty boxes to put the products. Each box represents product level of originality/ appropriateness (level 1/2/3/4)	PROCEDURE: (i) Read the supplemented descriptions. (ii) Classify products into separate four piles first according to the originality criteria and later the appropriateness criteria. RELIABILITY: Agreement between judges is **low, therefore judgment was not taken as data.** Pearson's correlation coefficient *r* Originality (pre): *r* = .101 Sig: .337 Appropriateness (pre): *r* = -.159. Sig .251 Originality (post): *r* = .310 Sig: .091 **Appropriateness (post):** ***r* = .411* Sig:.036**

Judgment technique	Judges	Judging Material	Procedure and Reliability Measures
Rank-Ordering Method (reliable)	1. Engineer 2. Senior Lecturer/Ph.D students in Electrical Engineering, Univ. of Sussex	FOR EXPERIMENT 1: (i) 9 FDI participants + 7 CPS participants x two phases = 32 products written descriptions from all participants. (ii) Instructions to the Judges (iii) The Judging Scheme (iv) A form to be filled after the judgement.	PROCEDURE: (i) Read the supplemented descriptions. (ii) Rank order all the products from the top to the bottom rank to avoid any sharing rank. RELIABILITY: Agreement between judges is **positive and with significant, high correlation in post-intervention scores:** Pearson's correlation coefficient *r* Originality (pre): *r* = .331 Sig.: 077 Appropriateness (pre): *r* = 050. Sig: 417 **Originality (post):** ***r* = 498* Sig: .013** **Appropriateness (post):** ***r* = 548** Sig: .006**
Rank-Ordering Method (reliable)	1. Senior Engineer . Senior Lecturer/Ph.D student in Electrical Engineering, Univ. of Sussex	FOR EXPERIMENT 2: (i) 9 FDII participants + 7 CPS participants x two phases = 32 products written descriptions from all participants. (ii) Instruction to the Judges (iii) The Judging Scheme (iv) A pro-forma to be filled after the judgement.	PROCEDURE: (i) Read the supplemented descriptions/sketches. (ii) Rank order all the products from the top to the bottom rank to avoid any sharing rank. RELIABILITY: Pearson's correlation coefficient *r* **positive, with significant, medium correlation.** **Originality (pre):** ***r* = .360* Sig: .025** **Appropriateness (pre):** ***r* = app.346* Sig: .030** **Originality (post):** ***r* = ori.311* Sig: .047** **Appropriateness (post):** ***r* = .244 Sig: .097**

*Correlation is significant at the 0.05 level (1-tailed).**Correlation is significant at the 0.01 level (1-tailed).

The table above shows that the Rank-Ordering Judging Method is better than the Classifying Method. Therefore, the product analyses were taken from the more reliable method, that is the Rank-Ordering Method for both Experiments 1 and 2.

Further, based on the literature reviewed, there were two criteria of creativity included in our judging procedures, namely Originality and Appropriateness. There was a negative correlation between the originality and appropriateness scores, with the overall $r = -0.40$ ($p = .005$, 1-tailed). This indicated there was a negative relationship between originality and appropriateness in terms of the judgements of inventiveness scores. Negative correlations indicate an increase or decrease in originality, correlates negatively, or gives opposite connotations as far as the appropriateness score is concerned. Originality and appropriateness, thus, are not redundant measures, indicating they measure different dimensions of creativity.

Basically, the ORIGINALITY criterion looked into the product novelty and attractiveness. On the other hand, the APPROPRIATENESS criterion looked into the product's feasibility and practicality. Since there was no perfect negative correlation, i.e., $r = -1.0$, we totalled up both criteria to get "The Total Inventiveness Score". Some other studies indicated a degree of overlap between originality and appropriateness in the electronics design (Amabile, 1983; Ullman, 1997). Then, considering the opinions from both judges, all the scores from the two judges were added up according to the experimental phases (pre- or post-intervention). The results from both judges would be more representative than using only a set of data from either of the judge.

This is the end of the procedure for the product judgment analysis. The actual participants' performance will be discussed in the Results Chapters.

3.6.2 Data Analyses Procedure for Cognitive Processes: Protocol Segmenting and Coding

Participants' verbal protocols were obtained and recorded using the 'think aloud' technique (Ericsson & Simon, 1993). There were a few steps to be taken before the transcribed protocols can be coded as data.

This section presents the segmentation processes according to certain units of aggregations that were adequate for the kind of analyses adopted in this study. Then the protocol coding procedure conducted upon the segmented protocols will follow.

3.6.2.1 The Segmentation Procedure

The goal of the segmentation procedure was to chunk the protocols into statements that conveyed a single thought, expression, or idea (Ericsson & Simon, 1984). The segmented protocols represent units of a single thought. The unit is then individually coded. This procedure enables a more systematic and in-depth screening of the thinking processes. There are, however, different approaches of individuating or parsing the protocols, through the 'content-based' segmentation; and the 'activity-based' segmentation (Goel & Pirolli, 1992). The current work used both ways of demarcating statements and applied whichever one provided the finer-grained individuation. Examples of content-based segmentation are when there are shifts in a topic or introduction of a new idea. Also, a lot of the protocols are connected ideas, but there are changes in terms of the level of abstraction, from a general principle to a concrete example, or from a concrete example to a more general principle. These levels are each considered as an individual ~~statements~~. Similarly, when one switches perspective, this new perspective can be separated into another individual segment. On the other hand, the activity-based segmentations use non-content cues such as pauses, phrases and sentence boundaries, and the making and breaking of contact between pen and paper. This was also observed during our segmentation procedure, only if the pauses were too long.

3.6.2.2 The Coding Procedure

The coding is adopted from previous studies in design, partly based on the one Goel & Pirolli (1992) had used. However, since we are looking at function versus non-function aspects of design development while observing how function-space search affects other aspects of design development, there were a few changes made. The coding in Goel and Pirolli (1992) was divided into four levels which were: (i) the general design activity *(experimental task statements, monitoring statements, design development, problem structuring and problem solving, miscellaneous)*; (ii) the problem solving steps *(problem operator, content, written/sketch mode, source)*; (iii) aspects of design development *(function, behaviour, structure, people, purpose and resources)*; (iv) modules and submodules aggregation of data dependent on the particular design tasks and the particular individual solving the task.

The difference between Goel and Pirolli's coding and this study's coding was in terms of the scopes of coding, which was meant to find different answers for the research at hand. The current study did not ask about the whole nature of the design process. We regarded the coding for **aspects of design developments** only (number (iii) in Goel and Pirolli's coding system) as the most important coding that can answer our research questions. This was because we were looking at function versus non-function aspects of design development while observing how the function-space search affected other aspects of design development. The rest of other codes are treated as 'miscellaneous'.

The special Coding Scheme was developed for coding processes. Simply put, we conducted the coding processes in the following steps:

EXPERIMENT 1 and 2:

(i) coding the aspects of the design development; and then

(ii) re-coding the transitions between these aspects of design development, using Microsoft Excel Software.

CASE STUDY:

(iii) depiction of the representational change using conceptual maps;

(iv) re-coding the coded function statements to find the different instances of function and indicate the operators of the functional search, using NVIVO12. Software. An in-depth explanation of this will be covered in Chapter 7.

The first pass of coding was straightforward. The second pass of coding for transitions between statements, however, was different. Each is explained next.

3.6.2.2.1 Definitions and Procedure for the Coding

The content codes were divided into six major aspects of the design development, while the rest of other ideas, which did not fall under design elements, were coded as 'miscellaneous.' The following elucidates what design elements are in general as compared to the non-design elements.

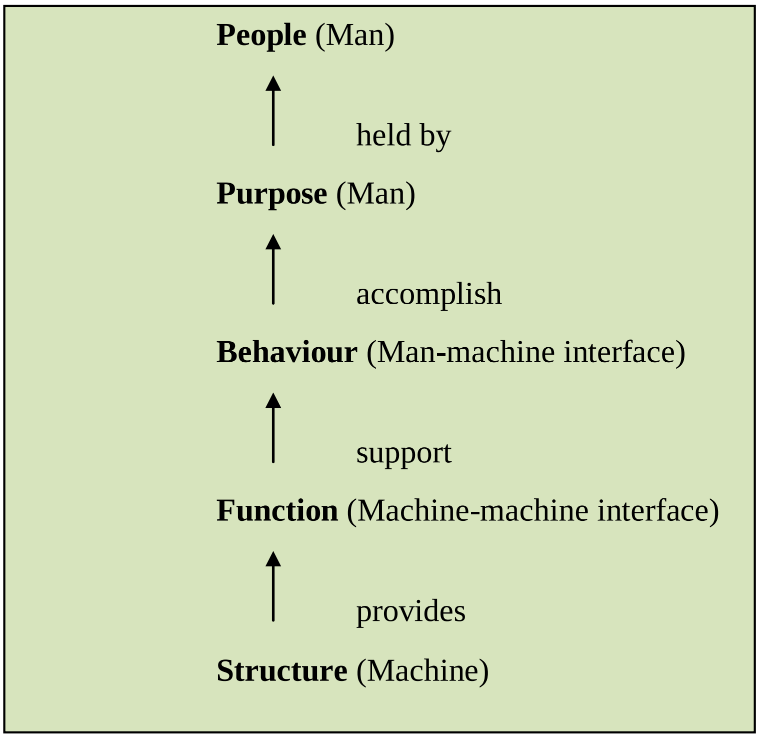


Figure 3. 8: Aspects of design development (adapted from Goel, 1995 p.242)

The aspects of the design development are desired, potential or actual ideas that constitute a design or invention. It helps characterise the device. The other coding, apart from the above, is called non-design statements. Non-design elements are normally used for supporting design ideas. They are not about the device features and do not directly lead to the decision-making process. Coded as ‘miscellaneous’ for the purpose of analysing the protocols of this research, non-design elements involve statements about facts or supporting evidence for proposing an idea. These statements do not contribute to making design decisions but are mentioned for the purpose of clarity of one’s explanation of ideas (e.g.: comparing the current status of technology). As a test for the non-design elements, facts and evidences do not change as ideas change. Facts are not necessarily mentioned during conceptualisation of an invention. Examples are as follows:

> “…room temperature will be different and human body will be different.”
>
> “People will come and lock and unlock it.”
>
> “Nowadays, what we are using in the car is just like direct frequency which can be easily tracked by the thief.”
>
> “I cannot listen to the person and to the radio at the same time right?”
>
> “What should I do to turn on and what should I do to turn off the music?”

Designers often criticise the current idea by specifying which behaviour is undesirable and that leads to what is desirable for the potential device. In the following example, the phrase "immediately cannot phone and contact the police" would fall under a 'behaviour' statement. However, a closer look reveals that the sentence is not a design idea, but it is considered a fact used for arguing over an idea. Thus, it is not an accepted idea for constructing the intended device. The sentence came from this segment: *"…but people cannot anything..like they cannot…Hm..it is not fast….they can only be aware of it but immediately it cannot phone and contact the police…"*

Table 3. 8: The Definition of the Aspects of Design Development
(full version attached in the thesis' Appendix)

Definition	Example
Function codes are statements that have to do with the desired, potential, or actual functionality of the artefacts. It involves machine-to-machine interfaces. In other words, the input/output/flow of device operations are functional statements.	*"from microprocessor, it can give to a control-like thing."*
Behaviour statements specify the behaviour the artefact is supposed to encourage and support. It involves changes of object moving in space over time or change in properties. It differs from function codes in that it identifies the point at which the user interacts with a machine or equipment being used, a man-machine interface. It involves physical/observable behaviour of the device as a ~~results~~ of human contact, without saying how this can happen. Designer uses behaviour statements to imagine the desirable machine's physical works. Behaviour statements also ~~includes~~ the limitations put by the designer as a consequence of having to specify which behaviour of interest.	*"as the alarm start, the owner of the house will know easily."* *"in radio mode, I cannot make calls"*
Structure statements have to do with the desired, potential, or actual form of the artefact. For example, *"It has only one number pad"* and "*we just need to introduce a button"* are structure statements. A generic component like "speaker", "earphones", and "laptop" are object-oriented and therefore, considered as structure statements. Structure concerns the form, size, shape and materials of artefacts.	*"the material should be light and soft"*
Purpose statements deal with the motives, intentions, and goals of the users.	*"And the advantage of this is there is very less chance of false alarm."*
People statements deal with the users of the artefact. It is to answer the question of "who are our clients?"	*"That will be very helpful for teachers."*
Resource statements consider resources, such as time, money, and people even though the statements do not specify the exact amount in numbers. It should just state the consideration of some relevant factors and how far these factors are taken into account.	*"To reduce cost and power consumption."*

The above definitions were used after they had been checked for reliability. The reliability of the coding scheme was tested by having an external coder (a PhD candidate from the School of Education, University of Sussex, and another from the School of Engineering and Informatics) to code sample of the protocols. The agreement between the external coder and the experimenter's code was high (87.5%).

The following table (the second column from the right) shows the sample of our coded data (the first pass of coding). The second pass of coding will be explained next.

Table 3. 9: The sample of the coding procedure conducted (Participant 8, Pre-Intervention Phase, task given was 'invent a tool a schoolteacher might use')

SEGMENT NO.	SEGMENTED PROTOCOLS	CODING DONE	First pass of analysis	Second pass of analysis
			Count the raw code	Count the transition
7	E: You have been rather quiet.	Exp	F= 1 B=0 St=1 Pe=1 Pu=1 Re=0 M= 3 occurences	Exp
8	P8: I am trying to find something useful, and meaningful.	M		M
9	E: Whatever comes up in your mind can be shared with others.	Exp		Exp
10	P8: I teach myself. And the biggest problem for me is marking the papers.	Pe		Pe
11	P8: So if I can make something to mark papers that will be really good.	Pu		Pu
12	P8: Does it have to be a very precise design or just a general one?	M		M
13	E: Make it as precise as you can.	Exp		Exp
14	P8: I was trying to think of a better idea. Otherwise I would just stick to my first idea to design a machine which could mark papers……………………..	Fu		Fu
15	P8: If it is a machine which would mark papers..	M		M
16	E: Keep talking	Exp		Exp
17	P8: If it is a machine to mark papers, presumably like a photocopy machine,	St		St

Note: St: Structure. Fu: Function. Pu: Purpose. Pe: People. Re: Resource. M: Miscellaneous. E: Experimenter. P8: Participant 8. Experimenter's statements were skipped during the analyses.

3.6.2.2.2 Procedure for the Coding Transition Analysis (The second pass coding)

The design process involves search of an iterative and non-logical nature. Research has shown that intra-representational change is another distinct characteristics of creativity (Karmiloff-Smith, 1990). The purposes for conducting the quantitative analysis of the transitions are: (i) to quantify the kinds and rate of recurrences of each kind of transition; and (ii) to explore whether participants stayed in a particular space most of the time during their search.

Fricke (1996) demonstrated that problem solving moves along the transition of flexible-methodical proceeding (with transition between similar design operators). The transition analysis in that study showed that there exists unreasonable methodical (illogical transition of design operators), and the mediocre method users who were not following the methodical guidelines properly (based on results that show no transition between any design operators). In the same vein, Sung and Kelley (2019) used transition analysis to depict the interaction between the different methods for design modelling, questioning, predicting, and designing during problem solving in design. Therefore, the transition analysis between the specific representations or methods could tell a different story as compared to just the descriptions of those representations and methods.

Sung and Kelley (2019) and Fricke (1996) are examples of two studies about problem solving which use transition analyses as an analysis method. In their studies, only limited sets of pre-defined transitions over a range of selected time intervals are counted. However, for the current analysis, we conducted thorough the transition analysis from the start of the problem solving session to its completion. The analysis of the transition between spaces is also an analysis approach for depicting the change of representations in Obaidellah (2012). In the study, the transition rates showed how the movements of the GPA pen is restricted towards adjacent chunks of the same grouping of the Rey-figure drawing which composed of a few sub-groups of the chunks such as the ‘fish chunk’ fin and gill, and the boxes and lines for the ‘shape chunk’. The analysis allows the identification of the chunks (represented by groups of stimuli) with hierarchical properties.

The Table 3.9 (see the last column to the right of ‘Second-pass Analysis, count of transition’) shows the coding for the transition analysis that we conducted.

The first-pass coding revealed which statements were used by the participants in either conditions (FDI or CPS). They did not, however, uncover the way participants processed all the information or how they ‘linked-up’ the invention aspects during the problem solving session. There was a need to look into the processes of transitions between the statements, where the flow of information can be characterised. This was possible by quantifying the successive moves made in the search based on the participants’ verbal protocols. As shown in the table, the same segmented protocols which were assigned with the above aspects during the first-pass coding were the source of this transition data. Therefore, there was no possibility of missing any kind of search during problem solving.

The transition analyses to characterise the search processes using protocols were justifiably thorough and exhaustive. They not only provided the raw data on the kinds and amounts of search. These protocols are verbatim; the actual flow of the search can be captured based on their verbalisations. The calculation of transitions is supported with the use of Microsoft Word Excel software as follows.

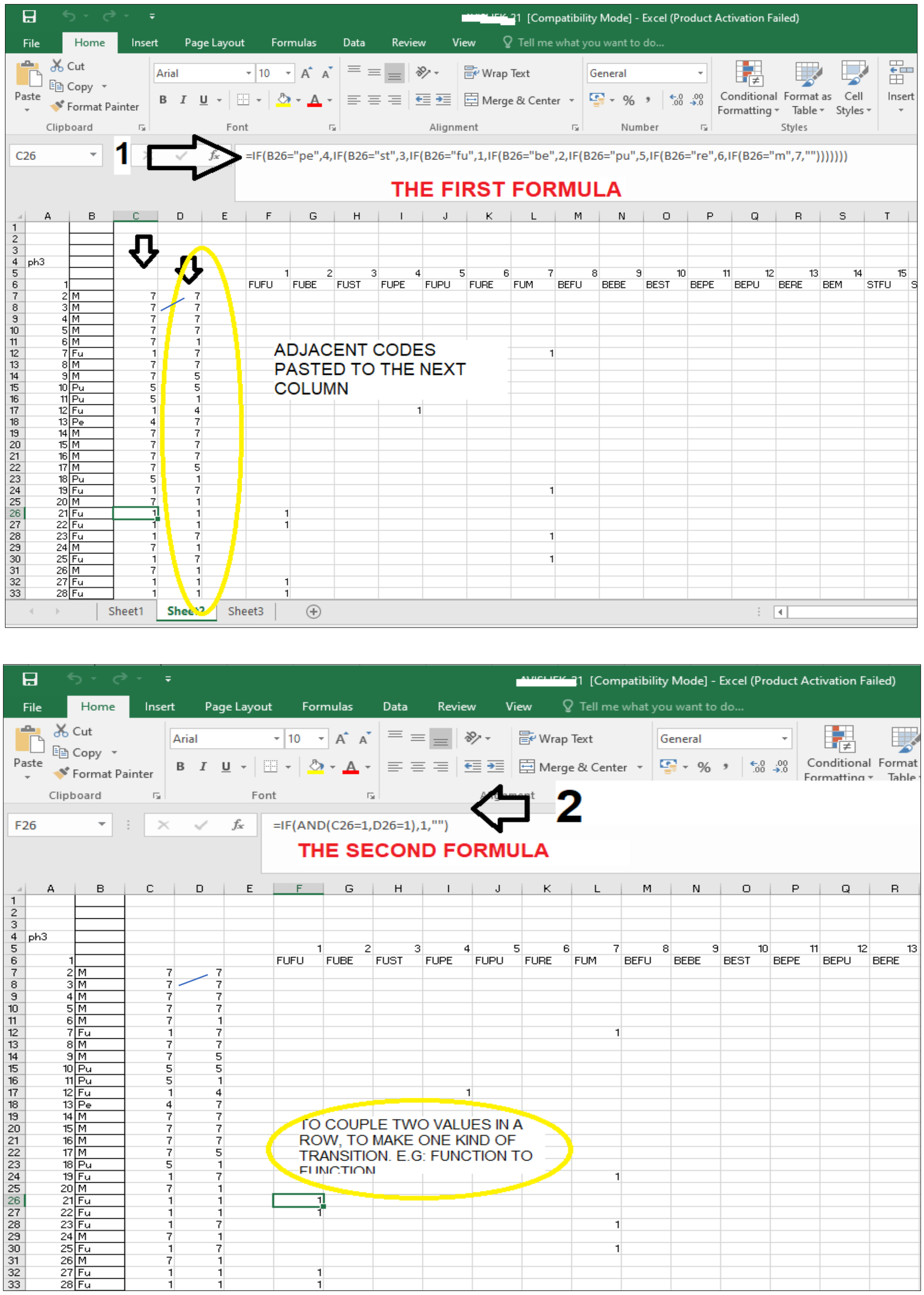


Figure 3. 9: The use of Microsoft Excel software to support the transition analysis (Formula 1 and 2).

Finally, the coding for the qualitative study will be explained in Chapter 7, together with the results of the qualitative analyses.

3.7 Chapter Conclusion

This chapter has presented the administration of three separate studies to answer the research questions under investigation. A mixed method was used whereby both quantitative experimental method and qualitative Case Study method were combined to produce patterns out of the data in a scientific manner. The experimental method objectively infers processes from the heeded protocols. Reliability and validity checks were conducted. Non-parametric statistics assume that data are not normally distributed, therefore continuous data such as ours yield less generalizable results. The qualitative study, in part, explored the meanings and interaction between the concepts heeded in the protocols rather than only the quantity of occurrences of concepts.

CHAPTER 4

Results 1: Before the Intervention

4.1 Introduction

The first objective of the research is to identify whether design students naturally use functional decomposition during the inventive problem solving before the ‘FDI’, ‘FDII’ and ‘CPS’ (the comparison group) interventions. In this chapter, the processes of problem solving in terms of the utterance of design aspects (function, behaviour, structure, people, purpose, resource) that are coded were quantitatively analysed. The second process which is the analysis of transition between the design aspects will follow. The final analysis is on the ratings of their products according to the external judges. The interim discussion and conclusion will close the chapter.

4.2 What is the amount of ‘function’ search before the FDI, FDII and CPS interventions?

There exists one commonality across participants in terms of the kinds of design elements that they considered before the interventions were given. As shown in the following table, the ‘function’, ‘structure’ and ‘purpose’ were the most important aspects to the participants identified from the raw data.

Table 4. 1: Participants' overall scores on the aspects of design development (the highest 3 percentages, are written in bold).

Aspects of Design Development	Grand Median (%) (FDI, FDII and CPS combined)
Function	**24.14**
Behaviour	3.7
Structure	**13.64**
People	5.55
Purpose	**13.95**
Resource	0
Miscellaneous	23.08

Note that since participants' verbosity is different from person to person, all kinds of aspects in raw data are first converted to percentages of utterance (i.e.: 100% is the overall individual protocol), before we use them as data.

Based on the above table, it can be concluded that during the conceptual phase of design, the aspects of 'function' (*Md*=24.14) was already the highest aspect uttered by all the participants before the intervention. The class of functionality and nature of how the function aspect is being explored is, however, not known until we conduct the qualitative analysis. The second highest design aspect considered was 'purpose' (*Md*=13.95) and followed closely by the 'structure' aspect with a Median score of 13.64. The 'function', 'purpose' and 'structure' aspects were the most useful kinds of information to project a specific design concept based on the analysis. The miscellaneous aspect is a general non-design aspect; it will not be analysed in the upcoming statistical tests.

Next, the descriptive analyses were conducted to identify the amounts of function search in the FDI, FDII and CPS group before the intervention. The descriptive data is shown in the figure below.

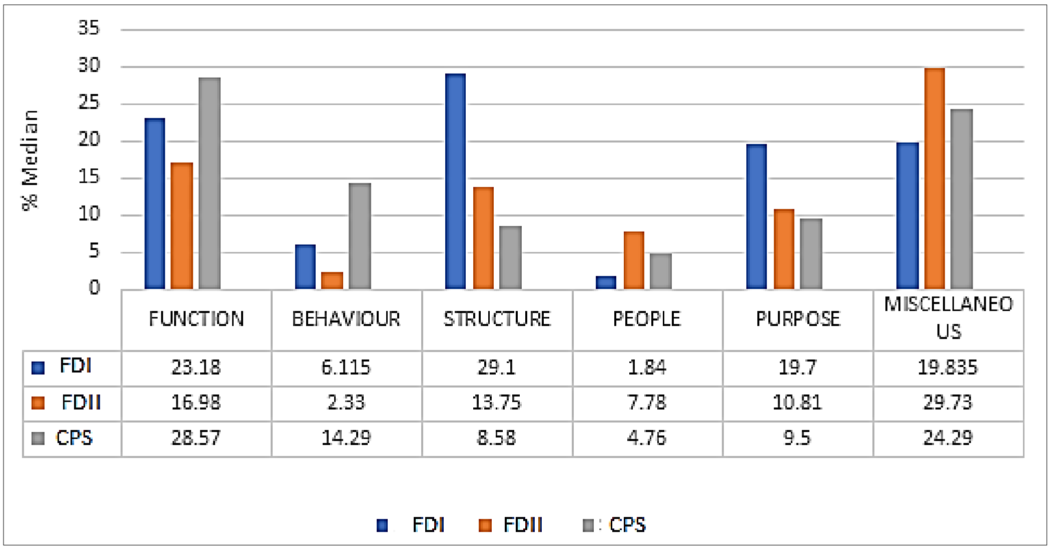


Figure 4. 1: The aspects of design development during the Pre-Intervention Phase (all groups)

A Kruskal Wallis test was conducted, and the results show that there was no significant difference between the three groups. The Chi Square value is shown in the following table.

Table 4. 2: The Results of the Kruskal Wallis Test to Measure All-Group Difference in terms of Design Aspects Uttered During the Pre-Intervention Phase

Design Aspects -->	FUNCTION	BEHAVIOUR	STRUCTURE	PEOPLE	PURPOSE	RESOURCE
Chi Square	1.495	10.251	5.467	2.084	.260	.815
Asymp. Sig.	.474	.006	.065	.353	.878	.665

In conclusion, the participants could be largely considered as holding similar characteristics at the start. In addition, the use of the function aspect of design at a high degree has been found across all groups even before the training. This will be discussed at the end of this chapter.

4.3 What are the interactions that exist between all the main design aspects before the FDI, FDII and CPS interventions?

This section presents the findings on the second process analysis with respect to the interaction between the six main design aspects. As already explained in the Procedure for Data Analysis section in Chapter 3, the Microsoft Excel software was used to calculate the segment-to-segment transitions. This was conducted during the second pass of the coding process on the same protocol transcripts. For the descriptive analysis, the transitions between all aspects are presented in the following matrices that represent each group separately. This is shown in the table below.

Table 4. 3: The Pre-Intervention Transitions between all Design Aspects

FDI

	F	B	S	PE	PU	RE
F	7.14	1.75	-	-	1.89	-
B	-	1.75	-	-	-	-
S	3.57	-	4.76	-	1.79	-
PE	-	-	-	-	-	-
PU	1.89	-	1.79	-	1.67	-
RE	-	-	-	-	-	-

FDII

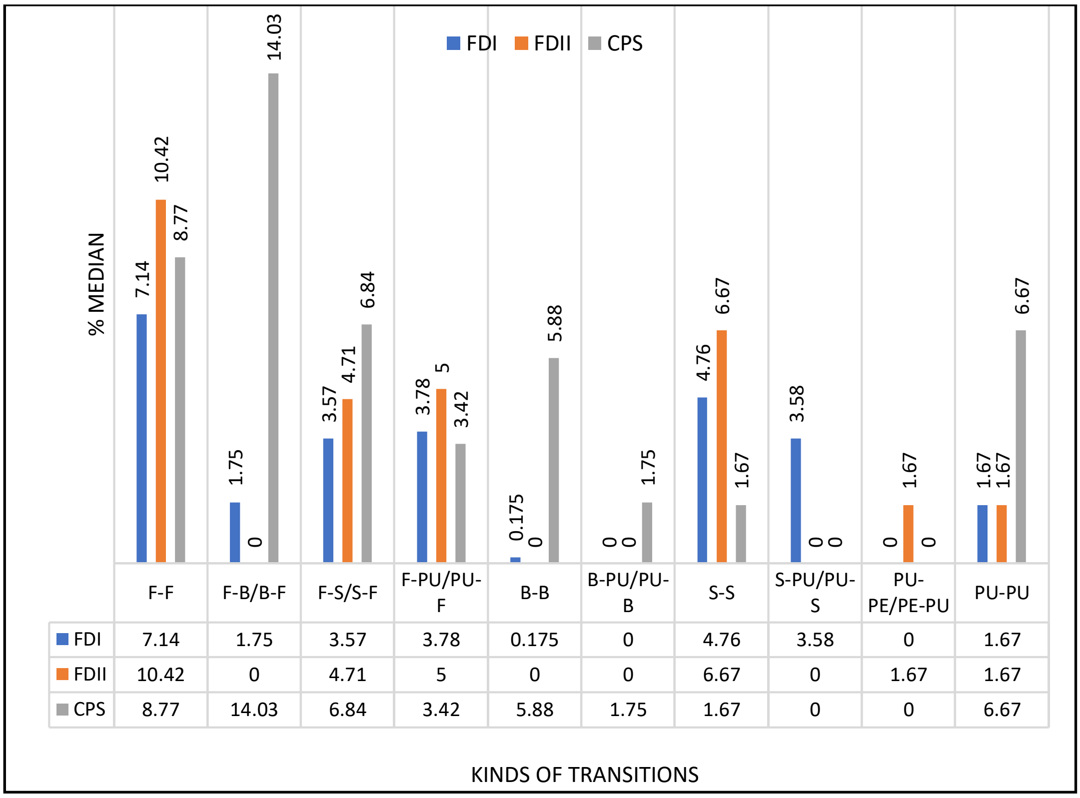
	F	B	S	PE	PU	RE
F	10.42	-	2.08	-	3.33	-
B	-	-	-	-	-	-
S	2.63	-	6.67	-	-	-
PE	-	-	1.67	1.67	-	-
PU	1.67	-	-	1.67	1.67	-
RE	-	-	-	-	-	-

CPS

	F	B	S	PE	PU	RE
F	8.77	8.77	3.33	-	1.75	-
B	5.26	5.88	-	-	1.75	-
S	3.51	1.67	1.67	-	-	-
PE	-	-	-	-	-	-
PU	1.67	-	-	-	6.67	-
RE	-	-	-	-	-	-

- Note: F=function, B=behaviour, S=structure, PE=people, PU=purpose, RE=resource.

The next figure is the histogram which shows the bi-directional transitions (involving two interchangeably same spaces) that were summed together. As mentioned earlier there were 36 possible transitions (6 aspects X 6 aspects) but here, only the major transitions were included in the following diagram.



	F-F	F-B/B-F	F-S/S-F	F-PU/PU-F	B-B	B-PU/PU-B	S-S	S-PU/PU-S	PU-PE/PE-PU	PU-PU
FDI	7.14	1.75	3.57	3.78	0.175	0	4.76	3.58	0	1.67
FDII	10.42	0	4.71	5	0	0	6.67	0	1.67	1.67
CPS	8.77	14.03	6.84	3.42	5.88	1.75	1.67	0	0	6.67

Figure 4. 2: Collapsed data of transitions in all groups.

In addition, the bi-directional transitions to and from the same aspects of design are collapsed together. For example, the function-to-behaviour and behaviour-to-function transitions are combined as a single score because the transitions involve similar design aspects, and to simplify the analysis.

From the histogram, it is shown that there are only 10 major transitions out of the 36 possible transitions between all design aspects. The approach to collapse the transitions to- and from the same design aspect is reasonable considering the analysis only interprets the kinds and rates transitions, regardless of which representation should come first along a problem solving episode. The transitions with the highest rate of occurrences are depicted in the following diagram.

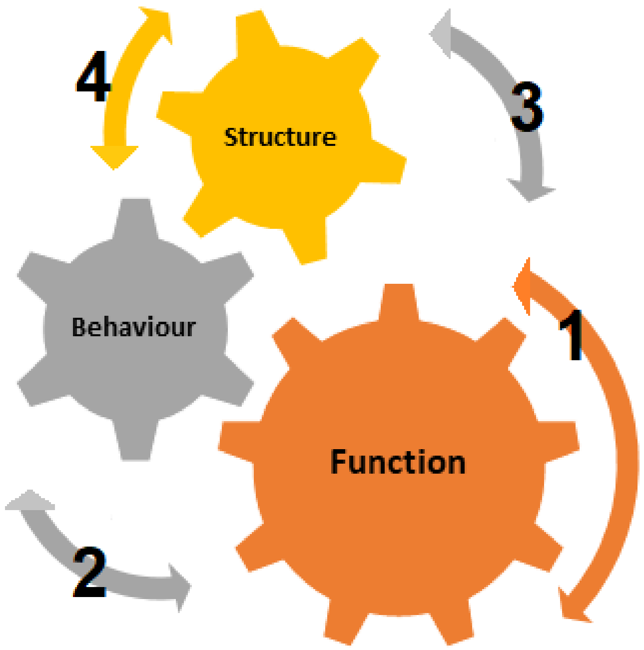


Figure 4. 3: The main transitions (function-to-function is the biggest transition), followed by function-to-behaviour and the rest, by ascending order.

There is a high (1) function-to-function transition, where the average across groups is (M=8.78). This is followed by (2) function-to-behaviour transition and vice versa (M=5.26). The third is function-to-structure transition (number 3) and vice versa (M=5.04), and lastly (number 4) is the structure-to-structure transitions with an average of 4.39.

Table 4. 4: The Results of the Product Judgment by External Judges

PARTICIPANTS		PRE-INTERVENTION SCORES				
		JUDGE 1 ORI	JUDGE 1 APP	JUDGE 2 ORI	JUDGE 2 APP	TOTAL INVENTIVENESS –TASK SOLVED
FDI	P1	13	9	15	2	**39-A**
	P3	13	2	10	10	**35-C**
	P4	15	15	2	11	**43-B**
	P5	9	14	3	5	**31-B**
	P6	16	14	9	4	**43-C**
	P7	11	8	13	8	**40-A**
	P8	14	9	8	1	**39-B**
	P9	17	16	13	15	**61-C**
	P10	7	6	6	13	**32-B**
CPS	P11	6	6	8	14	**34-A**
	P12	10	1	7	3	**21-C**
	P13	9	7	14	1	**31-A**
	P14	6	10	4	8	**28-B**
	P15	7	6	1	7	**21-C**
	P16	7	14	12	7	**40-A**
	P17	10	13	9	12	**44-B**
FDII	P21	2	9	3	18	**32-C**
	P22	12	16	6	4	**38-A**
	P23	12	11	10	14	**47-B**
	P24	12	12	17	11	**52-C**
	P25	3	2	11	6	**22-A**
	P26	3	12	13	9	**37-B**
	P27	14	13	18	12	**57-C**
	P28	10	3	1	5	**19-A**
	P29	1	5	1	6	**13-B**

*Notes: Highlighted in yellow are the best inventors.

The tasks assigned to the participants are shown on the right-most column in the table above. Based on the table above, there are potential students who could design original and appropriate products based on the judges' evaluation. The group-difference analysis needs to be conducted to see whether the participants of a particular group generally scores better ranks than the other groups, or whether certain groups always score the lowest.

To measure whether the groups are statistically similar before the interventions were given, the Kruskal Wallis test was conducted using the SPSS Software. The results are as follows.

Table 4. 5: The Kruskal Wallis test on the Difference between All Groups

	ORIGINALITY	APPROPRIATENES	TOTAL
Chi-square	2.855	.792	1.968
Asymp. Sig.	.240	.673	.374

In short, it is shown that there is no difference between the three groups before the interventions in terms of their inventiveness.

4.4 Interim Discussion and Conclusion

This chapter is directed towards finding out who the participants are in terms of the usage of FD and the ability to create original and appropriate products. It is found that the participants had used a lot of the function search and there is no quantitative difference across all groups with regards to the usage of function. Second, there is also no difference in terms of transitions between the design aspects. Ten kinds of transitions are found to be conducted while only four transitions are reported as being used at a greater rate by all the participants. The statistical analyses showed that they did not differ in terms of transitions before the interventions were given. Third, the results on the product judgment also showed that a few participants were capable of designing inventive products. The rest of the participants' abilities were judged to be ranging from between moderately inventive to less inventive. The statistical analyses conducted showed that the participants did not differ because there was no clear trend for the high rankings in a particular group. This means further interventions can be helpful for some who did not appear to be inventive during the pre-intervention phase.

According to the coding process we conducted, function cannot be justified just by looking at quantitative scores. This is because some functions could be mere repetitions or reiterations of the same concept, despite being high in numerical values. Therefore, qualitative analyses are needed to see how functional decomposition is actually used as a design method.

The Judging Method left the judgment totally to the Judges' experience since there is no template or rubric for how an invention should look like. The rank-ordering method indicates that their products are being rank-ordered according to the individual Tasks and are being compared against each other but not against any ideal rubric.

The general criteria for being novel, practical and useful can be subjectively perceived by the judges. However, the selection of our judges plays a big role in the success of our product evaluation, and that is proven to be effective. It is found both judges have similar background knowledge in the design field and that they agreed with each other as explained in the Pearson Correlation statistics reported in Chapter 3.

The next chapter should see whether the FDI training could affect the participants in terms of the processes of finding solutions by recalling functions and to see whether there is a change in how the search transits from one design aspect to another. The experiment will also shed light on whether the FDI training could improve the students' product inventiveness.

CHAPTER 5

Results 2: After the FDI Intervention

5.1 Introduction

The second objective of the research is to measure the degree of change in the process of inventive problem solving~~,~~ and change in terms of inventiveness of the products after the ‘FDI’ intervention, as compared to the other training method (CPS). In this chapter, similar with the flow of the results reported in Chapter 4, the processes of problem solving in terms of the participants’ utterances regarding the design aspects (function, behaviour, structure, people, purpose, and resource) that are coded were quantitatively analysed. The second process, which is the analysis of the transition between the design aspects, will follow. The final analysis is on the ratings of their products according to the external judges. All results are reported with regards to the FDI group against the same group’s pre-intervention phase, as well as against another group trained with the CPS method. The interim discussion and conclusion will close the chapter.

5.2 What is the amount of ‘function’ search after the FDI intervention?

Descriptive analyses were conducted to measure, firstly, the between-group change (FDI ‘versus’ CPS), and then, the within-group change (FDI, pre-intervention ‘versus’ post-intervention) on the effects of the interventions.

The following figures show the number of the kinds of aspects uttered by the experimental and the control group participants during the pre- and post-intervention phases. The experimental groups’ histogram shows a lot of ‘structure’ (Md = 28.57) statements during the pre-intervention phase.

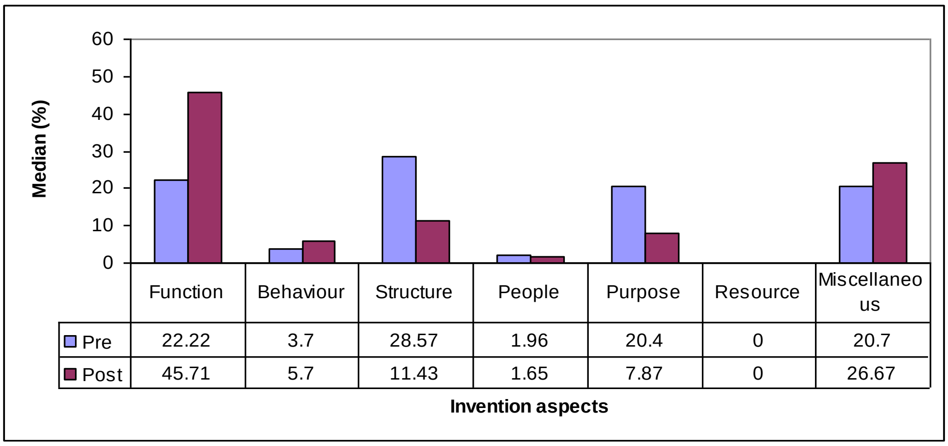


Figure 5. 1: The aspects of the design development considered by the experimental group (FDI group)

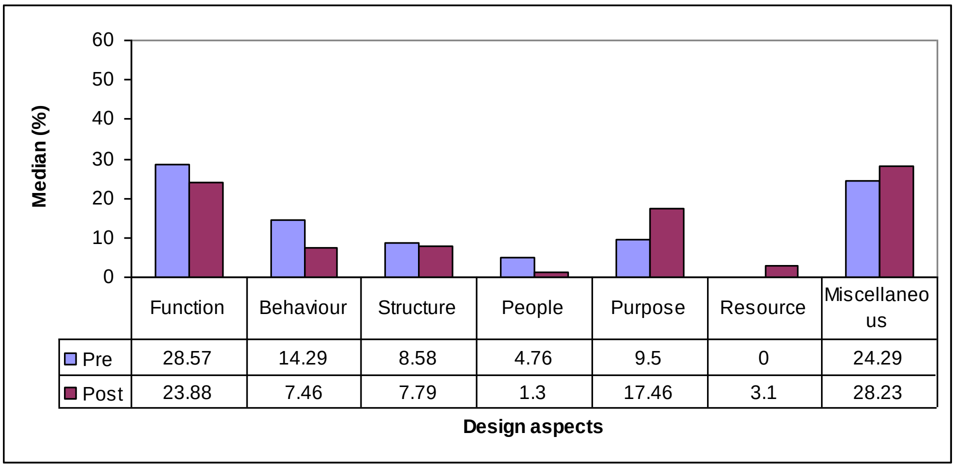


Figure 5. 2: The aspects of the design development considered by the comparison group (CPS group)

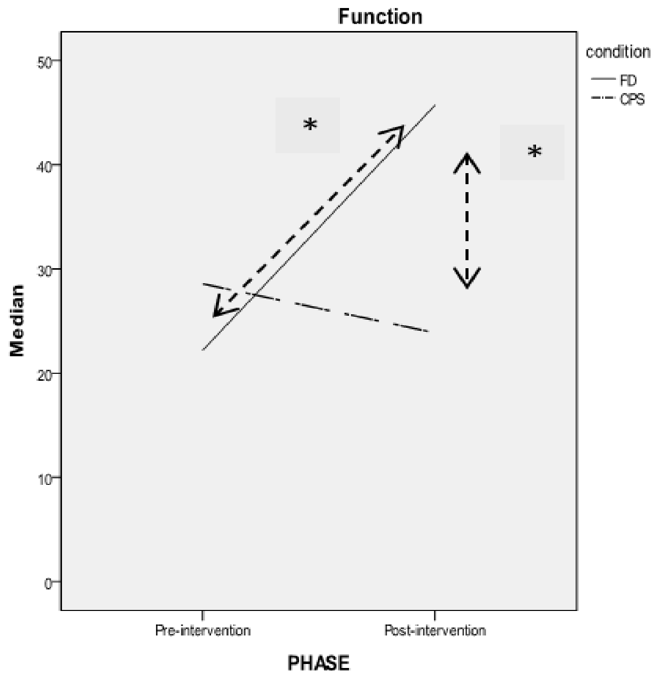
The comparison group, on the other hand, used a lot of 'function' statements (*Md* = 28.57) before the training.

The interventions caused an adverse effect to the participants of different groups. After the intervention, the median value of 'structure' statements used by the FDI group in the post-intervention phase dropped to only *Md*=11.43, but the 'function' statements had increased significantly (*Md* =45.71).

Contradictorily, the CPS group's utterance of 'function' and 'structure' aspects had decreased after the intervention. The two groups were also different, at the descriptive level, in the use of the 'purpose' aspects from the effect of the trainings.

A Mann-Whitney U Test was conducted to investigate whether the two groups were similar after the intervention. After the intervention, only the use of 'function' statements by these two groups was found to be significantly different. No other aspects changed.

The FDI group used more ‘function’ statements (*Md* =45.71) than the CPS group (*Md* =23.88), U = 12, *z* -2.064, p = .042, *r* = .0.52. The FDI training had caused an increase in the utterance of the ‘function’ aspect, and this is statistically significant, compared to the CPS training.



* Significant at alpha .05

Figure 5. 3: The within- and between-group change of the ‘function’ aspect of the design development

On the contrary, the CPS group did not show any significant change with respect to the use of all the aspects even though there is a slight drop in the use of the ‘function’ aspect search as shown in the line graph. This means that the CPS training has not had any effect on their search strategy.

The test results also show that apart from the between-group change after the interventions, there is also a significant pre- to post-intervention change within the FDI group over time. A Wilcoxon Signed Rank Test result revealed a statistically significant increase in the utterances of ‘function’ aspects following the participation in the FDI training, *z* = -2.666, p = .002 with a large effect size (*r* = .63). The median utterance of the ‘function’ aspect increased from pre-intervention (*Md* = 21.11) to post-intervention

(*Md* = 45.71). In addition, over time, the reduction in the use of 'structure' statements within the FDI group was not significant, z = -1.362, p = .102, (*Md* = 28.57 to *Md* = 11.43). The decrease of the 'purpose' aspect in the later phase is, however, statistically significant, z = -2.547, p = .004, with a large effect size (r = .60) among the FDI participants.

Furthermore, the CPS training had not had any significant impact on the participants, even though there was an increase in the use of 'purpose' statements as shown in the following graph.

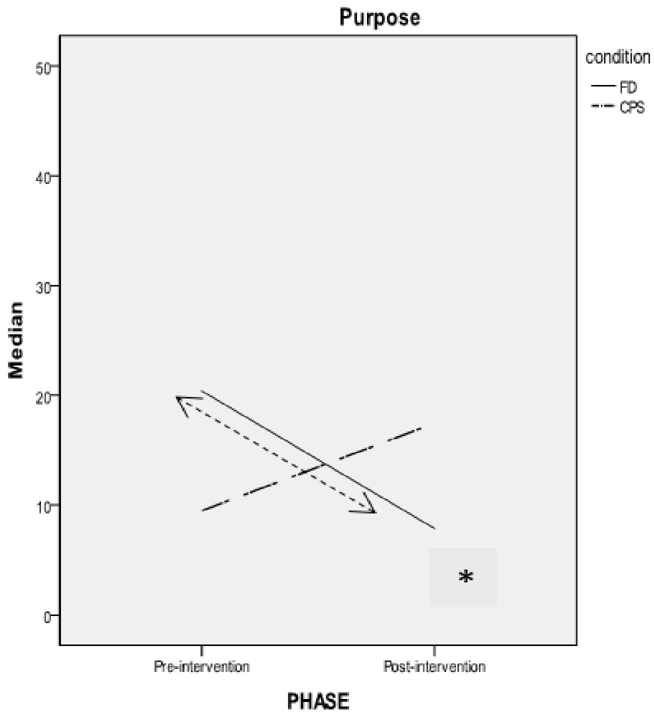


Figure 5. 4: The utterance of the 'purpose' aspect of design in both groups, across two phases.

In short, the change of search can only be seen in two design aspects, which are 'function' and 'purpose' aspects. The results confirmed that there is a significant between-group difference after the intervention in the use of 'function' aspects. In addition, there is a significant within-group change in the FDI group, and not in the CPS group. The changes are significant with respect to the increased use of function statements, and the drop in the use of 'purpose' statements within the FDI group.

5.3 What are the interactions that exist between all the main design aspects after the FDI intervention?

This section firstly presents the descriptive statistics for explaining the raw data of the frequency of transitions across the intervention type and time. After the general pattern is extracted, we will present the inferential statistics for answering the specific research questions posted earlier in this chapter.

Table 5. 1: The transition matrices for FDI and CPS groups

FDI Group:

PRE-INTERVENTION

Target

Given

	F	B	S	PE	PU	RE	M†
F	7.14	1.75	-	-	1.89	-	3.57
B	-	1.75	-	-	-	-	-
S	3.57	-	4.76	-	1.79	-	1.75
PE	-	-	-	-	-	-	-
PU	1.89	-	1.79	-	1.67	-	5
RE	-	-	-	-	-	-	-
M†	1.79	-	3.57	-	4	-	5

POST-INTERVENTION

	F	B	S	PE	PU	RE	M†
F	21.67	1.67	1.72	-	3.33	-	6.67
B	-	-	-	-	-	-	-
S	5	-	3.45	-	1.67	-	-
PE	-	-	-	-	-	-	-
PU	3.33	-	-	-	-	-	1.67
RE	-	-	-	-	-	-	-
M†	5.88	-	3.33	-	-	-	10

CPS Group:

PRE-INTERVENTION

	F	B	S	PE	PU	RE	M†
F	8.77	8.77	3.33	-	1.75	-	2.94
B	5.26	5.88	-	-	1.75	-	-
S	3.51	1.67	1.67	-	-	-	-
PE	-	-	-	-	-	-	-
PU	1.67	-	-	-	6.67	-	4.55
RE	-	-	-	-	-	-	-
M†	6.67	1.67	-	-	3.33	-	8.33

POST-INTERVENTION

	F	B	S	PE	PU	RE	M†
F	8.33	1.67	1.67	-	5	-	3.33
B	-	-	-	-	1.67	-	-
S	1.67	-	1.67	-	1.67	-	1.67
PE	-	-	-	-	1.67	-	-
PU	3.33	1.67	-	-	3.57	-	3.33
RE	-	-	-	-	-	-	-
M†	5	-	3.33	1.67	1.67	-	11.67

† Not included in the analysis. F=function, B=behaviour, S=structure, PE=people, PU=purpose, RE=resource, M=miscellaneous.

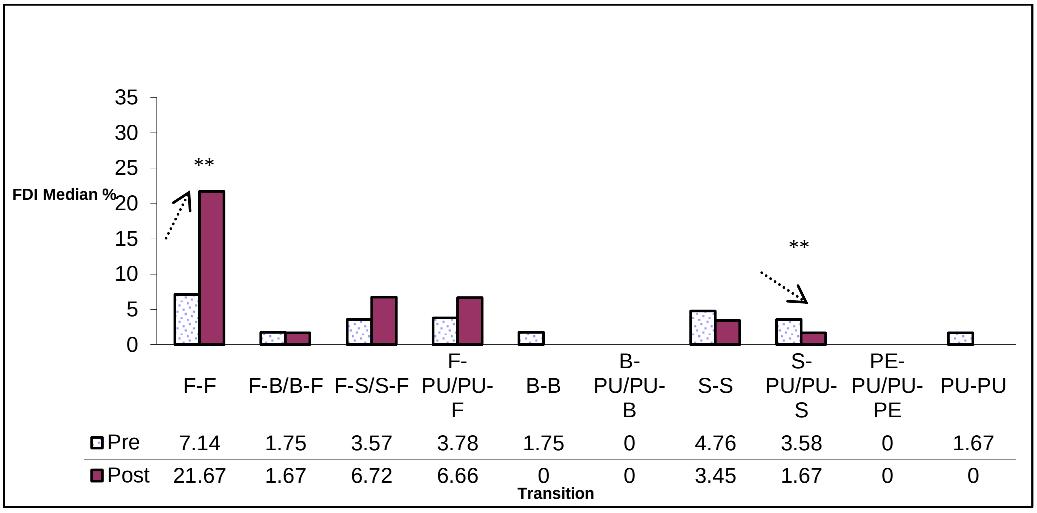
The transition step starts from the first leftmost column, then upward to the first row, e.g.: the box which contains value for behaviour-to-function transition (5.26) is the matrix connecting from B (in column 1) to F (in row 1).

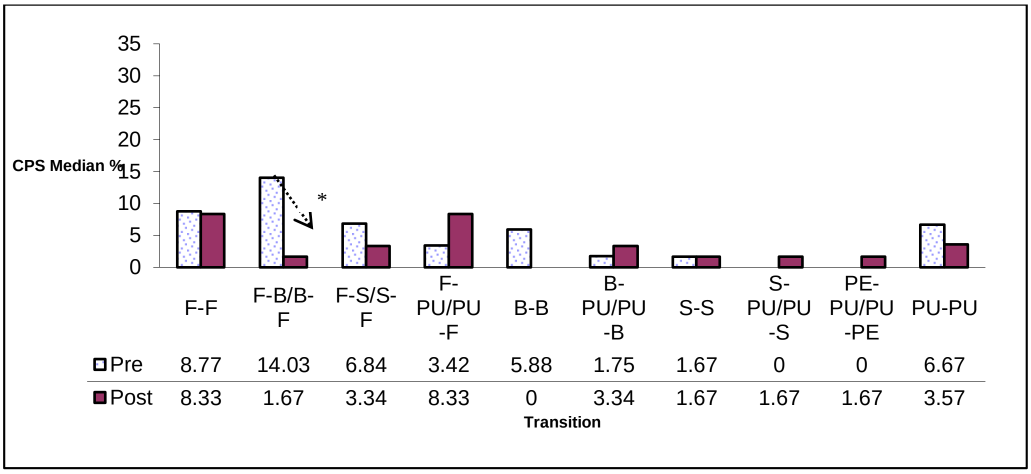
The same coded protocol transcripts were reanalysed in the second pass with the support of the Microsoft Excel software to count the frequency of the transitions as well as the kinds of transitions from one design aspects to another that covers each participant's protocol segments. This was explained in Chapter 3 (see the 'Procedure for Data Analysis' section).

'Transition matrices' (see Table 5.1) were developed and used to record the number of all possible transitions. The whole types of possible transitions are big (6x6=36 miscellaneous transition excluded). For the current study, the median scores are more representative of the data compared to the mean scores due to a lack of number of participants in each group (FDI group, P=9; CPS group, P7).

For the preliminary descriptive results, it was found that the FDI group made seventeen kinds of transitions before the intervention. This was reduced in the post-intervention phase to thirteen kinds of transitions. In contrast, the CPS group's transitions after the intervention increased to twenty kinds while the kinds of transitions made during the pre-intervention phase were only about eighteen. At the descriptive level, this implies a more disperse search that was happening among the CPS group during their problem solving process, since no clear remark on the specific exploration of a problem space with inter-related components ~~is~~ are seen in the CPS group.

The above median descriptive scores were too small to enable the use of more sophisticated statistics. Therefore, to identify the total number of intersections between the spaces, the data were collapsed by adding up all the bi-directional transitions together. For example, the purpose-to-structure and structure-to-purpose transitions both relate to the transitions involving the two relevant spaces, and therefore, were added up. The collapsed data will also tell specifically which space participants stay or transit most of the time regardless of the direction. The following shows the collapsed data on the bi-directional transitions.





** Significant at alpha = .01 * Significant at alpha = .05
- Note: F=function, B=behaviour, S=structure, PE=people, PU=purpose.

Figure 5. 5: Collapsed data of spaces of transitions in
FDI group (above) and CPS group (below)

The figures above are histograms which show the bi-directional transitions (involving two interchangeably same spaces) that were summed together. Further, inferential statistics were conducted to look at the effects of the interventions between- and within-group change after the interventions.

First, we presented the between-group change in the frequency and type of transitions. A Mann-Whitney U Test was conducted to investigate whether the two groups were similar in the kinds and rates of transitions after the intervention phase. The test revealed that there was no between-group difference in terms of the type of transition and the frequency of occurrences with regards to all kinds of transitions.

Second, we interpret the within-group change in the frequency and types of transitions. The significant results are highlighted in the histograms based on a Wilcoxon Signed Rank Test that we conducted. Here are the statistics:

- There is a statistically significant increase in the function-to-function transitions following the participation in the FDI training, z = -2.666, p = .004 with a large effect size (r = .63).
- There is a statistically significant drop in the structure-to-purpose/purpose-to-structure transitions in the FDI group, z = -2.240, p = .013, with a large effect size (r = .53).
- There was only one significant within-group effect from the CPS training, z = -2.240, p = .013, with a large effect size (r = .53). This was the F-B/B-F transitions that have dropped significantly after the intervention.

In conclusion, the analyses of the processes of transitions between spaces reveal interesting findings. The CPS group has added up on the **kinds** of transitions after the intervention. However, the **rates** of these transitions are not significantly different after the training as revealed by the statistics, except in the drop of function-to-behaviour transitions and vice versa. On the contrary, the FDI group showed a decrease in the **kinds** of transitions, but the **rates** of transitions had significantly changed. The change is seen in terms of the increased transitions between the function-to-function design aspect within the FDI group. The other change is the drop in purpose/purpose-to-structure transitions as seen in the group. There is only one significant change after the CPS intervention where participants show a significant drop in the function-to-behaviour/behaviour-to-function transitions.

5.4 Can design students invent inventive products after the FDI intervention?

As a general recapitulation, the product analysis is based on the 'Rank-Ordering' judgment method which is found to be statistically reliable according to the Pearson Correlation test, thus the judgment criteria are agreed upon by both judges. Moreover, the numerical values represent the ranks of the products assigned by the judges. Therefore, for example, since 'Rank 1' was the best and 'Rank 5', or '61' were worse than 1, the lower values (Rank 1, for instance) signify better results, and obviously, 'Rank 1' is followed by 'Rank 5' as the second-best ranking, then lastly, 'Rank 61' was the worst of all. The bigger values represent lower ranks to which the products are assigned to. Furthermore, the scores on Originality and Appropriateness are totalled up, together with both ratings given by the two judges, to round all the ratings into a grand score of the products' Total Inventiveness.

The P1 to P10 participants are those who fall into the FDI training while the CPS participants are identified as P11 to P17.

Table 5. 2: The Results of the Product Judgment in Experiment 1

PARTICIPANT ID	PRE-INTERVENTION SCORES					POST-INTERVENTION SCORES				
	Judge 1 ORI	Judge 1 APP	Judge 2 ORI	Judge 2 APP	TOTAL -TASK ASSIGNED	Judge 1 ORI	Judge 1 APP	Judge 2 ORI	Judge 2 APP	TOTAL -TASK ASSIGNED
FDI GROUP										
P1	13	9	15	2	39-A	15	15	12	13	55-C~
P3	13	2	10	10	35-C	2	4	7	15	28-B
P4	15	15	2	11	43-B	16	17	4	10	47-A
P5	9	14	3	5	31-B	8	4	6	6	24-C*
P6	16	14	9	4	43-C	14	4	17	17	52-A~
P7	11	8	13	8	40-A	11	11	15	2	39-C
P8	14	9	8	1	32-B	15	12	2	16	45-A
P9	17	16	13	15	61-C~	5	7	11	7	30-B
P10	7	6	6	13	32-B	6	7	14	9	36-C
CPS GROUP										
P11	6	6	8	14	34-A	4	1	5	4	14-B*
P12	10	1	7	3	21-C*	17	5	16	3	41-A
P13	9	7	14	1	31-A	9	8	8	16	41-C
P14	6	10	4	8	28-B	1	1	9	13	24-A*
P15	7	6	1	7	21-C*	8	8	15	2	33-B
P16	7	14	12	7	40-A	1	10	5	17	33-C
P17	10	13	9	12	44-B	18	17	11	14	60-C~

Notes: * The best products. ~ The worst products.

The details are shown in the table above. The tasks assigned to the participants are shown on the right-most column.

Based on the table above, there are potential students who could design original and appropriate products based on the judges' evaluation as well as students who did not perform well. We then conducted further tests to see whether the products improved as an effect of the interventions in both groups. In addition, the between-group difference analyses were also conducted to see whether participants of a particular group generally score better ranks than other groups, or whether any of the two groups always scored lower.

First, the product analyses looked into the descriptive test. This is followed by an ANOVA test for product judgments. Descriptive statistics revealed that all assumptions for conducting the parametric statistics were not violated. The Kolmogorov-Smirnov test revealed a non-significant value ($p > .05$), signifying a normal distribution of product scores.

Table 5. 3: Mean of the Product Inventiveness for FDI and CPS Groups

INVENTIVENESS CRITERIA	Condition	Pre-Intervention	Post-Intervention
		mean(SD)	mean(SD)
Originality	FDI	15 (5.96)	15.56(6.35)
	CPS	11 (6.56)	13.29(5.35)
Appropriateness	FDI	13.44(4.61)	16.78(6.48)
	CPS	13.00(4.61)	11.71(6.10)
Total inventiveness	**FDI**	**23.67(7.106)**	**27.11(5.689)**
	CPS	**21.00(8.145)**	**21.14(8.071)**

Based on the table above, both groups did not differ much during the pre-intervention phase in the ranking of originality and appropriateness. The results showed no interaction between training type and time, Wilk's Lambda = .954, $F(1, 14) = .046$, $p = >.05$, partial eta squared = .046. In brief, as shown in the results of the mixed ANOVA test conducted, there is zero within- and between-group effect of the FDI and CPS trainings on student product inventiveness.

5.5 Interim Discussion and Conclusion

This chapter is meant to present the results of the Experiment 1. The experiment caters to answering the research questions we stated earlier, and they are again shown as follows:

RQ2.1 What is the amount of 'function' search compared to the other main design aspects ('behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDI intervention?

RQ2.2 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDI intervention?

RQ2.3 Can design students invent inventive products after the FDI intervention?

The discussion here will be organised according to the flow of the research questions above.

First, the discussion looks into the results of the interventions on the cognitive processes in terms of the use of design aspects, in particular the function aspect among the FDI participants. This is presented in the following points.

Function-Space Search. There was a significant increase in the use of function statements as an effect of the FDI intervention on participants of the experimental group. This indicates active, directive problem solving. The CPS group has not changed in the use of function statements. Design problem solving should incorporate less amount of divergence and actual engineering knowledge should be used during the preliminary design stage as suggested by Sung and Kelley (2017).

Structure-Space Search. The high use of this kind of statement indicates design fixation. This is shown by the CPS group as an effect of the CPS intervention, even though the increase is not significant. The FDI group has a striking difference at the start as the pre-intervention difference in the use of structure statements is significantly higher than the other groups. However, the FDI training has caused a drop in structure search during the post-intervention phase even though that was not statistically significant.

Purpose and People-Space Search. During the problem structuring phase, a lot of people and purpose statements are used by designers (Goel and Pirolli, 1992). The FDI group has shown a significant drop in the use of purpose statement only. The small difference in people statements could be due to the fewer utterances of the kind of design aspect that was small in number, even during the pre-intervention phase. Very small difference cannot be detected using statistics. The CPS group used a lot more purpose statements as an effect of the intervention. However, this was not statistically significant.

The findings show that the FDI intervention has promoted search in the space of function, where the other spaces of search only were uttered minimally to give way to the increasing search in the function space, since the drop of purpose statements is significant.

Second, with regards to the **processes of transition**, we came up with the following conclusions.

Function-to-Function Transitions. There were significant within-group changes from the results of the FDI training. The F-F transitions has significantly increased in the FDI group.

Function-to-Behaviour Transitions and Vice Versa. The transition between F-B/B-F aspects of design has dropped significantly after the CPS intervention as a within-group effect. There is no significant pre- to post-intervention change of transition between the two spaces (function and behaviour) among the FDI participants.

Other possible transitions involving the function aspect of design are the function-to-purpose (F-PU/PU-F) transitions and function-to-structure transitions (F-S/S-F). However, due to the small number of utterances of purpose and structure statements, the SPSS was not able to draw any reliable measurement.

Structure-to-Purpose Transitions and Vice Versa. The FDI training has also caused a significant drop in S-PU/PU-S transitions as an effect of the intervention. This finding shows that there are lesser transitions between structure and purpose spaces in the FDI group during the post-intervention phase. Interestingly, this kind of transition was high during the pre-intervention phase. This could be a good indication that the FDI training has helped with the mitigation of fixation (Linsey, et al., 2010).

As shown in the transition matrices, there was an increase in the kinds of transitions conducted among CPS participants. The more dispersed transitions indicate an arbitrary search, with no recall of any domain knowledge (nomological constraints) but rather more on secondary social constraints.

Third, there is no effect in terms of **product** inventiveness. There are several explanations for the above findings. One is related to the experimental design that emphasised on the coding of elaborate protocols (each participant spent 2 hours to finish the experiment), apart from just the end products. This limits the experimenter from adding more participants since each participant will come individually and this will take time if there was an increase in participants.

Furthermore, unlike the experiments for non-design problem solving, the solution time span is defined by the attainment of definite ‘true’ answers given. In design problem solving, answers are open-ended. The design duration in the real world is decided by the clients and also personal constraints. Even variations may occur between two projects completed within the same time given. Therefore, we could consider the current participants’ experience of designing as only a part of the preliminary stage of design, as stated in the Chapter 1 of this thesis.

Another factor for the insignificant findings in the product analyses has to do with the transfer in knowledge-rich task as in design. The manner in which we can measure transfer in the training of thinking programs remains a debate (Ritchhart & Perkins, 2005). In Experiment 1, the problems given during the pre-intervention, intervention, as well as post-intervention phase were different. For example, the participant will be given Task A ("Invent an appliance that could catch a burglar") but given with Task B ("Invent a tool that a schoolteacher might use") during the post-intervention phase. This is not like the transfer tasks in the knowledge-lean problem solving tasks. For example, Nokes and Ohlsson (2005) used the letter sequence extrapolation tasks[3] to assess the degree of knowledge transfer and behaviour, while the task was a well-defined task. During the transfer phase, the questions given to the participants were varied, but the basic functions of the target domain and declarative knowledge components were still similar to the initial problem. Their participants were able to detect a pattern, and generate continuation in later phases. In our case, each time an inventive task was given, they were aware that the pattern itself needs to be built. No operations can be repeated as is. In the inventive tasks, the kinds of knowledge recalled involved different functions and declarative knowledge. Not only that, participants could vary in their depth of knowledge and problem-specific experiences. Thus, to measure the transfer rate in such kind of tasks is difficult.

To enrich the findings, we would cover other aspects that have changed qualitatively as the implicit effects of the trainings, and this is presented in the upcoming qualitative analysis chapter towards the end of this thesis.

Generally, the increase in the use of function statements is a finding that supports the research aim. The FDI training has changed the FDI group in their approach to problem solving as compared to the CPS group. The use of functional representations in engineering is proven in other studies as a more promising way than using other measures (Moss, Kotovsky and Cagan, 2006; Chi, 1992; Weber, 2006; Bradshaw, 1992; Chandrasekaran and Josephson, 1997; Kitamura et al., 2004).

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[3] "The learner is given a sequence of letters that exemplify a pattern, and he or she is asked to continue the sequence in such a way that the continuation also fits that pattern. As a simple example, to extrapolate the sequence ABMCDM to six places the participant would produce EFMGHM. To solve such a problem, the participant must first identify the pattern in the given sequence and then use that pattern to generate the continuation of the sequence. The first part, *pattern detection*, consists of studying the given part of the sequence to identify the relations between the letters. The second part, *sequence extrapolation*, requires a series of inferences based on the identified pattern, one for each position extrapolated (Nokes & Ohlsson, 2005, p.773)."

The post-intervention results indicated that the CPS training did not promote search in any particular space. There were a lot more kinds of transitions after the training, but the rates of each transition were lower than the pre-intervention phase because of their dispersed search. Since no clear pattern was seen among the comparison group who used the CPS method based on the quantitative findings, they were excluded from the Case Study analysis (see Chapter 7).

Design studies in the future should consider a longer problem solving period. We were not able conduct a lengthy invention processes with in-depth protocols that span for hours as in the case of the design problem solving in Goel and Pirolli's work (1992) or Ball, Maskill and Omerod (1998). There is a trade-off between attaining highly verbose protocols and human limitations during learning. In the case of our study, only 15 minutes were allocated for problem solving, making it hard to collect quantitatively ample evidence on the utterances of aspects of design development. This is because there is an additional one hour and 45 minutes of intervention in between the pre- and post-intervention phases.

In conclusion, the first experiment had answered the questions regarding the credibility of the FDI method in promoting inventiveness among designers. FDI has changed the way the participants approach their problem solving in a significant way. The next chapter presents the results of Experiment 2. The experiment is based on a different approach of function in design.

CHAPTER 6

Results 3: After the FDII Intervention

6.1 Introduction

This chapter will start with the analysis of aspects of design development and the transition between those aspects. Then, this is followed by the analyses on product inventiveness. As in the case with Experiment 1, the participants of FDII were assigned with the FD materials that are meant for crystallising the work in the 'black box' in design process. However, the current version of FD is different as it is based on the Functional Ontology approach by Kitamura et al., (2004). Here, function is encouraged through the use of explicit verb-operand statements, coupled with hierarchical diagrams that include two kinds of relationships that are the 'is-achieved-by' hierarchy and the 'is-a' hierarchy as introduced in Chapter 3 (the Material section).

We assumed no fundamental difference between FDI and FDII, since both are two different techniques strictly used to recall about device functionalities. This is because the quantitative analysis is targeted at comparing two philosophies of creativity: (1) 'creativity as conceptual learning and problem solving' as propagated in FDI and FDII; and (2) 'creativity as divergent-convergent thinking' as promoted in CPS. Therefore, no comparison was made between FDI and FDII groups. Experiment 2 used some parts of the data from Experiment 1. Data about the CPS intervention (comparison group) was again being compared against the current FDII group to derive statistical comparisons. We eliminated participant P30 from the analyses since the person had not used the given FDII strategy during the post-intervention phase. Therefore, only nine participants were left and included in the analyses of Experiment 2.

6.2 What is the amount of 'function' search compared to the other main design aspects after the FDII intervention?

The following figure shows the number of kinds of aspects uttered by the FDII group during the pre- and post-intervention phases. Descriptively, the increase from *Md* =29.73 to *Md* =30.88 in the post-intervention indicated that they had explicitly used the FDII strategy even before the training, and the method had intensified after the intervention. However, the CPS group, who has already used FD during pre-intervention phase (*Md* =28.57), has shown a slight drop after the training with respect to the use of the function aspect (*Md* =23.88). This is shown in the figures below.

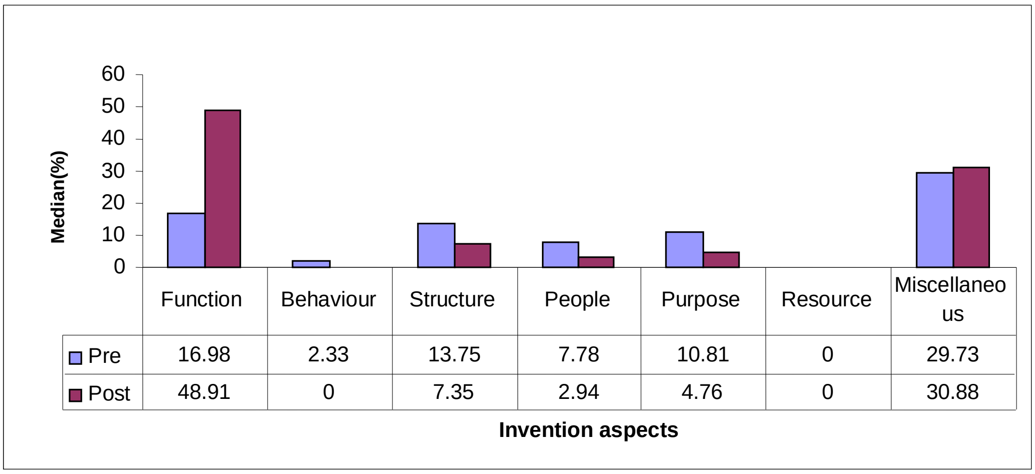


Figure 6. 1: The aspects of invention development (FDII group)

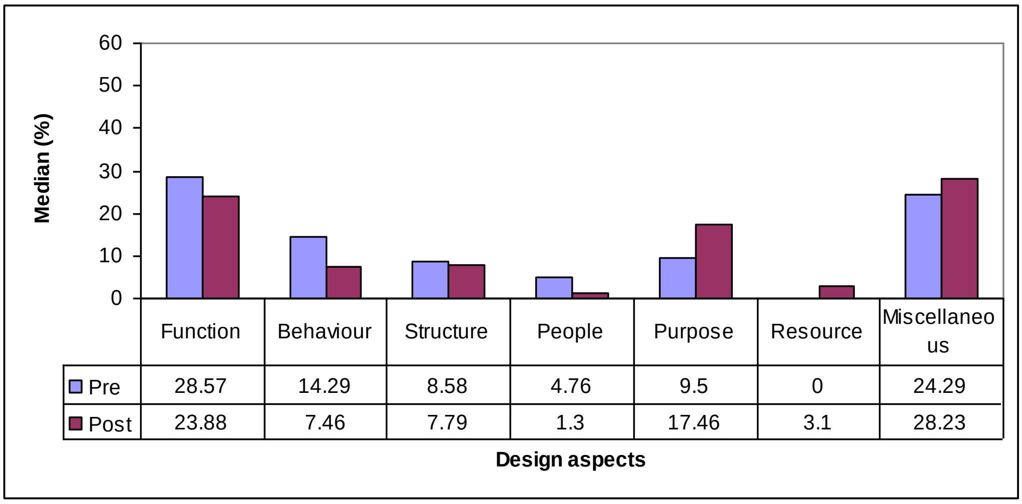
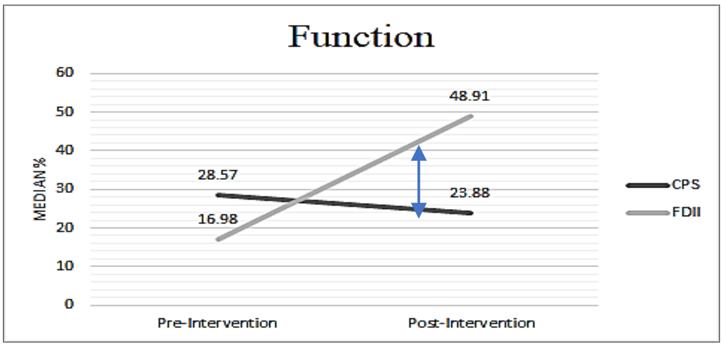


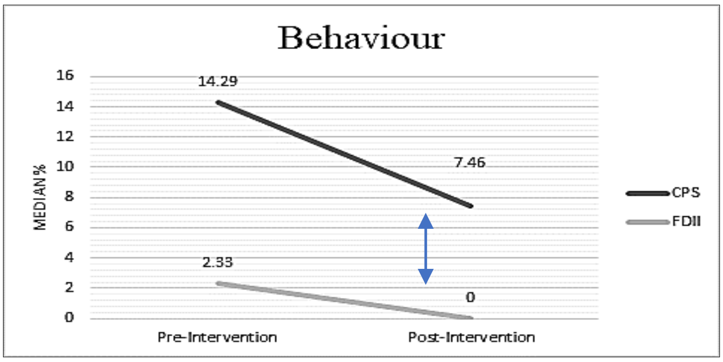
Figure 6. 2: The aspects of invention development (CPS group)

Generally, there was no within-group effect in both trainings. The median utterance of the 'function' aspect increased from pre-intervention (*Md* =16.98) to post-intervention (*Md* =48.91) but this was not significant, z = -1.599, p = .064 with a medium effect size (*r* = .38) based on a Wilcoxon Signed Rank Test conducted.

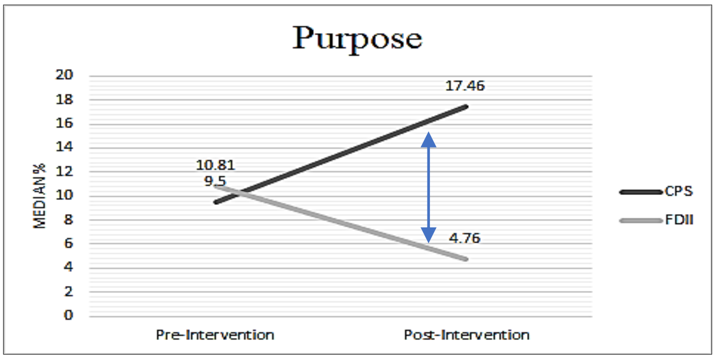
(a)



(b)



(c)



Note: Blue arrows shows changes are significant at p = < 0.05

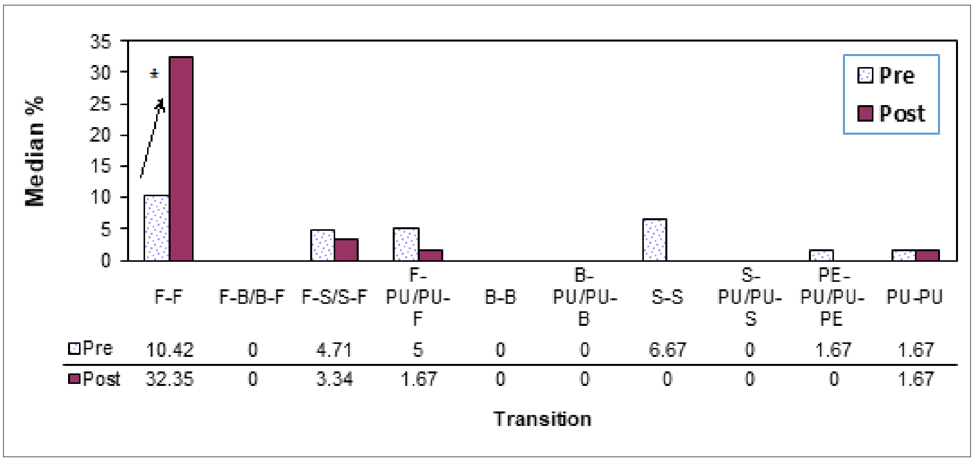
Figure 6. 3: The difference between FDII and CPS in terms of selected aspects of design development (a) Function, (b) Behaviour and (c) Purpose).

Next, a Mann-Whitney U Test was conducted to investigate the between-group effects of the trainings (FDII and CPS). The differences are depicted in the line graphs in Figure 6.3. They were different with respect to the use of the 'function', 'behaviour' and 'purpose' aspects. In the post-intervention, the FDII group used more 'function' statements compared to the CPS group U = 4, z -2.911, p = .002, r = .73. However, the FDII group's use of 'behaviour' and 'purpose' statements was lower than the CPS group. The differences of the two aspects are significant: U = 2, z -3.17, p = .001, r = .79 ('behaviour' statements), as well as the 'purpose' statements: U = 11, z -2.17, p = .031, r = .54.

In short, the only difference between the FDII and CPS training can be seen during the post-intervention phase. There is, however, no indication that both trainings had changed each individual groups as compared to before the interventions.

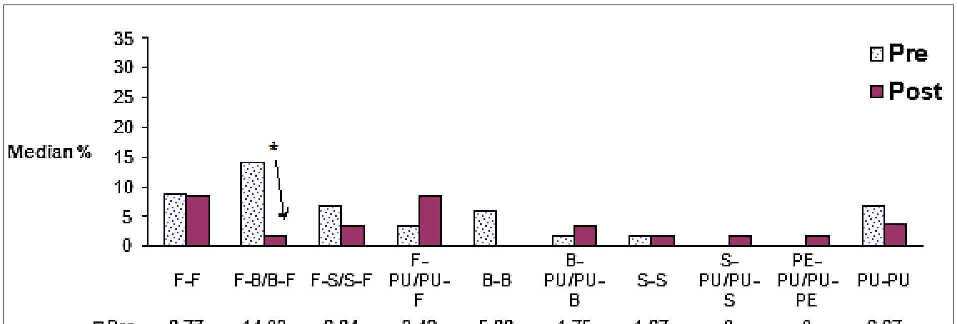
6.3 What are the interactions that exist between all the main design aspects ('function', 'behaviour', 'structure', 'people', 'purpose' and 'resource') after the FDII intervention?

The analysis of the transitions was meant to assess the degree of transits from one kind of design aspect to another. The descriptive results are shown in the following figures



* Significant at alpha = .05 - Note: F=function, B=behaviour, S=structure, PE=people, PU=purpose.

Figure 6. 4: Transitions in FD II group



	F-F	F-B/B-F	F-S/S-F	F-PU/PU-F	B-B	B-PU/PU-B	S-S	S-PU/PU-S	PE-PU/PU-PE	PU-PU
Pre	8.77	14.03	6.84	3.42	5.88	1.75	1.67	0	0	6.67
Post	8.33	1.67	3.34	8.33	0	3.34	1.67	1.67	1.67	3.57

* Significant at alpha = .05 - Note: F=function, B=behaviour, S=structure, PE=people, PU=purpose.

Figure 6. 5: Transitions in CPS group

The above figures are histograms which show the bi-directional transitions (involving two interchangeably same spaces) that were summed together. The analysis with regards to the transition rates will start with the between-group analysis, followed by the within-group analysis later.

A Mann-Whitney U Test was conducted to investigate whether the two groups (FDII and CPS) were similar in the kinds and rate of transitions. After the intervention, it was found that the difference between the two groups rests in the function-to- function transitions only, U = 6, z -2.67, p = .005, with a large effect size, r = .67. The FDII group transited within the 'function' space (*Md* = 32.35, n = 9) more than the CPS group (*Md* = 8.33, n = 7).

Another test was conducted to evaluate the within-group change in the frequency and types of transitions, if any. The significant results are highlighted in the histograms based on a Wilcoxon Signed Rank Test that we conducted. It is found that following the participation in the FDII training, the FDII participants stayed in the function space more in the post-intervention (*Md* =32.35) than the pre-intervention phase (*Md* = 10.42), z = -1.718, p = .046 with a medium effect size (r = .41). The other transition aspects were not significantly different before and after the intervention. This will be discussed at the end of this chapter.

Further, there was only one significant result for the within-group effect of the CPS training, and that was the F-B/B-F transitions, z = -2.240, p = .013, with a large effect size (r = .53).

6.4 Can students design inventive products after the FDII intervention?

The following table shows the pre- to post-intervention change in the originality and appropriateness of the products invented by the FDII group at the descriptive level. A better rank (smaller mean values) was seen in both inventiveness criteria after the intervention. It went down from *M*=16.00 to *M*=14.11 for product originality, and from *M*=18.22 to *M*=17.11 for product appropriateness. This is subject to further inferential statistics.

Table 6. 1: Mean of Product Inventiveness for all participants (FDI, FDII and CPS Groups)

INVENTIVENESS CRITERIA	Condition	Pre-Intervention	Post-Intervention
		mean(SD)	mean(SD)
Originality	**FDII**	**16.00(9.192)**	**14.11(7.769)**
	CPS	15.71(5.345)	17.29(9.304)
Appropriateness	**FDII**	**18.22(7.225)**	**17.11(9.103)**
	CPS	15.57(7.547)	16.29(9.340)
Total Inventiveness	**FDII**	**17.11(8.2)**	**15.61(8.44)**
	CPS	15.64 (6.45)	16.79(9.3)

The paired samples t-test conducted showed an insignificant improvement from the pre- to post-intervention phase, $t(8) = .486$, $p = .64$ (two-tailed) in terms of product originality. The mean improvement was 1.889 with a 95% confidence interval ranging from -7.08 to 10.86. The participants' improvement in product appropriateness was also not statistically significant, $t(8) = .322$, $p = .76$ (two-tailed). The mean improvement was only 1.111 with a 95% confidence interval ranging from -6.84 to 9.07. Therefore, this finding of the product aspect of invention outcome in Experiment 2 has shown no effect of the FDII intervention on product inventiveness. The answer for RQ 2.3 is that after the FDII training, students in the experimental cannot design significantly more inventive products based on time and group.

6.5 Interim Discussion and Conclusion

The final section of this chapter presents the overall conclusion and discusses the important aspects of the study that needs to be articulated. There were three research questions for Experiment 2. The first is (RQ3.1) on the amount of ‘function’ search compared to the other main design aspects (‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) after the FDII intervention. Then, we seek to answer on the interactions that exist between all the main design aspects (‘function’, ‘behaviour’, ‘structure’, ‘people’, ‘purpose’ and ‘resource’) after the FDII intervention (RQ3.2). Lastly, (RQ3.3) focused on whether students can design inventive products after the FDII intervention.

First, it was found that the FDII group was different from the CPS method with respect to the use of the ‘function’ aspect, and this is statistically significant. There was also a significant difference between the two groups with respect to the use of behaviour and purpose statements where the CPS group showed a higher usage of the behaviour and purpose statements after the intervention. This implied that the CPS training enhanced search in other aspects, even though this difference was not seen during the pre-intervention phase. The CPS group showed a difference only in the post-intervention effects in comparison to the FDII group. Alternatively, the difference is also pronounced because the use of behaviour and purpose statements among the FDII group was very low as an effect of the FDII intervention.

There was no within-group effect that was seen after the intervention in both groups.

Then, the transition analyses showed rapid transitions between the function-to-function statements within the FDII group after the intervention. This indicated that the function-to-function transition occurred at a significantly lower rate, but this changed after the intervention. It is important to highlight that the frequency of the function statements (derived through the first-pass coding) among the FDII participants was not statistically and significantly higher after the intervention compared to the pre-intervention processes. However, the transition analysis shows a rapid function-to-function utterance which has improved significantly after the FDII intervention. This means a lot of participants in the FDII group moved immediately from one function to another function aspect most of the time. This is one of the intervention effects, since the transition pattern was different although the general count of function was high. This was not the case during the pre-intervention phase where their F-F transitions were significantly lower, even though the quantity of function statements was equally high before the intervention. This shows that the transition analysis tells a different story about how the intervention has changed the FDII group method of problem solving.

Moreover, there were quantitatively low transitions involving function to other design aspects such as function-to-people transitions, function-to-behaviour, function-to-structure, or function-to-purpose. We argue that these transitions occur at a minimum, thereby does not allow any stringent analysis using statistics. The fact that these other aspects are still used by the participants showed that the quantitative analysis underrepresents the other kinds of transitions between the design aspects that may change the landscape of problem solving, qualitatively. Therefore, the qualitative analysis is recommended for other studies in the future to demonstrate how function and other aspects of design interact in the process of the design conceptualisation. We are not going to do that because that exceeds the scope of the qualitative study which is to explore the properties of search of the function aspect only.

Lastly, the results from the product analyses showed both the FDII and CPS groups were able to come up with inventive designs. No significant difference was found in terms of product inventiveness regardless of the phases of interventions.

Based on the descriptive data, participants in the FDII group had already used functional decomposition since the start. This is confirmed in the statistics where no within-group difference is detected among the FDII participants in terms of the utterance of the function aspect of design.

The results confirm there was no change in the product scores as an intervention effect. It can be inferred those participants who have already searched in the function aspects will not find the training to be beneficial, thereby the product outcomes stayed in the same condition even after the intervention. This meant that the FDII training was a great help only to participants who had not used functional decomposition at all from the start. The next chapter will further examine on the nature of search in design problem solving after the training interventions, qualitatively.

CHAPTER 7

Results 3: The Qualitative Effects of FD: Analysis of the Control Strategy and Goal Definition

7.1 Introduction

Based on the Problem Space Theory, there are two things that define problem solving effectiveness: (i) the amount of information; and (ii) the organisation of that information. Both are elements of a problem representation (Chi, et. al., 1982; Vanlehn, 1989). A representation permits many appropriate inferences to be drawn so that the problem can be simplified and reduced, while the core issues are tackled in an intelligible manner. Based on the Problem Space Theory by Newell and Simon (1972), a representation consists of an initial state, goal state, heuristics or operators, and the task environment. The characteristics of the design task environment are explained in the Literature Review. The role of the current study is to identify the development of concepts from the start to the end of the problem solving session, as well as the operators that participants had used in organizing their problem representations. In this chapter, we regard the concepts as the *control* system and the operators as indications of the *goal* organisation or more specifically, problem decomposition.

For instance, a problem-solver who searches for information on the Internet may get overwhelmed with the abundant amount of information available in the World Wide Web. To deal with the high amount of competing information from various sources, a searcher should practice some degree of *control*. Also, within the context of the 'Internet-searching' task environment, powerful processing units can speed up the search processes through an efficient and reliable CPU execution to reach the problem-solver's search *goal*s. Non-overlapping, energy-saving, and clear tracking of vectors among the interlinking information (in forms of sub-goals) can accelerate the *goal* definition. Linkages or organizations are constitutive of a holistic goal. An inefficient organisation does not bring a problem-solver closer to the goal, but even farther away from the goal.

Both *control* and *goal* are aspects of the problem representations that should be studied to characterise problem solving processes in human subjects that precede performance (Newell & Simon, 1972; Simon, 1981).

It is reiterated here that the FD properties is a design method being promoted. It is one of the potential design methods that directly identifies the control system. Effective rulesets are achieved through decomposition that resolves possible conflicting elements, in order to come up with reasonably apt and coherent organization (i.e.: the holistic goal). Finding adequate functional decomposition properties need to be supported with data in the forms of direct referrals to the actual incidents in the problem solving episodes. For example, it is found that the control systems based on the ‘function’ results in a better recall of mechanical devices, while the control system based on ‘structure’ or physical appearance results in superficial representations, and this directly caused a weak performance by novices (Casakin, 2004; Hmelo-Silver & Pfeffer, 2004; Ho, 2001; Melançon, 2008; Moss et al., 2006).

The structure-space search or the tendency to build representation based on surface problem criteria is also identified as a characteristic of novice problem-solvers (Bradshaw, 1992; Casakin, 2004; Hmelo-Silver & Pfeffer, 2004; Linsey et al., 2010). Previous works used the qualitative analysis to look into the antecedents of the structural and functional representation more closely. It is suspected that the structure-space search may impede exploration, in that problem solving may stop the moment a problem-solver regards the design activity only as a process of finding a matching solution~~s~~ already created in the past. This results in a short exploration, depicted in short conceptual maps derived from the participants’ protocol data. It is noticeable that understanding the functions of a system indicates a more elaborate network of concepts and principles representing the key phenomena and their interrelationships (Hmelo-Silver & Pfeffer, 2004). Therefore, it was not surprising to see that the experts in Hmelo-Silver and Pfeffer’s work mentioned functional elements more than behavioural and structural concepts, as multiple behaviours and structures may combine to perform various functions. This implies that the structure-space search may not be able to form an elaborate system, manifested in a limited exploration space.

Also, the processes of *goal* definition demonstrated by design students in our study as an effect of FD intervention need to be analysed qualitatively since concepts are stored in closely-knit chunk features (Chi & Koeske, 1983). Apart from transition analysis involving functions in the previous studies in Chapters 4, 5 and 6, qualitative analysis here is to depict interlinking operators by coding the decomposition heuristics used by the participants. The purpose of the second analysis is also to find the pointers on decomposition actions or moves that brought problem-solvers to the goal. The distributions of the operators along the pre- and the post-intervention problem solving processes can also tell different stories about what kind of operators the participants were using in different phases to organise their design conceptualisation.

According to Korovkin et al. (2018), problem solving in ill-defined problems such as design involves a representation system that is already sensitive to errors. Therefore, the question is not on whether a conceptualisation is 'right' or 'wrong', but rather the question is about which one is the 'better' or 'worse' conceptualisation (Goel & Pirolli, 1992). We suspect that the tricky aspect of design problem solving is more on over-glossing of ready tangible solutions, where physical artefacts may hinder re-definition of goals of new tasks that are given by the clients. In this regard, designers are unaware that to choose ready 'true' solutions is more like a novice-like approach, may be because designers are contented by the fact that the ready solutions are proven to be 'true' based on earlier pre-cursor inventions and designs. FD is essential in design instruction, to instil such awareness that an 'ontological shift' from the structure-space search to function-space is necessary, to provide 'better' design solutions (Chi, 1997). A previous design solution might have worked before, but it may need necessary adjustments on the currently defined new design needs.

The intentional shift to functional representations also stems from the scientific cognitive research on working memory as an executive component of human information-processing system. The limited capacity of the working memory inhibits the arbitrary information maximization of recall, and thus, urges for only specific, manageable concepts (Ball et al., 1998; Wiley & Jarosz, 2012). Small problem units are what accelerate consequent moves towards goal achievement. Here, the word 'small' implies the symbolic meanings that are non-tangible. A designer, similar to any problem-solver, needs to 'translate' forms into the smallest units of knowledge, probably in units of the simplest vocabularies. These vocabularies (such as verbs or action words in FD) are kept nowhere other than in the long-term memory storage. This is the basic of information-processing system. The basic units are workable units which they enter the working memory storage for further re-descriptions and re-representations.

Apart from knowledge, methods associated with a certain kind of task are part and parcel of the internal representation of all problems. This helps efficient problem solving and thus, clear knowledge recall and non-arbitrary results (Newell & Simon, 1972).

The capability of the experts to develop effective internal representation which resulted in clear outcomes can be revealed through qualitative analysis that review the entire set of experts' representation based on the data from their verbal protocols (Ericsson & Simon, 1993). Prior studies show that based on the analyses of their protocols, experts: (i) are better at recognition of connections; (ii) have multiple ways to solve problems; (iii) develop well-structured representations of problem to check results against; (iv) work-forward, in that they develop a more efficient system and sets of sub routines that can solve several types of problems within a task environment (Ball et al., 1997; Chi, et. al., 1982). Solving a problem becomes a matter of applying existing sub-routines to problems and sub-problems. Even though none of our participants are experts, the characterization of experts' representation can be used as a baseline for measuring their post-intervention performance qualitatively, as an effect of the current intervention of FD (Bradshaw, 1992b; Moss, J., Kotovsky, K., & Cagan, 2006).

In this study, the purpose of the qualitative analysis is not to specify explicit processing such as progress monitoring, implementation of heuristics, and operations within the problem space such as the case in the Physics domain (Chi, et. al., 1982), or chess domain (Chase & Simon, 1973). Problem solving of 'wicked problems' in design involves the rejection of incorrect representations and ineffective rulesets right from the initial problem solving stage (Korovkin et al., 2018). The designers' evaluation function is a matter of subjective analysis based on a lot of factors, including nomological and social factors (Goel & Pirolli, 1992). This means that since the control system in design does not require constant monitoring or implementation of explicit heuristics, the analysis should be looking at how design students select and construct better solutions and reject unsatisfying applications of solution to the current design problems as a manifestation of the students' control system.

As described in Chapters 4, 5 and 6, the FD intervention given has shown such effects when the functional search has significantly increased among the FDI and FDII groups, demonstrating a high degree of *control*. Moreover, the organisation of *goals* based on functionality are also closely knitted since the Function-to-Function transitions have also improved significantly based on the statistical data. The role of this chapter is then to further explore how *control* systems based on function helped with the conceptualisation of design through the actual exploration of the participants' natural expressions of functions based on their protocols. The inter-linking of functions can also be further depicted through qualitative analysis, in addition to the quantitative transition analysis conducted in Chapters 4, 5 and 6 based on Experiments 1 and 2. This is because designers extract *goals* and conduct further sub-goaling of functional components in the abstraction hierarchies (Goel & Pirolli, 1992). The abstraction hierarchies will be understood only through ordering of concepts taken from the protocols qualitatively. This is not well-captured through the surface transition analyses.

In this chapter, the exercise of *control* and *goal* definition are going to be presented by detailing out the representations developed by the participants before and after the FD interventions were given. This is unlike the expert-novice studies which measure the two groups and treated them as absolute categories, i.e.: the novices 'versus' the experts (e.g.: Ball et al., 2004; Chi, et. al., 1982). Here, we examine how design problem solving skills can be attained through declarative FD training interventions as a relative approach to understand human expertise. Training can elevate novices into experts through the explicit adoption of expert-like strategies that logically improve future performance (Chi, 2006). A lot of expert-novice studies look into the NATURE of the two groups, but our qualitative study examines the NATURE OF THE CHANGE in the participants as the results of change in the kinds of representations they used. This approach is widely used in assessing learning performance, but so far, we have not found any representation analysis in the studies that assess problem solving performance, especially in the engineering design domain.

For analysing the effects of FD, we look at whether FD has affected problem representation within the same individuals who possess a common body of knowledge at the initial pre-intervention phase. No clear pattern of change is seen among the comparison group who used the CPS method based on the quantitative findings and therefore, they were excluded from the Case Study analysis.

The upcoming section explains the Research Questions specifically for the qualitative analysis. Then, the method section presents the study design, participants selected, instruments, data collection procedure, and analysis procedure. The results section lays out the qualitative findings that may answer the research questions. The chapter ends with the discussion and interim conclusion.

7.2 Questions

The following continues with the previous Research Questions: RQ1, RQ2, and RQ3 that we have already answered in the previous chapters. In specific, the current chapter seeks to answer RQ4 that is rephrased as follows:

> *(RQ4.1) How has FD changed the control system from arbitrary and shallow concepts to deeper conceptualisation of functions?*

The properties of FD can be extracted from the representational change at the level of kinds of concepts used by problem-solvers in our study. The conceptualisation depends on the success in explication of design solutions in a structured and integrated manner. The depth-first or breadth-first searches are common outcomes for the analysis on conceptualization processes conducted by the control system.

> *(RQ 4.2) How has FD changed the goal definition through decomposition and sub-goaling operators?*

The properties of FD can be extracted from the representational change at the level of the operators used by ~~the~~ problem-solvers in our study. Completeness and coherence of an internal representation are manifestations of arrangement operators, which in turn, determines the ease of arriving at a final defined goal (i.e.: design solution) and its accuracy. The processes of establishing links and decomposing whilst conducting the function-space search can be identified through the coding of the operators.

7.3 Method

This section explains the administration of the qualitative analysis to ensure reliable and valid outcomes.

7.3.1 Design

The method adopted is Case Study. This method allows exploratory research on a small group of participants to describe interesting properties that are characteristics of the selected participants. The focus is not on making generalisations, but only on deriving certain criteria of the participants' representations more closely through the inclusion of immeasurable qualities that may not be evident in the quantitative analysis.

7.3.2 Participants

The same participants from Experiments 1 and 2 were the population (Group FDI N=9; Group FDII N=9), but we selected only eight (N=8) participants via purposive sampling. Four participants from the FDI (P3, P5, P7 and P9) and four participants from the FDII (P23, P24, P26 and P27) groups were selected (‘P’ stands for participants; while single digit numbers refer to the participants from the FDI group; numbers 11 to 20 the CPS group; and lastly numbers 21 to 30 the FDII group). The samples bear certain criteria that could give answers to the specific research question asked for in the current Case Study. First, we chose the participants with the highest pre-to post- intervention DIFFERENCE with regards to product inventiveness. Second, we chose only the participants with the highest DIFFERENCE in terms of the quantity of the function-space search based on the quantity of ‘function’ statements uttered in their protocols. This is to ensure impact of FD is clearly deduced from the extreme cases, then ensure richer findings on nature of representational change that has occurred in these participants after the interventions. They are students who performed well because improvement can be seen based on the margin of change between the pre- to the post-intervention scores. Since both FDI and FDII groups had rich representations based on the device’s function as proven in the findings of Experiments 1 and 2, no CPS participant was qualified to be the participants for the Case Study. The previous findings also proved that there was no significant change in the CPS group in the use of function and other statements after the intervention, thereby making the pre-intervention data of the selected participants from the FDI and FDII groups as a comparable set of data to those of the CPS group.

The other 10 participants were not selected. A participant (P21) scored about the same for both product and usage of function-space search. P22, P25, and P28 decreased in use of function statements, but there was an improvement in terms of their product judgment. On the contrary, P1, P4, P6, P8, P10, and P29 have increased their usage of function statements. However, there was a drop in the product inventiveness score from the intervention effects. Based on the product analysis in Experiments 1 and 2, there is inconclusive findings on the participants’ performance based on the ratings of the design products as evaluated by the external judges. Due to this, we did not consider data analysis based on the improved product outcomes only. There were no other interesting phenomena to be considered based on the other participants who have already searched in the space of function during the pre-intervention phase. Their representations are comparable to the selected participants who improved their function search in the later phase and therefore, there is no need to select these ‘gifted’ or advanced participants. Furthermore, we did not control for the pre-intervention design method that they can adopt. We clearly communicated that they may use ‘any’ design method to conduct the pre-intervention design problem solving. Therefore, these postgraduate participants may have the experience with using FD since they have completed at least one major design project during their undergraduate studies. Therefore, they did not benefit from the FD interventions.

Table 7. 1: The Participants selected via Purposive Sampling Technique

PARTICIPANT	**PRE- TO POST-INTERVENTION DIFFERENCE (Time 1 – Time 2)**	
	Product Improvement (margin of difference)	**Improvement in terms of Function-space search** (The negative (-) scores indicate post-intervention values of function search are higher compared to the pre-intervention.
P3	7	-42.57
P5	7	-21.54
P7	3	-22.42
P9	31	-20.18
P23	17	-44.42
P24	21	-38.13
P26	9	-37.8
P27	24	-51.01

7.3.3 Instruments

In qualitative research design, the researcher is a learner who reflects on the data that the researcher is an instrument itself (Corbin & Strauss, 2008; Merriam, 1998; Strauss & Corbin, 1994; Wa-Mbaleka, 2020). The qualitative analysis emphasises a high degree of sensitivity and familiarity with the collective data in order to turn human cognitive processes and experience into something more meaningful. The qualitative data requires connecting themes emerging from the data in specific contexts. The instruments in the qualitative studies evolve whilst conducting the analysis.

To answer the first research question on their control strategy, we build conceptual maps for the design ideas (see Bakouli & Jimoyiannis, 2016; Novak & Canas, 2006 for studies on conceptual maps). Conceptual maps were used to thoroughly depict how problem-solvers meaningfully derive solutions in the whole space based on the protocols.

Next, the second instrument for the second question was the coding scheme for the analysis of the design operators. We conducted a bottom-up coding process based on what can be deduced from the current protocols of the selected design students. This is because there were only limited problem solving operators found in the literature, and those operators were sometimes meant for a non-design task environment (e.g.: Menekse & Chi, 2018; Zhang et al., 2009).

According to the Literature Review reported in Chapter 2, FD involves operators for identifying: (i) the actual **works** the artefact is to conduct in order to function; (ii) the operators for showing works that are identified but then **neglected** to develop better alternative representations; and (iii) the operators that indicate the **placement** or localisation of the overall sub-goals of functions to make coherent final representations. These three main aspects of FD were identified in the protocols before they were grouped into the sub-categories and the decomposition operators as shown in Table 7.2.

Table 7. 2: Coding Scheme for Goal Definition (Decomposition Operators) within the Function-Space Search

CATEGORY OF OPERATOR	SUB-CATEGORY	OPERATORS
WORK	**Add Constraints**	***(1) add complexity:*** To state solution in a vague way
		(2) defer judgment, fluency: To derive new solution concepts without worrying about the quality of the concepts
	Goals & Sub-goals	***(3) suggest work:*** To state specific actions that reflect device's intended functions
		(4) suggest technology: To state the name of specific technological solutions that are already known to perform a certain function
NEGLECT	**Selection**	***(5) general plan:*** To state a broad functional concept in the highest abstraction
		(6) simplify complexity: To restate elements from functional component elements and give up other irrelevant or less relevant elements
	Drop Constraints	***(7) assimilate solution:*** To figure out comparable exemplar solutions so that attentional demands is reduced
		(8) draw limitations: To indicate the properties that should not be included into the problem space
		(9) reject: To explicitly delete a line of conceptualisation

PLACEMENT	**Analysis**	***(10) elaborate properties*** To designate properties to a self-contained function
		(11) explore, question, redefine To inquire and challenge a proposed function
		(12) preconditions in environment To acknowledge the contexts the function will be implemented
		(13) reiterate suggestion To highlight a main function
	Synthesis	***(14) originate concept*** To coin functional concepts using new derived words never found before because there is no similar precursor concepts
		(15) put into order To clearly define linkages one after another
		(16) relate, decompose, organise To define linkages with possible flexible re-arrangements
		(17) results To confirm that the goal is reached

7.3.4 Data Collection Procedure

The verbal protocol analysis procedure was already described in Chapter 3. No new data is collected for the Case Study. The participants' protocols in forms of heeded verbalization were re-used to analyse and depict the properties of the participants' internal representations across the pre- and post-intervention phases.

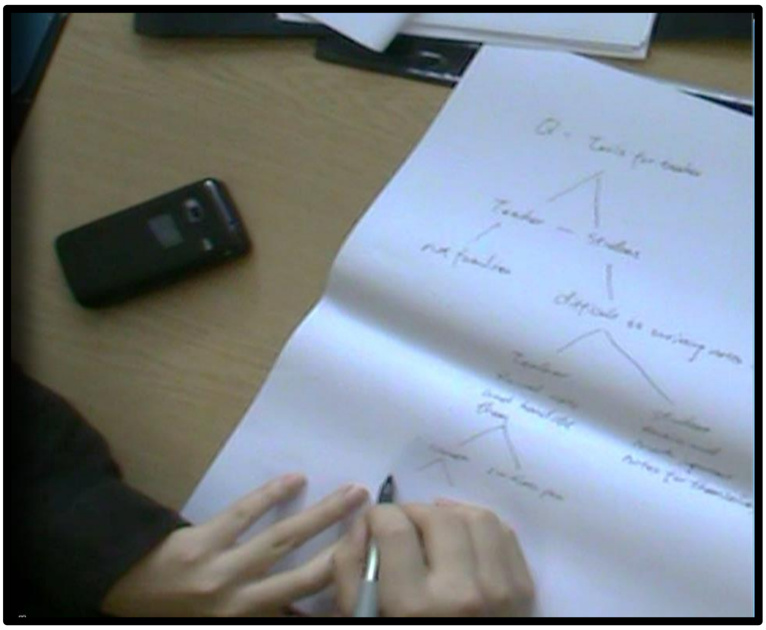


Figure 7. 1: Qualitative analysis examines the converging data from the protocols including different modes of problem solving such as writing, sketching and verbalization.

Figure 7.1 is the screenshot from the video-taped protocols. It shows an external movement that was simultaneously recorded while collecting the verbal protocol data. The process of representation-making is better captured through the multiple modes of activities or data ‘triangulation’. This is explained next.

7.3.4.1 Reliability and Validity of Protocol Analysis

Reliability and validity are essential elements in every qualitative research work. According to Creswell (2009), qualitative reliability is attained when the researcher's approach is consistent across various projects. This is realised through appointing a second coder to code the subset of protocols. We have appointed the external coder to ensure the reliability of our coding scheme of the design aspects as mentioned in Chapter 3. However, the coding scheme for the development of conceptual maps to depict the control system of only a few selected Case Study participants is qualitatively different because a participant’s representation could be different from one participant to another. As qualitative studies regard the researcher as a learner, there is then no such need to find a second coder for building the conceptual mapping, for a small number of participants.

On the other hand, qualitative validity means that the researcher checks for the accuracy of the findings by employing certain procedures. Smagorinsky (1989) highlighted some approaches to ensure the validity of the verbal protocol data. Validity is attainable through:

- Comparing the result of: (i) concurrent protocols (verbal utterances simultaneously with the performance of task); and (ii) retrospective debriefing (Taylor & Dionne, 2000). During retrospective debriefing, a subject is asked to talk about cognitive processes that have occurred at an earlier time.

  For the current qualitative analysis, the retrospective debriefing was used to validate the protocols. We have already collected the participants’ retrospective debriefing (see Figure 3.6), even though this supporting evidence was abandoned during the quantitative analyses in the previous experiments.
- Triangulation: The processes must be supported by several forms of evidence including video and audio recordings, sketches, annotations, eye-tracking machine, etc.

According to Creswell (2009), one of the methods of ensuring internal validity in qualitative analysis is by doing triangulation. Triangulation is an approach where the data is analysed through multiple sources. In this study, the forms of evidence that are taken are: (i) protocol transcripts; (ii) audio and video data; (iii) participants' annotations; and (iv) participants' final design descriptions.

7.3.5 Data Analysis Procedure

In the prior studies on the role of representation in learning, better representations of successful students are what caused the lack of errors (Chi, 2009), and faster solution (Hoffman et al., 2014). However, the representational change in design is not about discriminating the 'true' from the 'wrong' representation of solutions as mentioned earlier; neither is it about the solution span. In the current work, all students were given the same duration of 15 minutes to solve the design tasks given.

When conducting the qualitative analyses, we took two logical analysis steps to reflect the two research questions.

Table 7. 3: The Instruments and Analysis Methods for the Case Study

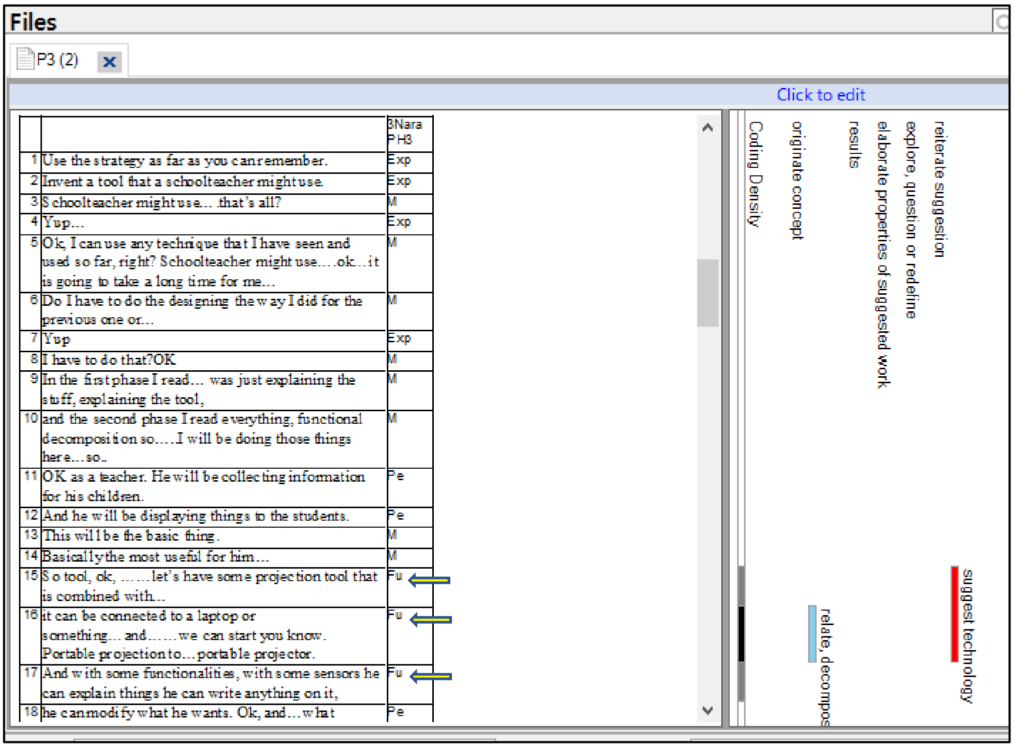
ASPECT OF PROBLEM SPACE (REPRESENTATION)	INSTRUMENT	ANALYSIS METHOD	REFERENCES
Control	Conceptual map and protocol quotes based on FUNCTION design aspect uttered in the protocols	Depiction of the conceptual maps using chart-maker application	Chi et al., 1982; Chi & Koeske, 1983; Coulston & Ford, 2004; Hmelo-Silver & Pfeffer, 2004; Kitamura et al., 2004; Liikkanen & Perttula, 2009; Moss et al., 2006
Goals	Coding scheme for the OPERATORS of decomposition heuristics used	Coding of decomposition heuristics using the NVIVO Software	Chu et al., 2010; Goel & Pirolli, 1992; Menekse & Chi, 2018; Sung & Kelley, 2019

There were two coding processes for answering the two different aspects of representation that we separately put into the two research questions. First, the segmentation for the conceptual map covers the whole design concepts. This takes a coarse-grain segmentation approach where the non-design concepts, such as meta-statements, are coded as 'miscellaneous' and are then left out from the analysis. The coding for the first type of analysis here is targeted at depicting the entire control system of the participants as they adopted the function-space search. This entails tracing the knowledge units into conceptual maps including the rejected functional concepts. This means that every participant's conceptual map is *unique* because they depict each participants' representation of the design problem. Since the depiction is to illustrate the change in the nature of the participants' problem representations, both the pre- and post-intervention protocols of the selected participants were taken as data. This is to make due comparisons between the pre- to post intervention representations of problems.

There were 16 conceptual maps (8 pre-intervention~~,~~ and 8 post-intervention maps) which were further described and explored by bringing in the actual protocol quotes from the participants where necessary. The findings of this conceptual mapping analysis are visual depictions of the entire control systems that illustrate the glaring difference in the recall of concepts.

Second, since we were also interested to explore on the decomposition operators used by the participants, we turned to the fine-grained segmentation that were available based on the Experiments 1 and 2 data. In this third-pass coding, we reduced the scope of operators to when the participants used the function-space search only. This is shown in the following figure. This is also to uncover the implicit decomposition that is not directly expressed verbally but only detectable through the identification of sub-functions and neighbouring principles based on the stated functionalities in the protocols. As a reminder, the protocols were the same data used during Experiments 1 and 2. The first-pass coding was the 'function', 'behaviour', 'structure', 'people', 'purpose' and 'resource' coding; the second-pass was the transition analysis coding. The first and second-pass coding were meant for quantitative analyses.

The NVIVO software has features that can highlight the coded parts of the protocol with coloured stripes as shown in the following two figures.



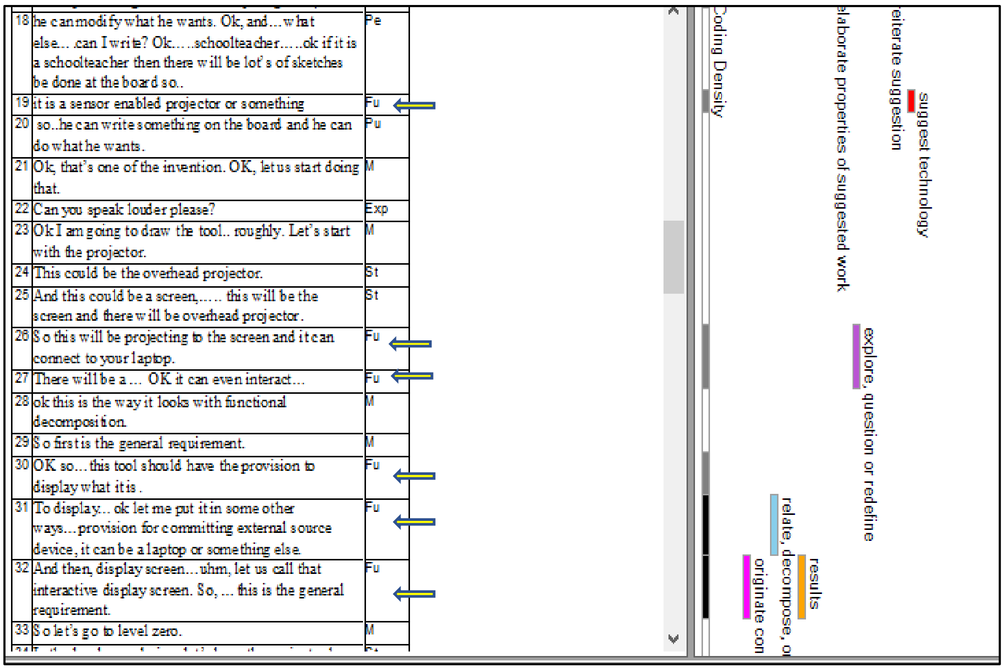
Files

P3 (2)

Click to edit

		3Nara PH3
1	Use the strategy as far as you can remember.	Exp
2	Invent a tool that a schoolteacher might use.	Exp
3	Schoolteacher might use... that's all?	M
4	Yup...	Exp
5	Ok, I can use any technique that I have seen and used so far, right? Schoolteacher might use....ok...it is going to take a long time for me...	M
6	Do I have to do the designing the way I did for the previous one or...	M
7	Yup	Exp
8	I have to do that?OK	M
9	In the first phase I read... was just explaining the stuff, explaining the tool,	M
10	and the second phase I read everything, functional decomposition so.... I will be doing those things here...so..	M
11	OK as a teacher. He will be collecting information for his children.	Pe
12	And he will be displaying things to the students.	Pe
13	This will be the basic thing.	M
14	Basically the most useful for him...	M
15	So tool, ok, ...let's have some projection tool that is combined with...	Fu
16	it can be connected to a laptop or something... and......we can start you know. Portable projection to... portable projector.	Fu
17	And with some functionalities, with some sensors he can explain things he can write anything on it,	Fu
18	he can modify what he wants. Ok, and... what	Pe

(…Image continued below)



18	he can modify what he wants. Ok, and... what else... can I write? Ok.....schoolteacher.....ok if it is a schoolteacher then there will be lot's of sketches be done at the board so..	Pe
19	it is a sensor enabled projector or something	Fu
20	so..he can write something on the board and he can do what he wants.	Fu
21	Ok, that's one of the invention. OK, let us start doing that.	M
22	Can you speak louder please?	Exp
23	Ok I am going to draw the tool.. roughly. Let's start with the projector.	M
24	This could be the overhead projector.	St
25	And this could be a screen,..... this will be the screen and there will be overhead projector.	St
26	So this will be projecting to the screen and it can connect to your laptop.	Fu
27	There will be a .... OK it can even interact...	Fu
28	ok this is the way it looks with functional decomposition.	M
29	So first is the general requirement.	M
30	OK so... this tool should have the provision to display what it is .	Fu
31	To display... ok let me put it in some other ways...provision for committing external source device, it can be a laptop or something else.	Fu
32	And then, display screen....uhm, let us call that interactive display screen. So, ... this is the general requirement.	Fu
33	So let's go to level zero.	M

NOTE: We coded the function statements ('Fu') only. The function segments are marked with the yellow arrows.

Figure 7. 2: The Coding Stripes (colourful marks on the rightmost column) that indicate exact locations of coded protocols.

We coded only the segments already coded with ‘Fu’ (the initial for ‘function’) codes. After conducting a thorough coding of all the transcripts, we came up with 17 codes explained earlier in the ‘Instrument’ section.

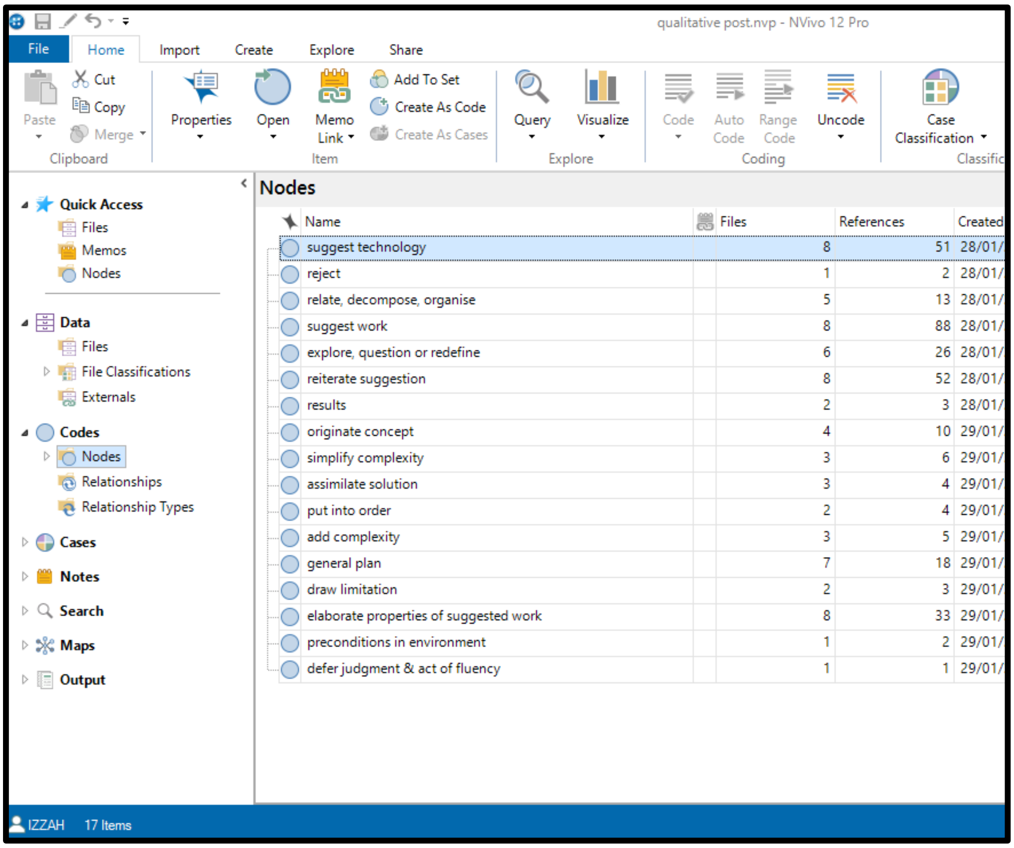


Figure 7. 3: The finalised operator codes on an NVIVO display (17 codes).

The software was helpful during the coding. Through it, the implicit decomposition was made explicit, and we ensured that no interesting interpretations are left out from the coding of the function statements into further properties.

It is rare to find explicit statement such as, “I am splitting the functions into three sub-functions”. What we have found from the previous experience in the analysis of the Experiment 1 and 2 instead, was decomposition that can only be traced through linking words such as “because”, “in addition” and others. However, this is also subjective. The most identifiable decomposition is through detection of suggested technological solutions and other direct function-related expressions. This is the reason why the coded segments from Experiments 1 and 2 are still relevant for our current analyses, except that we eliminated utterances other than function statements. The segmentation and coding procedures in general are to sample the most relevant data units. As Chi (1997) put it:

> Once verbal data are collected and transcribed, the first step of the analysis is for the researcher to decide whether to analyse the entire corpus of the protocols or some samples (Chi, 1997, p. 282).

Briefly, the coding details out the properties of the goal definition through the use of decomposition operators. This means functional search operates in many different moves; the function search allows dynamic revisions of the representations. Although all the decomposition operators are not quantitatively rigorous for theory-testing, the treatment of ‘function’ as a design concept into one big category is also unjustifiably the right approach since the meaning of function is utterly rich and deep (Bohm et al., 2017).

The current study attempts to explore the decomposition operators with reference to the Literature Review conducted. The quantitative analysis only measured the quantity of the function codes, and this reflects the merit of function as an important design aspect. However, the cognitive processes can be analysed qualitatively and more richly by exploring the implicit operators that made all the decomposition and structuring of function possible.

One of the contributions of this qualitative analysis is that we provide the preliminary language for decomposition operators as far as functional search is concerned. This richness explains elements that are complex yet explainable in the problem representations (Linsey et al., 2010; Moss et al., 2006). The operators can move problem-solvers from one state to another to develop the design conceptualisation. The ‘moves’ are detectable in the participants’ expressions. Operators that bring a problem-solver closer to the goal, i.e.: the design descriptions are also proven by the progress in design. There is no sufficient, ‘start-to-finish’ progress in the non-complex shallow and arbitrary search, since there is no steady transformation of design conceptualisation.

7.4 Results

The results section will be divided into two sub-sections. Each represents the two different aspects of the representational change (in line with the two research questions) among the selected participants.

7.4.1 The conceptual maps showing participants control system based on functional representation

In this section, first, the general summary of depth- versus breadth-first search is presented in Table 7.4.

Table 7. 4: Summaries of the control system used by the subjects

PARTICIPANT	PHASE	STRUCTURAL RECOGNITION (%) (Simple Search)	DEPTH-FIRST (%) (Suspended input-output specifications)	BREADTH-FIRST (%) (Immediate input-output specifications)	Number of DEAD-ENDS (Mental clutter/ stuck)
P3	*PRE*	*50*	*50*	*0*	*1*
	POST	0	0	100	0
P5	*PRE*	*0*	*80*	*20*	*2*
	POST	0	0	100	0
P7	*PRE*	*20*	*60*	*20*	*1*
	POST	0	10	90	1
P9	PRE	*90*	*5*	*5*	*0*
	POST	0	5	95	0
P23	*PRE*	*100*	*0*	*0*	*5*
	POST	0	0	100	0
P24	*PRE*	*90*	*0*	*10*	*0*
	POST	0	20	80	0
P26	*PRE*	*10*	*90*	*0*	*1*
	POST	0	0	100	0
P27	*PRE*	*100*	*0*	*0*	*3*
	POST	0	0	100	0

Notes: Pre-intervention scores in Italics

Based on the table above, the FD intervention has changed the participants' control system. The search through the space can be inferred from the breadth-first search strategy adopted by the participants after the FDI and FDII interventions. Further, a lot of structural searches are recorded amongst the participants before the interventions were given. Since the structures are recalled in bulks, no decomposition can be commenced, and this is illustrated in the small number of concepts recalled. Moreover, the FD intervention has successfully helped the participants in avoiding mental clutter problems where unfruitful progress is seen along the lines of a given concept. Initially, before the intervention, all of the participants faced trouble getting stuck during the design ideation except in one case.

Next, the conceptual maps present the depictions of concepts that are cited from the actual protocol transcripts. Apart from the recall of key concepts, the maps also illustrate the: (i) **abstraction hierarchies** into several levels as the effects of control system based on the functionality that allows extensive free addition of functions that fill in the definite scopes; and (ii) **origination of function names** that has never existed before to integrate the design conceptualisation into coherent representations.

In the following conceptual maps, the straight lines (______) link the concepts directly uttered as a succession to each other based on the heeded protocols. A lot of straight lines represent~~s~~ a depth-first search. The numbers (e.g.: “1, 2, 3…”) show the flow of the conceptualisation. The dotted lines (**…**) show the illogical visit to the upper-level concepts. A lot of horizontal dotted lines represent~~s~~ a breadth-first search. The quoted words in bold (e.g.: **“digital signal”**) are new function names originated based on the participant’s protocols. The cross marks (“X”) indicate dead-ends.

7.4.1.1 The Nature of Abstraction Hierarchies and New Concepts before the FD Interventions

Before the intervention, the majority of the selected participants conducted a depth-first search, defined as a control system that arbitrarily recalls a diverse design concept and avoids any immediate exploration of ~~a~~ particular concepts. A lack of look-over behaviour was identified as there are a lot of dead-ends, showing no explicit integration of diverse solutions into a single coherent conceptualisation.

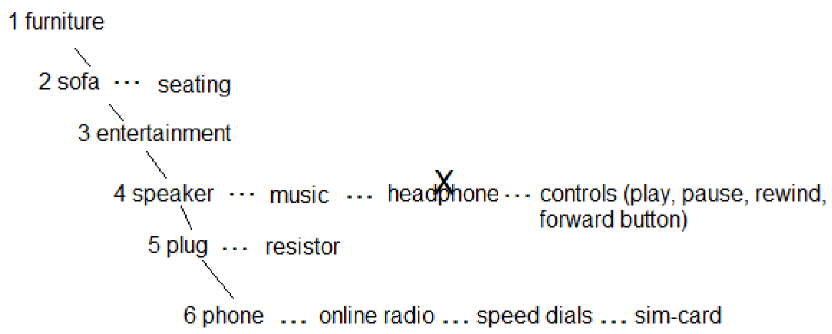


Figure 7. 4: P3's Conceptual Map (Pre-Intervention Phase, TASK C)

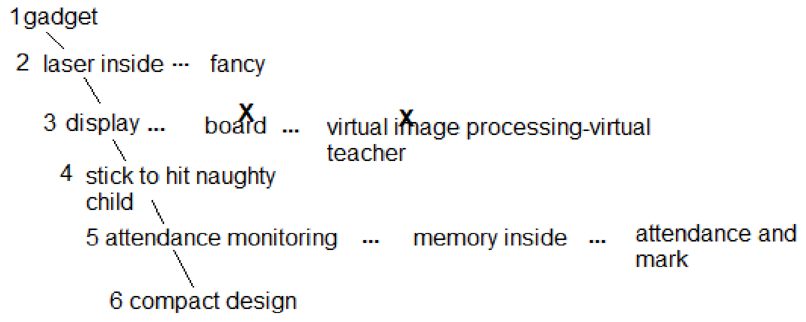


Figure 7. 5: P5's Conceptual Map (Pre-Intervention Phase, TASK B)

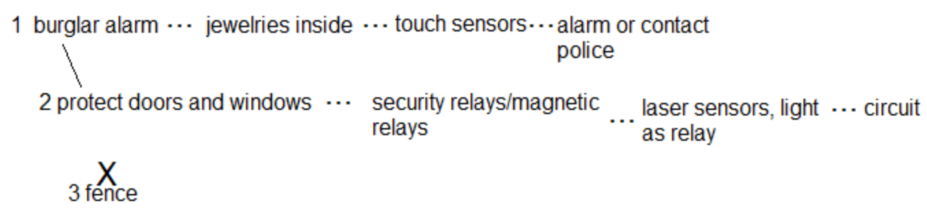


Figure 7. 6: P7's Conceptual Map (Pre-Intervention Phase, TASK A)

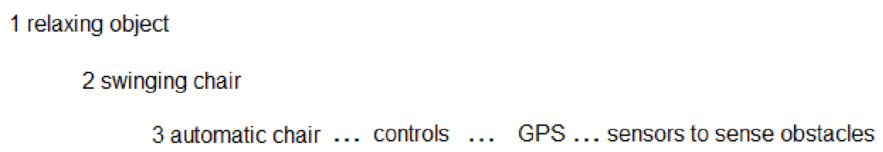


Figure 7. 7: P9's Conceptual Map (Pre-Intervention Phase, TASK C)

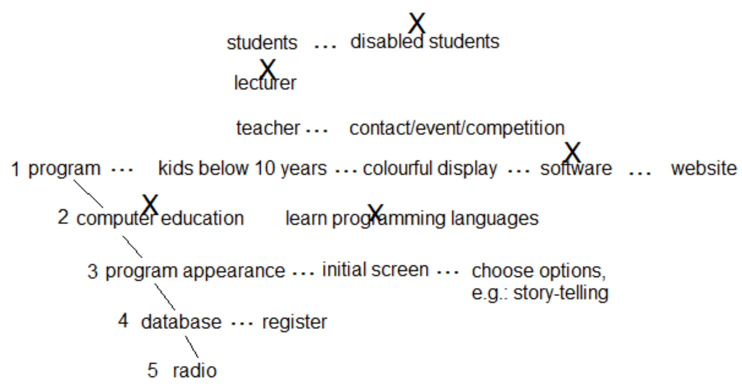


Figure 7. 8: P23's Conceptual Map (Pre-Intervention Phase, TASK B)

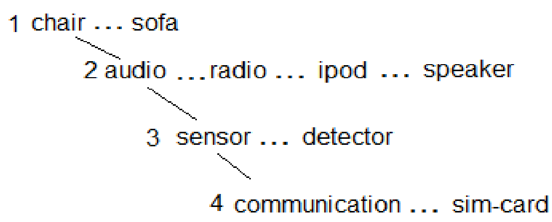


Figure 7. 9: P24's Conceptual Map (Pre-Intervention Phase, TASK C)

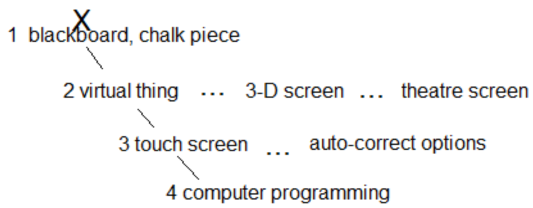


Figure 7. 10: P26's Conceptual Map (Pre-Intervention Phase, TASK B)

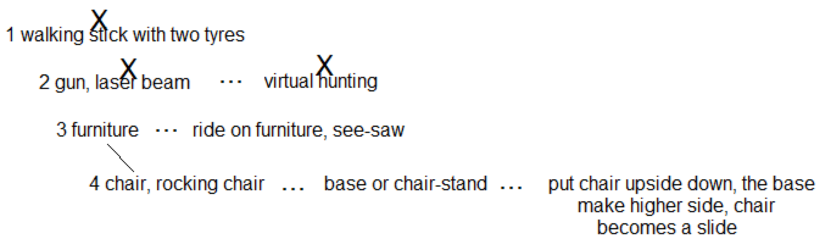


Figure 7. 11: P27's Conceptual Map (Pre-Intervention Phase, TASK C)

Furthermore, the conceptual space is considerably small due to the limited amount of concepts. This indicates a shallow design abstraction into only one or two levels of hierarchies. For example, based on the protocols, Participant P9 said:

> "So basically I want to design a thing that they are going to relax on it and also….uhm, you know, they need to feel you know like..what is the altitude…so that they feel very happy about that, so a chair, a swinging chair, OK. [Drawing]…a swinging chair, anytime a blind people can sit on that for swinging…

> Anytime they feel like, OK they feel relaxed, more relaxed and also feel the air. And also feel not so lonely, feel like a child, enjoy the moment something like that…
> Any other thing? May be this thing can be used only at home but when they go out this thing can't come to use.
>
> So I am going to draw you know like automatic chair…hm….full of controls, digital controls, having some sensors tool, which can actually guide them…. where to go. Like, if there is any obstacle, they don't have to ask someone else,…
>
> …In thinking of that I designed this chair. Another thing is that I find it hard you know every time I go out using a walking stick, so it will be better like I use GPS or something. If I have better maps without his knowledge, he will definitely don't fall. And find correct way to get back home."

The following is the sketch of furniture by this participant.

Figure 7. 12: The P9's Sketches for Task C (Pre-Intervention)

Another protocol excerpts from participant P24 (Pre-Intervention, Task C) regarding the incident of dead-ends are shown below.

> "…furniture, furniture, furniture…I could make all furniture which is…transmit sensor….
> but it should give entertainment as well…what other furniture can we do…trying to find something, trying to find something…….uhm…blind people, blind people, furniture, sofa, uh.. this is for entertainment….[write the requirement] and blind people [write this] so…basically only it has got

> be audio..[write this] there is no vision, yes…may be uhm…we need some smart stuff…hm….I am stuck. Hm, if I am stuck can I wait for the next 15 minutes, I mean I can't think of anything else."

Participants were found to be wandering around similar concepts without naming any verbal expressions or conducting input-output analysis that can guide the search through controllable and explainable concepts.

7.4.1.2 The Nature of Abstraction Hierarchies and New Concepts after the FD Interventions

Here, the following conceptual maps are compared with the maps of the same participants during the pre-intervention phase above. The qualitative analysis through the depiction of participants' conceptualisation provides real data on the nature of the control system as one criteria for establishing representations during problem solving. The data revealed that representations do not have to provide the maximum number of alternatives for one given task, as this is not the way the working memory operates. After the FD interventions, the participants had produced more functional concepts. Moreover, more intricate linkages between concepts were identified using the breadth-first strategy. There were no dead-ends and thus, search traverses through promising concepts that satisfy the design requirements. This is illustrated in the following conceptual maps.

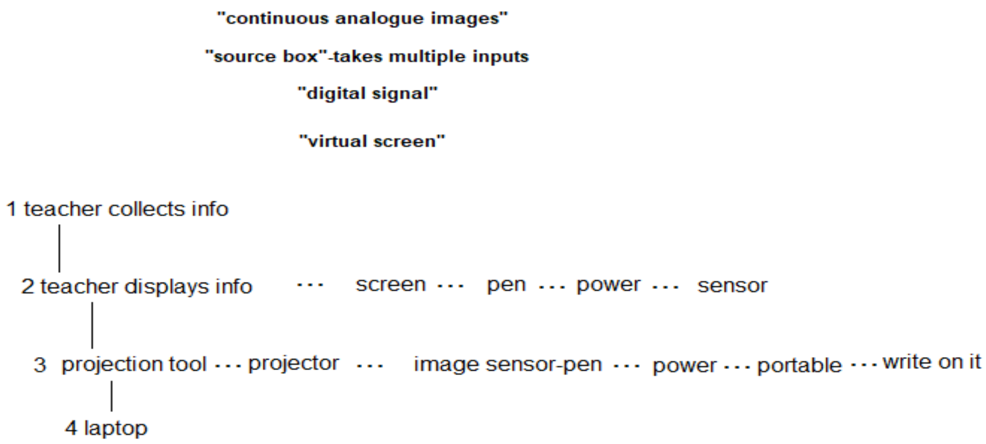


Figure 7. 13: P3's Conceptual Map (Post-Intervention Phase, TASK B)

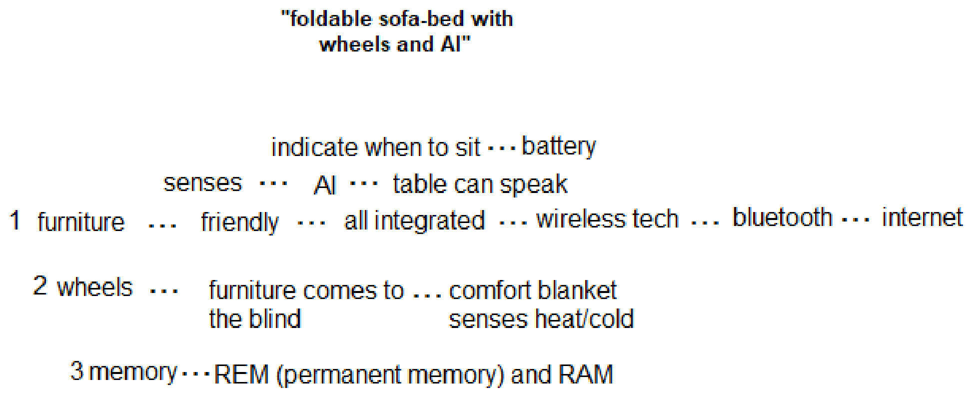


Figure 7. 14: P5's Conceptual Map (Post-Intervention Phase, TASK C)

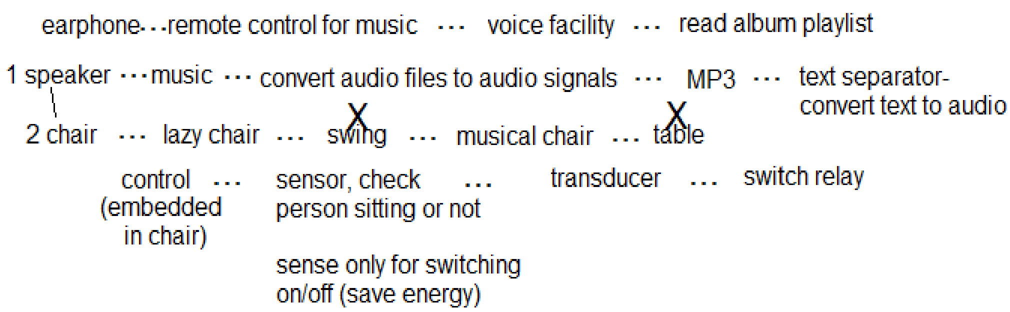


Figure 7. 15: P7's Conceptual Map (Post-Intervention Phase, TASK C)

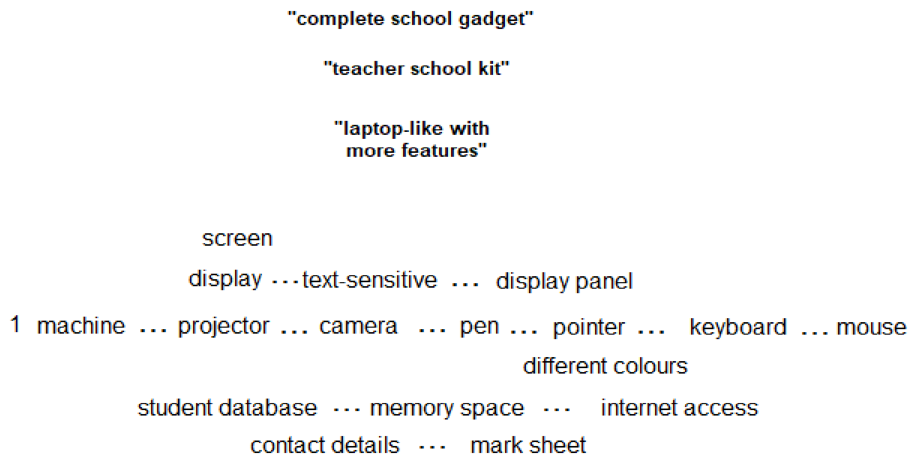


Figure 7. 16: P9's Conceptual Map (Post-Intervention Phase, TASK B)

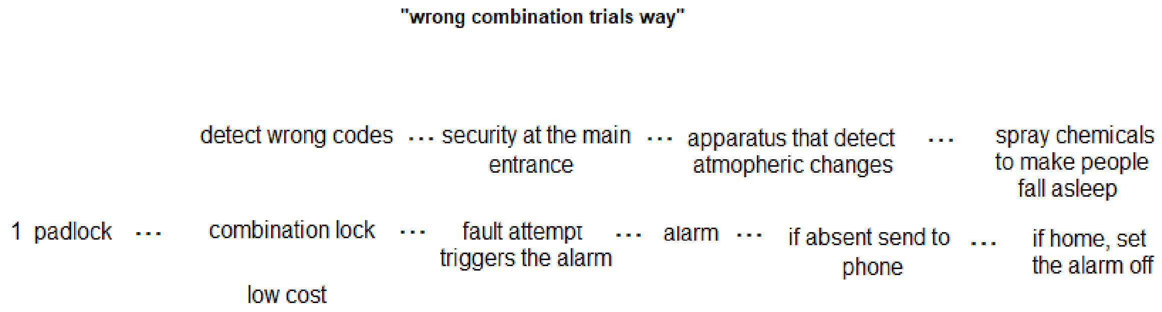


Figure 7. 17: P23's Conceptual Map (Post-Intervention Phase, TASK A)

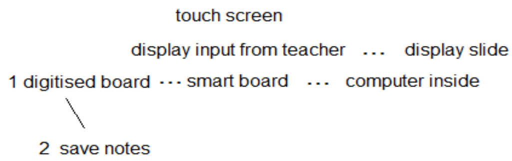


Figure 7. 18: P24's Conceptual Map (Post-Intervention Phase, TASK B)

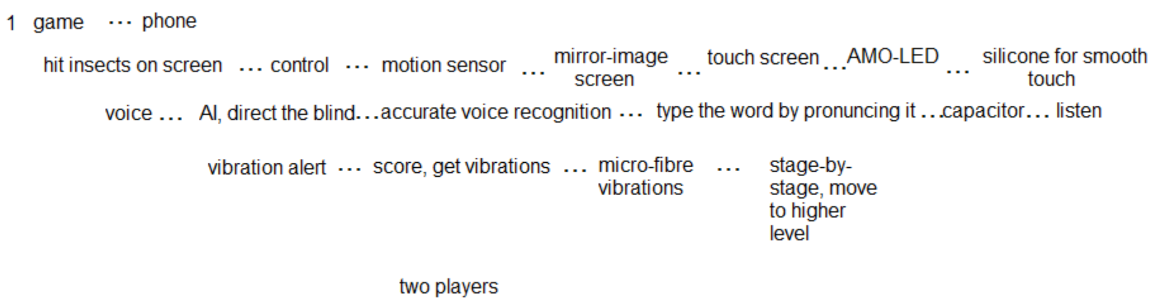


Figure 7. 19: P26's Conceptual Map (Post-Intervention Phase, TASK C)

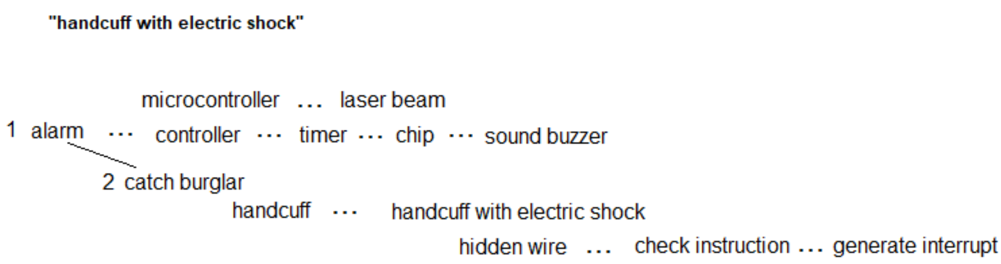


Figure 7. 20: P27's Conceptual Map (Post-Intervention Phase, TASK A)

Based on the conceptual maps (Figures 7.36 to 7.43), more concepts are recalled despite the smaller picks of initial general functional concepts. The FD intervention helped in explicating the implicit concepts that are recalled in a non-arbitrary manner; more concepts are listed horizontally. The following protocol excerpt from Participant P7's protocols (Post-Intervention Phase) show how FD helped control the trafficking of information.

> "Because most of them know what the music player does…it just converts the audio files into uhm..audio signals. So I don't need to define this one, right? It is subdivided, I don't need to subdivide like…The music player is basically a digital file. To code the audio signal, and uhm, with this it converts from…but this have the subvalues…or…subsystem like…what the…now it has, OK ya, now it has changed actually! First like the whole system was like big, this things..but now the MP3 player …and every thing we have..just we have uhm, BSP chip actually, and the DSB software that's it.
> So what it does is, using this hardware, using this software what it does is, it converts the MP3 file into an audio file that is it. "

P7 had closely followed the FDI method based on the protocols and also the sketches and annotations. The search is limited to defining the INPUT and OUTPUT relationship between all the concepts. Only after the clarification of functions was conducted that he was surprised that the solution is a well-known "DSP chip". The participants' sketches and annotations are shown in the following figure.

Furthermore, as depicted in the conceptual maps (Figure 7.19), the number of concepts was increasing as soon as participants became aware of the aspects of the device's functions that can be achieved through the implementation of several technologies. Since there were many available technological solutions, the control system ensured the integration of the entire concepts so that the flow of concepts contributed to the generation of coherent representations. This means elements of the problems can be matched to solutions as soon as the problem is structured into smaller functional elements once the levels of abstraction hierarchies are explicitly developed. This can also be seen in P9.

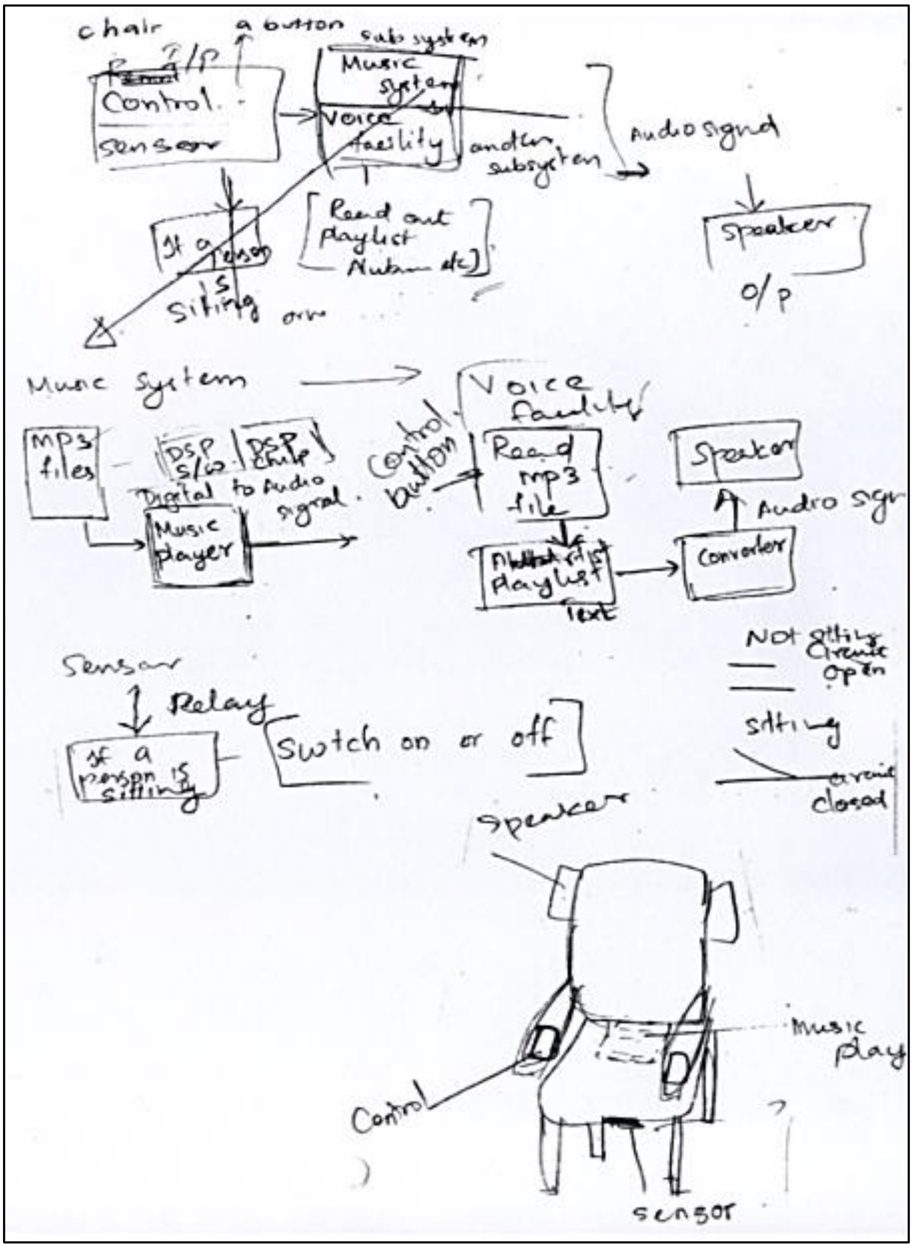


Figure 7. 21: Participant’s sketch (P7)

Participant P9 said:

“I would say this as a teacher school kit…teacher can have access…like it is a kind of laptop but with more number of features on it. Like it consists of a camera, projector etc.
it should be like….all inbuilt. It should not be complex.
It should be of the same way you know, like a laptop. So, ya, that’s all. It should have the access you know.

Input should be a keyboard, obviously a keyboard….a mouse…hm…any other things like pen drive…or anything. Output should be a display panel, a screen, and then projector display,

…and even… the teacher should see the display and the projector…then…yes, that is all.
Printer is on….so basically my idea is everything should work as a computer machine…other things like, yup projector is an extra added thing, so she can carry anywhere.
Can save a lot of money, and then huge store of memory so that she can store a huge database and access to internet then can store a lot of data or useful information. And uhm, interactive, with the use of wifi…ok these are all the things like pendrive or anything can be input.

[writing] Then I can say a detailed diagram.
So a detailed diagram could be like this,
a keyboard, and then mouse and then other peripherals.
So altogether connected to the system…. "

It can be concluded that P9 had searched along the line of functional properties of a teacher school-kit. This provided him with a streamed exploration that comes from his own recollections, rather than doing an abrupt copying of whatever images of technology that had come across the participant's mind. This is how the diagram looks like after the FDI intervention:

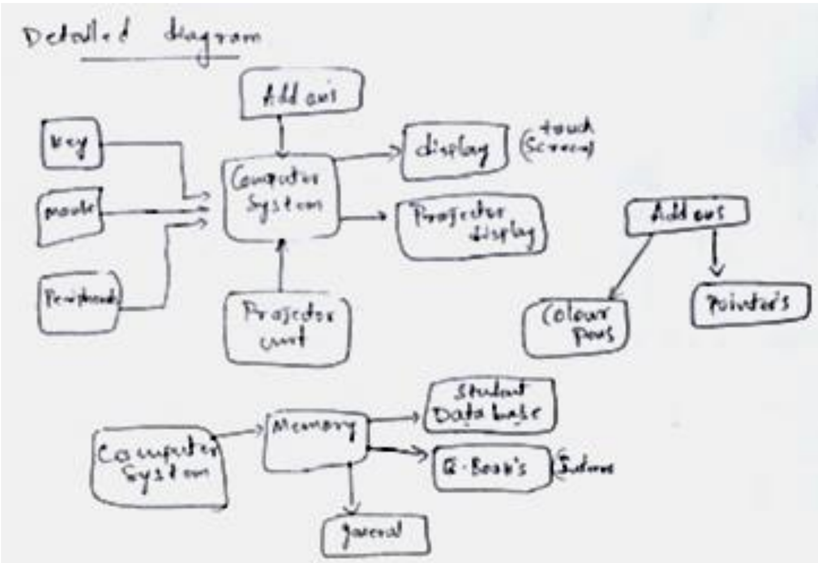


Figure 7. 22: The P9's annotations (Post-Intervention, TASK B)

Note that concepts were integrated while no object was sketched. In the same vein, Participant P23's protocols also showed manifestation of abstraction hierarchies as follows:

“So the first way is uhm…false key for padlock way [write this]. Second may be..hm..wrong trials for combination lock…[correct this]wrong combination trials way. The third one…last one..spray detector way..so these are the ways.

You know the problem may be when the burglar sprays something, some chemicals to make people fall asleep, so this problem can be solved through the secondary, supplementary function [draw circle] detect atmospheric, sudden atmospheric changes [connecting line problem to function]. This should be….use a red pen…[redraw the circles, and problem box by black pen]…………………….principles used in this case is, should be some detector…<u>signal detector</u> [write and draw in principle box] and the next one is <u>chemical constituent detector</u> [write and draw in principle box] it should detect…principles used for this would be chemicals detection in the atmosphere.
…

I use the same technique here and then there should be one more that **<u>makes (into a few) level</u>**, so what should be done. Like when the people are not at home, then the hm…..machine is trying to send a message but they are going to detect the entry of the burglar through this chip again.It is going to be rewritten again. Hm…….ok….I can set a timer, nobody is going to come to this house before this time,

So I can set a timer [write ‘set a timer’…] and then if any them need to pass a house there should be some pass codes [go back to the step 2] timer to record absence from house so if any [write this] attempt is made before that, a message is actually sent [and write all this]. So I am going to set a timer and sending the message maybe to the mobile phone, send…send a message to mobile or contact number if somebody or…someone might deactivate timer[draw a problem box].
If burglar does that we should follow the previous technique, so the solution lies here [connecting link to the first way, triggering alarm] so think of, I am done with this.

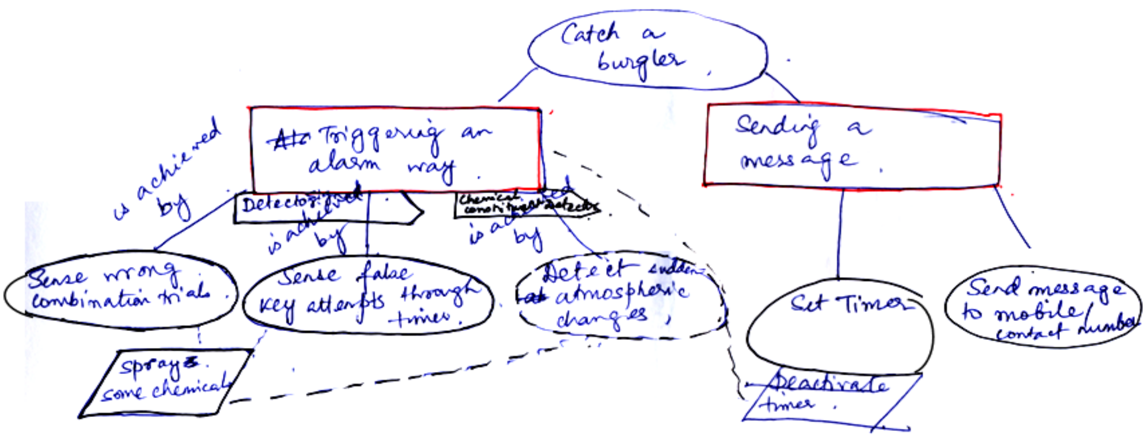


Figure 7. 23: The P23's annotations (Post-Intervention, TASK A)

The figure above shows Participant P23's annotations in a form of hierarchical diagram. Clear linking is shown between the concepts that appeared to be organised in levels.

In addition, the use of INPUT-OUTPUT for FDI method and GERUNDS and VERB-OPERAND expressions together with the *'is-achieved-by'* and '*is-a*' hierarchies for the FDII method have helped the participant in controlling the search progress. For example, this is how Participant P27 had used the Verb-Operand expressions:

> "…operand is you know, [draw a rectangle] burglar, burglar is operand [fill this in the rectangle, write'operand'] and verb is [draw a rectangle and write 'verb' on top of it] sound buzzer and give electric shock…and explore the way of function achievement is verb plus ing…[refer handout 1] by sensing…by laser beam…[redraw the sound buzzer into a rectangular shape/cancel the circle] OK…electric shock…
> this is…this is laser beam…. and the electric wire is here, and the laser beam is cut..hm…part of way function…OK….[going back and forth to the handouts]….operand, operand…[write 'operand' on the circle]."

In short, problem solving in design can be inferred from the nature of representations that are used by designers. Since FD is promoted to enhance representation-making process, a perceptually different criteria of conceptual maps are found between the pre- and the post-intervention representations. Both protocols and sketches support the conceptual mappings that were validated through the revision of the subject's retrospective debriefing, so that the analysis of the conceptual mappings captures the actual meanings of the concepts and their relationships that appeared in the heeded protocols. Based on the conceptual maps, the exploration of spaces can be characterised through the depth and breadth of the conceptualisation. This reflects the control system which restricts the relevant concepts and develops interlinkages to explicate the design solutions.

7.4.2 The participants' use of decomposition operators.

The purpose of the second qualitative analysis is to explore the change in the use of the decomposition operators as an effect of FD interventions. The following table (Table 7.11) is the descriptive findings of the pre- to post-intervention change in terms of the sub-goaling/decomposition operators used. As we have explained in the Instrument section, the coding is directed towards the identification of different types of functional expressions through the role of a function that serves to achieve the design goals.

Table 7. 5: Functional decomposition operators (Pre-and Post-intervention) used by all the selected participants

MAIN CATEGORY	SUB-CATEGORY	OPERATORS	PRE-INTERVENTION		POST-INTERVENTION	
			NO OF PARTICIPANTS	NO OF REFERENCE	NO OF PARTICIPANTS	NO OF REFERENCE
WORK	Add Constraints	*add complexity*	*4*	***5***	*3*	***5***
		defer judgment, fluency	*0*	***0***	*1*	***1***
	Goals & Sub-goals	*suggest work*	*8*	***23***	*8*	***88***
		suggest technology	*8*	***19***	*8*	***51***
NEGLECT	Selection	*general plan*	*5*	***6***	*7*	***18***
		simplify complexity	*0*	***0***	*3*	***6***
	Drop Constraints	*assimilate solution*	*2*	***2***	*3*	***4***
		draw limitations	*0*	***0***	*2*	***3***
		reject	*0*	***0***	*1*	***2***
PLACEMENT	Analysis	*elaborate properties*	*3*	***3***	*8*	***33***
		explore, question, redefine	*5*	***7***	*6*	***26***
		preconditions in environment	*0*	*0*	*1*	*2*
		reiterate suggestion	*2*	*2*	*8*	*52*
	Synthesis	*originate concept*	*0*	*0*	*4*	*10*
		put into order	*0*	*0*	*2*	*4*
		relate, decompose, organise	*1*	*1*	*5*	*13*
		results	*1*	*1*	*2*	*3*

The analysis may, however, be limited to the *existence and naming* of the decomposition operators found in the protocols of our selected participants. No plausible inference can be made due to the small number of participants. The Literature Review has identified three major categorisations of decomposition operators that are based on function analysis, which are: (i) the WORK a function is to perform; (ii) the NEGLECTED work; and (iii) the PLACEMENT of selected work. The NVIVO Software was used to code the protocols. 17 kinds of operators are found to be used by the selected participants as shown in the table above.

Due to the small occurrence of the operators, no further analysis was conducted. The NVIVO Software provided percentages of the proportions of certain coded protocols relative to the entire protocols of each participant. The highest operators (suggest work, suggest technology, reiterate suggestion, and elaborate properties) median of percentages are shown below.

Table 7. 6: The most Used Decomposition Operators

Phase \ Operator	Suggest tech (%)	Suggest work (%)	Reiterate suggestion (%)	Elaborate properties of suggested works (%)
	Median (N=8)			
Pre-intervention	2.105	2.53	0.9	0.85
Post-intervention	7.445	10.845	6.32	3.245

The relationship between the decomposition operators with the prior conceptual mapping analysis is that the former looked at the way problem-solvers control the search path, but the latter tried to adduce the actual hidden decomposition operators that are otherwise implicit. General problem solving and design operators are not our main concern here since the operators are meant to capture the organisation of functionalities only. This is because other kinds of search are not complex searches. For example, the structure-space search, as shown in the conceptual maps of some of the participants during the pre-intervention phase, are rather shallow.

7.5 Interim Discussion and Conclusion

The qualitative analyses of the extracted data from the coding processes have shown a large qualitative difference with respect to how FD has substantially affected the way participants controlled the search path, as well as the operators of decomposition. The main findings of the qualitative Case Study altogether showed a preference for the function-space search over other kinds of search. This is because before the intervention, there is a less fruitful search as inferred from the resultant shallow conceptual maps, and small number of decomposition operators (but this finding is not generalizable to other cases). The majority of the search space before the intervention may be characterised as a structure-space search, and this is presumably consistent for those participants who were not trained with FD. The structure-space search is normally accompanied with sketches of a tangible, artistic object exploration rather than a conceptual exploration.

According to Linsey et al. 2010, the structure-space search causes design fixation. We found out that there is an even worse effect of the structure-space search in that no easy integration can be made of tangible indecomposable parts, causing a ‘stuck’ situation that we marked with “X” in the conceptual maps as the dead-ends. It is impossible to move along the direction of problems that are matching to old solutions without attempting any new problem definitions. Unfruitful concepts or the dead-ends cause mental clutter, and consume energy and the limited capacity of the working memory (Korovkin et al., 2018). This may result in stopping the whole problem solving process because there is no appropriate internal representation that is recalled and can potentially be developed in the first place (Newell & Simon, 1972).

Fluency and deferring of judgment promoted in the divergent-convergent thinking trainings must not overlook the importance of relying on the most stable knowledge structure that is the basis of operating problem solutions. It is shown that even in the FDI and FDII groups, fluency operators are used (see Table 7.5). However, a closer look on the conceptual maps show that the generation of alternative options occur not at the central, but rather at the peripheral aspects of the design, presumably involving only the lower-level concepts in the function hierarchy. This is an important finding that supports ‘satisficing’ and non-divergence in design (Ball et al., 1998).

The decomposition operators show that the problem solving in design reflects all the processes of generalisation, discrimination as well as strengthening (Anderson’s ACT* Theory, Anderson, 1983). The processes of design can be referred to as the conjunction or disjunction of existing ideas. Some parts of information to be developed in design are adapted. Others are included to allow for an extensive exploration of missing concepts and components of a design. Moreover, the application and materialisation of design concepts require strengthening or deliberate testing later. Wherever applicable, disjunction happens when designers decompose and rearrange functions to avoid being succumbed to old meanings of the components (Anderson, 1993).

To make uniform concepts and connections more interesting, there were attempts to originate or coin new functions such as *"wrong combination trials way"*, *"burglar alarm with handcuff"*, and *"source box"*. A hierarchy is composed of an organisation of old and new concepts—novelty streaming from understanding the necessity of adding a new additional concept, not because of a sudden 'eureka' moment. This describes the exact quality of being inventive where new concepts are generated.

Furthermore, the participants who have been trained with FD interventions have benefited from the introduction of vocabularies that support the FD heuristics. Representation provides a situation that can be used to check one's errors. Since conceptual understanding is a continuous process, this situation can also present an opportunity to adjust, upgrade or even falsify data (Goel, 2013; Newell & Simon, 1972). Vocabularies such as 'is-achieved-by' hierarchy, 'verb-operand', 'black-box', etc. are initiated to structure a problem representation. Memory, as the cornerstone of problem solving, is enhanced using the directed recall of one's prior knowledge. Based on the findings, the similarity between FDI and FDII lies in their capability to build abstract hierarchies that can inform the layered organisation of linkages of information.

As revealed in other studies on the nature of representation in problem solving, representations that are created by the participants played significant roles in instilling awareness of the superiority of the function-space search (Moss et al., 2006). Further, the manner in which concepts are organised helped explication of problem elements that were rather implicit before the representation-making process was conducted.

In conclusion, establishing links between concepts involves practice derived from past experience. Connections made are manifestations of the rich and explicit representations that differentiate between the more knowledgeable and less knowledgeable problem-solvers (Karmiloff-Smith, 1992). Meaningless linkages result in the incompletion of concepts where no localisation has occurred. The superficial search results in jumping arbitrarily from one concept to another. This is demonstrated in the occurrences of 'dead-ends' where these are the concepts that could not contribute to the participants' conceptualisation and being dropped altogether from the entire search episode.

CHAPTER 8

Discussions and Conclusion

8.1 Introduction

This chapter starts with statements of the issues and research questions. The answers and justifications for the answers will be explained in four separate headings that represent the four questions. The link between the findings with the literature will then be discussed, and limitations of the current studies are indicated. Lastly, the recommendations for future research are laid out at the end.

8.2 The Findings and Justifications

At the outset of the thesis, we underlined some of the issues that necessitate the current investigation. There is no common ground for approaching FD in the literature. FD has not been used for the purpose of enhancing creativity and inventiveness in engineering design classrooms. The approach taken was based on the Problem Space Theory, which provides scientific evidence on the cognitive processes of creativity and discovery. Problem solving relies on the characteristics of the task environment; while the human information-processing system that is adaptive to the need of different situations remains a constant.

The intervention studies are to promote representational changes through the use of FD methods. First, the distinction between function and other design development aspects are quantitatively explored before the intervention sessions. This was to detect whether there exist patterns of implementation of function-space search even before the intervention. Second, another issue was on whether FD should be regarded as a creative method. Since the Cognitive Science field specialises in the studies on human cognitive processes rather than the measures of personal creativity aptitudes, the FD method in general can be flexibly adapted to suit creative problem solving demands, in order to be considered as a creative method. The characteristics of the creative problem solving in the domain of engineering design are different from the creativity studies of lower complexity. The inventive design problem solving requires underpinning creative acts at the highest level. Hayes (1990) highlighted that:

> I will restrict the meaning of the term (creativity) in two ways: First, I will be concerned solely with creative productivity, that is, with creativity expressed in the actual production of creative works and not with the unexpressed potential for producing such works. Second, I will be concerned only with creative acts at the highest level, that is, with the best and most valued works of our artists, scientists, and scholars (p. 135).

Therefore, in the same vein, the current study is directed towards the FD intervention in solving highly complex design problems that require creativity.

The FD method can be used in training as a proper learning agenda of a scientific problem solving in the same way conceptualisation in all learning and acquisition of skills are promoted. The implementation of FD intervention is highly relied on who the learners are in terms of their prior learning and acquired skills.

The last issue pertains to whether divergent-convergent thinking methods are compatible to the FD intervention, and if so, what the conclusions are from comparing the two methods (FD versus CPS). As we take the Problem Space Theory as the theoretical stance in the current investigation, the accounts of the effectiveness on any particular creative or non-creative design methods must be based on how the particular method promotes representational changes. Therefore, the distinction made will be based solely on the characteristics of the representations of the participants of any particular group as they adopt the given design method.

The following sub-sections detail out the comparisons we made based on the factors attributed to the representational change during problem solving, as an effect of the FD intervention programmes.

8.2.1 RQ1: Do design students naturally use FD during the process of inventive problem solving before the FDI, FDII, CPS interventions?

This first question is on who the participants are in terms of the usage of FD and the ability to create original and appropriate products before the interventions. It is found that the participants had used a lot of function search, and there is no quantitative difference across all groups with regards to the usage of function. Second, there is also no difference in terms of transitions between the design aspects. 10 kinds of transitions are found to be conducted while only four transitions are reported as being used at a greater rate by all participants. The statistical analyses showed that they did not differ in terms of transitions before the interventions were given. Third, the results on product judgment also showed that a few participants were capable of designing inventive products but no conclusive findings can be made because the difference between the rate of inventiveness among the FDI, FDII and CPS groups were not significant.

This indicates that there is no evidence to rule out the participants who have already used FD totally because all of them seem to have used function. It must also be acknowledged that some of them show a low number of utterances during the functional design aspect before the intervention, but they are only small in number.

8.2.2 RQ2: Is there change in the process of inventive problem solving after the FDI intervention?

First, the discussion looks into the results of the interventions on the cognitive processes in terms of the use of design aspects, in particular the function aspect, among the FDI participants. This is presented in the following points.

There was a significant increase in the use of function statements as an effect of the FDI intervention on the FDI participants. The most important results are even though they started the same way before the intervention, the CPS group has not changed in the use of function statements during the post-intervention phase. The FDI training has caused a drop in the structure search during the post-intervention phase, but it was not statistically significant. The FDI group has shown a significant drop in the use of purpose statements only. The small difference in people statement could be due to the fewer number of utterances of this kind in the design aspect even during the pre-intervention phase. A difference that is too small cannot be detected using statistics.

There were also significant within-group changes as a result of the FDI training. The F-F transitions have significantly increased in the FDI group. The FDI training has also caused a significant drop in S-PU/PU-S transitions as an effect of the intervention. This could be a good indication that the FDI training has helped with the mitigation of fixation (Linsey, et al., 2010).

The transition between F-B/B-F aspects of design has dropped significantly after the CPS intervention as a within-group effect, indicating a unique effect of divergence-convergence training. Descriptively, there was a rise only in the *kinds* of transitions (not in the rate of transition for each category of transition) conducted among CPS participants. The transitions between diverse spaces indicate arbitrary search, with no recall of domain knowledge (nomological constraints), but rather more on secondary social constraints.

Third, there is no effect in terms of **product** inventiveness. In conclusion, the first experiment had answered the questions regarding the credibility of the FDI method in promoting inventiveness among designers. FDI has changed the way participants approach their problem solving in a significant way, but the CPS has not.

8.2.3 RQ3: Is there a change in the process of inventive problem solving after the FDII intervention?

There was no within-group effect that is seen after the interventions in both groups. These results were similar with regards to CPS group, but not with FDII. This indicates that participants in FDII group have used a high degree of function search even before the intervention, but no within-group effect is seen.

As with the between-group effect, it is found that the FDII group is different from the CPS method with respect to the use of the 'function' aspect, and this is statistically significant.

The transition analysis tells a different story about how the intervention has changed the FDII group's method of problem solving. The transition analyses showed rapid transitions between function-to-function statements within the FDII group after the intervention. The use of the function aspect among FDII participants is not statistically and significantly higher after the intervention compared to the pre-intervention processes since they already searched in function space. However, the transition analysis shows a rapid function-to-function utterance which has improved significantly after the FDII intervention, contradictory with the low pre-intervention transitions of functions. This means that a lot of participants in the FDII group moved from one function, then immediately to another function aspect most of the time, as one of the intervention effects. The F-F transition should be high because in the schema theory, adjacency of all family concepts shows high processing in one class of information (Obaidellah, 2012).

8.2.4 RQ 4.1 How did FD change the control system from arbitrary and shallow concepts to a deeper conceptualisation of functions? 4.2 How did FD change the goal definition through decomposition and sub-goaling operators?

The Case Study has contributed to the understanding on how function, as a class of representation, is important for problem solving in engineering domain. Functions are the conceptual abstraction of engineering principles and concepts stored in the long-term memory. Functional concepts are more solvable rather than non-conceptual tangible machines or artefacts. The agents of problem solving processes are the information already embedded in the problem-solver's memory that is adapted to task environments. Therefore, adding tangible solutions from structural or perceptually cues outside of the memory is counter-intuitive to how the human information-processing system is engineered.

The qualitative Case Study answered the questions on whether there is evidence on the properties of coherent internal representations during the design problem solving. The aspects of representations that we examined are the control system; as well as the operators that drive the problem solving moves to enable meaningful information chunking and localisation (Bechtel & Richardson, 2010). The protocol analysis method provides various sources of evidence that together, converge at the point that the representational change has occurred after the FDI and FDII participants, at least with reference to the 8 selected participants. Further, the decomposition operators that were coded also revealed implicit decomposition as well as explicit decomposition that may not be clearly revealed through the quantitative analysis.

8.3 Limitations

Overall, the limitations of the current study lie in the constraints regarding the demanding conflict between measuring the 'product effect' that requires a high amount–of participation. It suffices with analysing a few participants' protocols to capture the 'process effect'. The product analysis had not been successful in gathering enough data to accurately measure any aspect of change in terms of the products due to the weak results coming from a few participants.

Moreover, design is a long process. This is the drawback of in-vitro studies like the current investigation. This is to give way to the understanding of specific phenomenon of using FD for promoting the representational change as designers started to conceptualise a design idea. Focusing only the preliminary design phase may restrict the findings to only a limited design phase. However, the current investigation leads to further questions that future studies interested in studying FD may attempt to answer, such as if FD can be implemented during the prototype-building or detailed design phase? At least, we knew that FD can potentially help design conceptualisation at the preliminary design stage. The nature of in-vitro studies makes it more practical for us to use simple design problems inTask A, Task B and Task C as stated in Chapter 3 (The "Procedure" section):

TASK A: Invent an appliance that could catch a burglar.

TASK B: Invent a tool that a schoolteacher might use.

TASK C: Invent an item of furniture for the blind that can also be used for entertainment.

However, the tasks, such as the above, are adequate for laboratory settings as far as the participants' attention span, participatory charges, and cost of design and sketching materials are concerned.

Moreover, we identify that the filtration of less skilled participants particularly in the FD method only was not easy to be executed. However, we minimised the risks of calling the wrong participants by asking: **For whom FD might be of help?** We suggest that for any class of problem that requires a problem-solver's specific knowledge of Task A and specific Skill 1, there are four kinds of probabilities. The treatment should address the actual need of the individuals. For example, the current study resembles the Learner B's situation below. The other probabilities of the categories of potential participants are also simulated, together with the suggestions. The tick mark (√) below shows the condition that necessitates FD training or any related skill:

Learner A's Situation: "I know Task A, I have 'Skill 1'":

Suggestion: No class or expert guidance needed, no skill training needed.

Learner B's Situation: "I know Task A, I don't have 'Skill 1'":
Suggestion: No class or expert guidance needed, SKILL TRAINING IS NEEDED. √

Learner C's Situation: "I do not know Task A, I have 'Skill 1'":
Suggestion: Classes or expert guidance needed, no skill training needed.

Learner D's Situation: "I do not know Task A, I don't have 'Skill 1'":
Suggestion: Class or expert guidance needed, SKILL TRAINING IS NEEDED. √

In our situation, the skilled-unskilled participants are not easily tractable. Most of the participants have searched in the function space, but they lacked monitoring of the problem space using FD operators. Unlike learning declarative knowledge, to learn problem solving takes high variability of problem solving skills, such as analytical and synthetic skills. There are also uncontrolled aspects to the inventive skill, such as their personal experience with the related devices before participating in the experiments.

The FD method is one of the various design methods. The promising methods are the ones found to be useful by many (Mehalik & Schunn, 2006; Scott et al., 2004). However, adapting a skill to solve a problem is the challenge. As all problems change and evolve, skills passively change and evolve too according to the state of knowledge. Long-term exposure to diverse problems can enhance learning transfer; while continuous learning can enhance expertise. Expertise is measurable but learning transfer (in design and other fields) is defined by how far the solutions fulfil the needs of specific transfer situations. A lot of these needs in design, however, are unique to the clients' experience. Therefore, researchers in this line should be aware of this limitation in terms of the subjective evaluation of the design success, which is not written in books and scientific journals, but only in the minds of the clients.

Design instructors and practitioners should strive to face new problems, so that knowledge can solve future unknown problems. Mathematics, as a field of knowledge, provides a range of problem solving formulas that must be tested within a wide range of task environment. Similarly, applications and software are sophistications of problem solving tools, just like the FD method we are developing. Not only should trainings of creativity be developed, they need to be tested in new situations in order to be fully utilised.

The Problem Space Theory entails problem solving and knowledge acquisition which are two important factors of success. The new concept of the final design is stored back as a new memory, after being reflected in the mind of the designer. At the backdrop of this process lies a basic information processing system. The following diagram illustrates the interaction between the available memory including the 'method store' and 'internal general knowledge'.

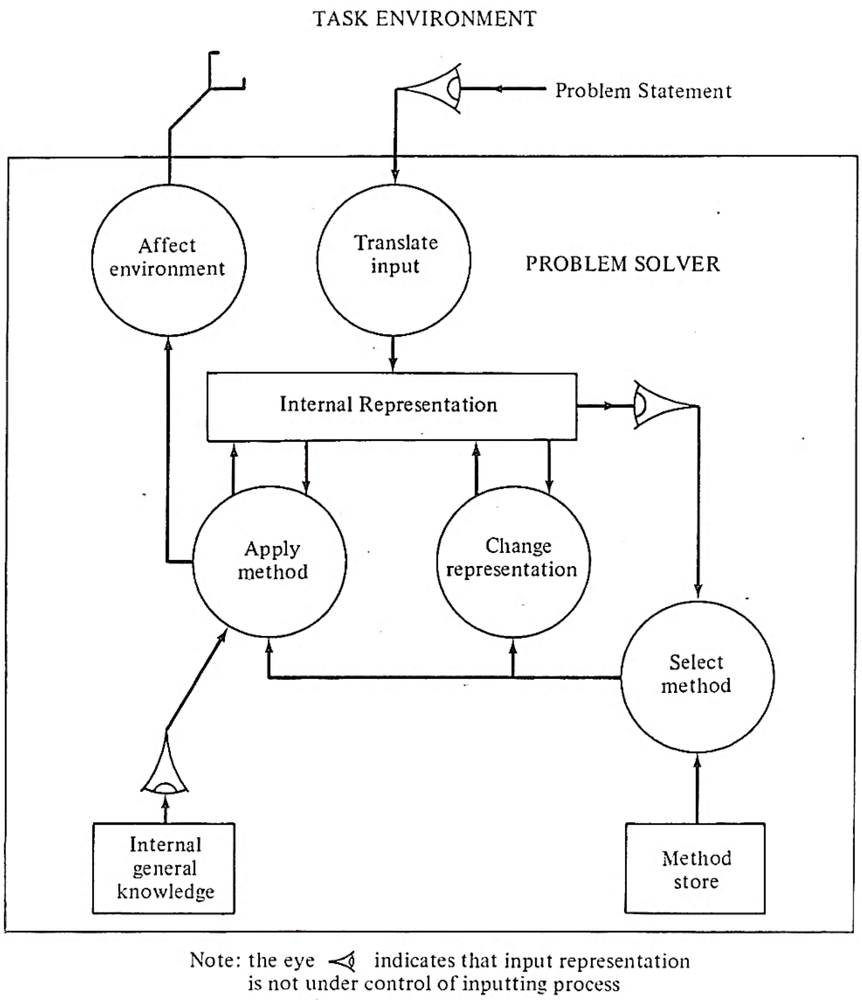


Figure 8. 1: The Components of Problem solving and the Role of Methods (Newell and Simon, 1972, p. 88).

The above shows how a problem solving method guides a problem solving process. The 'internal general knowledge' and 'method store' both reside in the available long-term memory storage. This storage system feeds new information and methods during the problem solving process. Towards the end, the long-term storage dynamically codes information about good methods together with viable information for a specific context, as a result of the new problem solving experience.

When given a task to solve, initially, the input translation mechanism produces an internal representation of the external environment. The process of problem solving proceeds in the framework of the internal representation. Once a problem is represented internally, the information-processing system responds by choosing a particular problem solving method. The method, then, informs the subsequent search. This shows that a method selected, can significantly change components in a problem representation following elements suggested by the method (VanLehn, 1989).

Methods can be less helpful when it is not given the right treatment by the users. For instance, the 'TRIZ' method (TRIZ is a Russian acronym for the 'Theory of Inventive Problem Solving') developed in 1946 by a Soviet engineer and researcher Genrich Altshuller, was used until the current time and is still undergoing improvement based on critiques. Atshuller discovered heuristics and inventive principles in TRIZ after several years of study and reviewing over 200,000 successful patents. Tsai (2008) implemented TRIZ in the domain of mechanical engineering design. TRIZ could be described as a philosophy, a methodology or a toolkit (see the figure below). TRIZ heuristics help users identify problems, solve contradictions, effectively use available resources, and understand paths of technical evolution and development. The results found that TRIZ is more practical compared to other innovation methods.

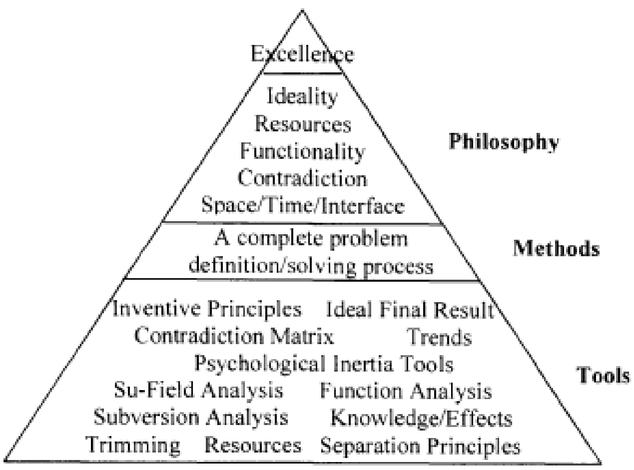


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Figure 8. 2: Hierarchical view of TRIZ (Tsai, 2008)

However, there was a low reporting on the adoption of TRIZ. Tsai found out that the factors leading to the lack of usage of TRIZ are:

i. A procedure problem as there is no specific procedure to guide users on how to use TRIZ in a design project.
ii. People have wrong impressions about TRIZ because this technique should add to the skills one has and not replace those skills.
iii. Companies' problems which includes management and commercial secrets.
iv. Psychological problems such as people don't want to learn, feel scared of changing; confused with the use of TRIZ in a design project.
v. People will expect that TRIZ should provide the final solution but not just possible directions to the final solution.

The last problem tells us that heuristic can guide one’s process of invention, but without adequate knowledge in the problem’s domain, using TRIZ turns out to be less meaningful. The findings also show that a good problem solving method is a good method only when it can serve the needs and characteristics of a problem-solver in specific domains. Also, a method is non-prescriptive but an external tool to help speed up and manage invention processes.

In addition, with regards to the creativity ratings, in fact, problem solving in design is wicked, in the sense that the designers have no privilege to be right or wrong, unlike learning and problem solving processes in benign problems (Goel & Pirolli, 1992). This is because the concern of any technological invention is the improvisation of current designs. Since technologies are made to function well, available artefacts can practically still be relevant for as long as the artefacts are visible and usable. For instance, the design of paper clips at the current day is still meaningfully acceptable and as inventive as it still appeals to the users in its own way. The rating of product’s inventiveness, as such, may be more meaningful in finding areas of technologies that have not been made available yet, and where improvements are **necessary**. Function is like a ‘grammar rule’ that necessitates an invention. The rule is also affected by the social ecosystem (i.e. constraints) apart from the rules or functions within an artefact. For instance, even though the Concorde airplane is the best at the time it was launched, it has stopped flying since 2003 due to its costly maintenance. There is no necessity of having a high-tech flight at the expense of extra funds. In fact, it costs a lot to maintain a *very inventive* artefact. Humans will resort to using available technology, so that more resource could be leveraged for other more important and basic life purposes. Technological artefacts that surround us are deemed useful for as long as human work is supported and no social norm or rule is broken. This is a reflection of the 'human-centred design' highlighted in Chapter 1.

8.4 Recommendations

There are a few recommendations for future research in the relevant areas. First, the study on Cognitive Load, especially about 'split attention' and redundancy, has widely examined the kinds of representations that are helpful in the field of multimedia (e.g.: Fenesi et al., 2016). The study of redundancy in design problem solving may inform us on specific mechanisms for maximising creativity performance, in terms of mitigation of redundancies in the external representations.

Next, the exploration from function to other spaces has been studied extensively in design. For instance, there are studies that examine the interactions between the Function, Behaviour and Structure spaces (Gero et al., n.d.; Gero & Kannengiesser, 2004; Umeda et al., 1996). We recommend taking one step back to study every aspect of design separately; the way we conducted the recent studies that only picked out the function aspect of the design to further understand this particular type of design aspect. This is done without undermining the fact that the design is a complex problem solving pursuit which involved multiple representations. It is suggested that in the field of Industrial Design, the Structure-to-Structure search, or what is coined as a 'function-follow-form' principle, can be a good approach for diversifying design ideas (Hannah, 2002). Even though this is against the 'form-follow-function' principle promoted in FD, the nature of the structure that is unfinished, ambiguous and simple yet perceptually interesting, may help designers during the later phases of the design, if not during the preliminary design phase, since the design process is long. Further, attributes of pre-inventive forms, such as an ambiguity in an unfinished sketch in a person's painting, are found to be the prime improver for the upcoming ideation according to the Geneplore Model (Finke, 1996). The structure element of the design can foster human visual imagery as long as the images are incomplete because a finished form may cause a design fixation.

The assessment of creative products is a field of study that is also developing, especially in the context of design instruction, as well as product analysis for marketing purposes that is crucial as far as the industry is concerned. We suggest that product creativity can holistically be analysed through Design Syntactic Analysis, Design Intent Analysis or Direct Functional Identification judgment methods (Kamil et al., 2019). These product analysis methods detail out the functional aspects that can be driven out through judges' markings on the actual design sketch. The drawbacks of using the general Judging Scheme, like what we used with certain criteria, is that interpretations need to be related to the judgment criteria, but no reference is made as to which component of the device fulfils which functionality.

The works on FD is still on going. FD, like any other thinking skills, should be put in context in order to be viable. Research partnership may enrich the current findings on FD. FD can be learned, unlearned (to give way to better conceptualisations of FD in the future) and also re-learned (to take new approaches from many perspectives) by the industry, design experts, anthropologists as well as Cognitive Science laboratories. There is no 'one-size-fits-all' formula for how to implement FD.

In conclusion, this thesis has answered all four research questions. For the participants that were included in the current studies, the FD interventions are found to be useful for fostering functional search, which would be reduced if such a search is not promoted, or being disrupted due to other arbitrary information, as with the case of the CPS method. The quantitative analysis covers only quantifiable aspects of the data, while the qualitative analysis that we adopted has complemented the findings through an analysis of aspects of representations on specific cases. These conclusions are subject to further investigations on the credibility of FD method in design, which may progress from the limitations highlighted in the current work.

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Appendices

(A) THINK ALOUD WITH RETROSPECTIVE REPORTS

In this experiment I am interested in what you think about when you find answers to some questions that I am going to ask you to answer. In order to do this I am going to ask you to think aloud as you work on the problem given. What I mean by think aloud is that I want you to tell me **everything** you are thinking from the time you first see the question until you give an answer. I would like you to talk aloud constantly from the time I present each problem until you have given your final answer to the question.

I don't want you to try to plan out what you say or try to explain to me what you are saying. Just act as if you are **alone** in the room speaking to yourself. It is most important that you keep talking. If you are silent for any long period of time I will ask you to talk. Do you understand what I want you to do?

1. Good, now we will begin with some practice problems.

*"**Use** the following shape to form a meaningful object others can recognize."*

(Retrospective debriefing) Good, now I want to see how much you can remember about what you were thinking from the time you read the question until you gave the answer. I am interested in what you actually can remember rather than what you think you must have thought. If possible I would like you to tell about your memories in sequence in which they occurred while working on the question. Please tell me if you are uncertain about any of your memories. I don't want you to work on solving the problem again, just report all that you can remember thinking about when answering the question. Now tell me what you remember.

2. Good. Now I will give you two more practice problems before we proceed with the main experiment. I want you to do the same thing for each of these problems. I want you to think aloud as before as you think about the question and after you have answered it I will ask you to report all that you can remember about your thinking. Any questions? Here is your next problem.

*"**Combine** the following shapes to form a meaningful object others can recognize."*

(Retrospective debriefing) Now tell me all that you can remember about your thinking.

3. Good, now here is another practice problem. Please think aloud as you find the answer to the task.

*"**Complete** the following shapes to form a meaningful object others can recognize."*

(Retrospective debriefing) Now tell me all that you can remember about your thinking.

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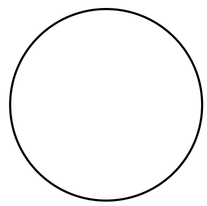
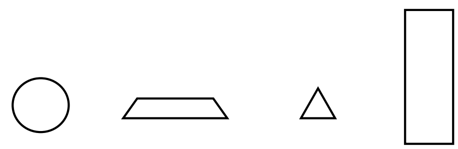
Name of participant:…………………………………………………………

Date:………………………………………..

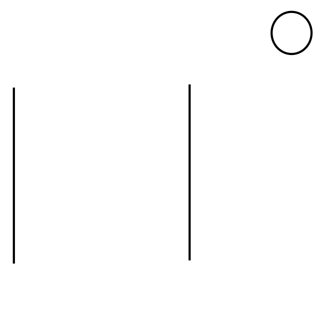
1. **Use** the following shape to form a meaningful object that others can recognize. Use the space below to sketch your idea.



2. **Combine** the following shapes to form a meaningful object others can recognize. You may vary the size of the shapes and also use the objects more than once. Please use the space below.



3. **Complete** the following shapes to form a meaningful object others can recognize. Use the shapes and do not redraw these shapes.



(B) GUIDELINE FOR PARTICIPANTS (GENERAL PROCEDURE)

Representation and Cognition Lab, School of Informatics

Cognitive Science Experiment

GENERAL PROCEDURE OF THE EXPERIMENT

Project Title: Learning How to Conceptualize an Inventive Design While Self-Explaining

PHASE 1 *(33 minutes)

- Briefing on PHASE 1 by the experimenter (3 minutes)
- Practice/screening of the participants:
Giving think aloud protocols and retrospective debriefing (5 minutes)
- Answering the problem solving task (TASK 1)
**Think aloud + retrospective debriefing + written description (15 + 5 + 5 minutes)
- Break

PHASE 2 *(60 minutes)

- Briefing on PHASE 2 by the experimenter (3 minutes)
- Read and discuss 'Self-explanation' handout (2 minutes)
- Intervention Phase:
Learning the given inventive strategy while self-explaining (30 minutes)
- Break
- Answering the problem solving task (TASK 2)
**Think aloud + retrospective debriefing + written description (15 + 5 + 5 minutes)
- Break

PHASE 3 *(28 minutes)

- Briefing on PHASE 3 by the experimenter (3 minutes)
- Answering the problem solving task (TASK 3)
**Think aloud + retrospective debriefing + written description (15 + 5 + 5 minutes)
* Time estimated which does not include breaks.
** - Think aloud means to talk aloud as one think when solving a given problem. (See attachment 1)
- Retrospective debriefing is given at the end of each problem solving session to report on the overall sequence of the processes of problem solving as far as a participant could remember
- This written description need to be in forms of essay-format writing with diagrams and sketches where details of the invented devices are outlined to ease the judgment procedure later.

(C) THE FDI MATERIAL

Handout 1

Please generate as many explanations as you can as you follow this module (pages 1 - 6). As a reminder, pause when you see this sign ( ) and try to explain the particular statement you have just read. However, you can explain more if you like.

FUNCTIONAL DECOMPOSITION PROCESS

- Functional decomposition (FD) is the analysis of the **goal** of a device. The role of this strategy in design is to clearly *define* the intended system at each level.

- As illustrated in Figure 1, Level 0 may compose of the first level design which highlights the requirements or criteria of the device. These requirements are the behavior you want the device to perform.

- Based on the requirements, structure the general input, functionality and output of the overall device. Examples will be given in Handout 2. The following chart illustrates the steps involve in FD.

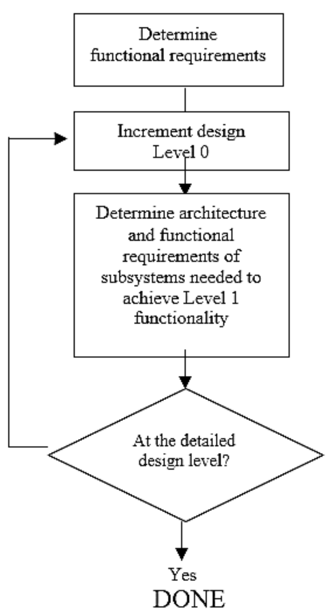


Figure 1: Functional decomposition process

- Next, break down the device's general functionality into sub functions (also called modules and sub modules). This is called Level 1 design. The interacting subcomponents and interfaces will show the overall device function. Now define the functionality of each subcomponent individually as long as it does not deviate from the original device goal.

- A detailed design level is achieved when cohesive conceptualization of a device is derived by a designer. If parts are not clear, then the device is less cohesive. Think of it as a hierarchy where a more general function is organized and defined at the higher-level structure. The goal moves from general to more specific level until a detailed and cohesive functionality of the intended device is achieved.

- The following are three heuristics of functional decomposition to remember:

1) MODULARITY: Maximize cohesion and minimize coupling.

1.1) Inventors break down their ideas into modules and submodules. Each module is self-contained and independent in that it does not share any signals, goals, or data with other modules. It can operate without one another. In other words, modules are not 'coupled'. Another purpose of functional decomposition is to minimize coupling. In contrast, if the two sub modules do depend upon each other in some way to operate properly, then they are coupled. When systems are highly coupled, it is difficult to change one without impacting the other.

1.2) To organize the whole components, you need to localise the functions and sub functions. Maximum coherence can be achieved by clearly showing how chunks of components **connect** and function in terms of *input, output* and *functionality*. Do this according to the level of complexity of the modules. For example start by four top-level functions before going into the details of the subcomponents within the modules. Any conflicts should be resolved at each level of design.

2) SIMILARITY: Gather together like components into common subcomponents.

3) SYSTEMATICITY: The subcomponents at a given level should be of roughly the same **level of complexity**.

Handout 2

EXAMPLE DIAGRAMS FOR FUNCTIONAL DECOMPOSITION

Example Task: “To invent/design scientific instrument that can tell you when the temperature changes”. The new concept chosen in this example is a “digital thermometer”.

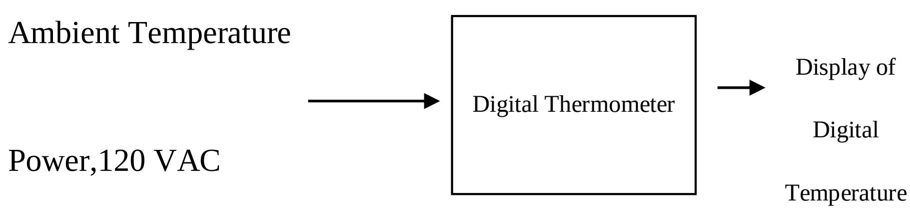
1. General requirements:

• Measure temperatures between 0 and 200°C.

• Has an accuracy of 0.35% over the entire range.

• Must display the temperature digitally, and include one digit beyond the decimal point.

2. The first level of the design (Level 0):



(INPUT)(FUNCTIONALITY-general)(OUTPUT)

Figure 1: Level 0 description of the digital thermometer.

2.1 Definition of this level of the system:

Module Digital Thermometer *Inputs* □ Ambient temperature. □ Power. 120 V AC to power *Outputs* □ Digital display of temperature. 0-200°C. A total of four digits displayed, with one digit beyond the decimal point. *Functionality* Displays temperature on digital readout with 0.35% accuracy over range.

3. Level 1 Design

- Perhaps the most important part of the design is the second level, which defines the main system architecture. The architecture selected is shown in Figure 2. It is valuable to describe the operation of the architecture at each level of the design. The content and type of diagram can vary. The concept here is to convert the temperature into an analog voltage, convert that to a digital and ultimately display it using LEDs.

- In order for that to occur, the sampled digital data is transformed from binary to binary-coded decimal, and then sent to an LED driver.

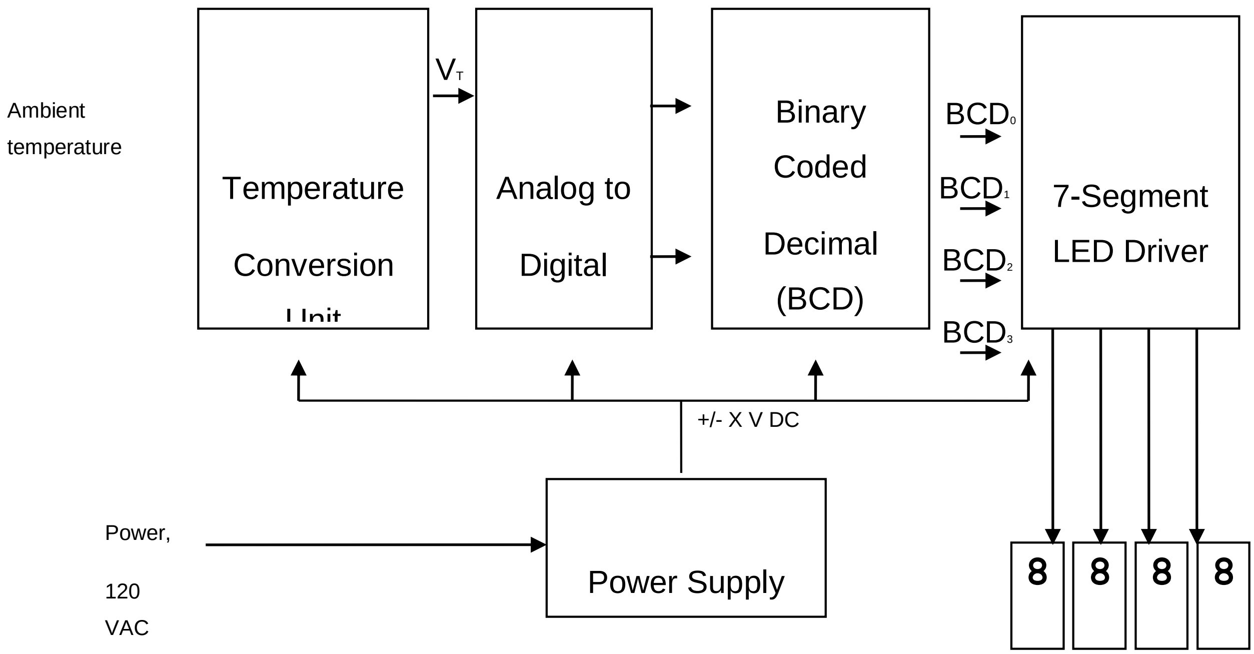


Figure2: Level 1 design of the digital thermometer.

3.1 Definition of this level of the system:

- The modules will then be described in terms of input, output and functionality.

a) Defining temperature conversion unit.

Module Temperature Conversion Unit *Inputs* □ Ambient temperature. □ Power. __ V DC to power the electronics *Outputs* □ Temperature proportional voltage. $V_T = \alpha T$, and ranges from __ to __ VDC. *Functionality* Produces an output voltage that is linearly proportional to temperature. It must achieve an accuracy of ___ %.

- It is important to identify the inputs and outputs in as much detail as possible. However, many of the details are not likely to be known on a first pass, and they are simply left blank to fill in later. Now consider the A/D converter.

b) Defining A/D Converter

Module A/D Converter
Inputs □ V_T = voltage proportional to
temperature. __ V range.
□ Power. __ V DC.
□ Clock. System clock at frequency of__ Hz.
Outputs □ _ bit binary representation of V_T.
Functionality Converts analog input to binary digital output.

- For the A/D converter there are again unknowns. The number of bits is very important since it influences the accuracy, and it can be shown that 10 bits are needed for this problem.

c) Defining BCD Conversion Unit

Module BCD Conversion Unit
Inputs □ 10 bit binary number. Represents range 0.0-200.0°C.
□ Power. __ V DC.
Outputs □ BCD_0 = 4-bit BCD representation of decimal point.
□ BCD_1 = 4-bit BCD representation of one’s digit.
□ BCD_2 = 4-bit BCD representation of ten’s digit.
□ BCD_3 = 4-bit BCD representation of hundred’s digit.
Functionality Converts the 10 bit binary number to BCD representation of temperature. Must refresh the displays twice per second.

- The objective of the BCD conversion unit is fairly simple, although the component level design of the circuitry to accomplish the conversion is not. Remember, at this stage of design you are defining your actual goal for the device. Basically, the later detail design stage will be based on these definitions.

- In the same way, the rest of the modules will then be defined according to the input, output and its functionality. This can be followed by further breaking down the sub modules into its definitions based on input, output and functionality for each sub modules within a module (which is not covered in this session). In a real design task, the more complex levels of definitions of sub modules can be done for concretization of your device’s actual functionality.

(D) THE FD II MATERIAL AND EXERCISE SHEET (SHEET A)

Handout 1:

FUNCTIONAL DECOMPOSITION PROCESS

Functional decomposition (FD) is a strategy to analyse the goals of a device. It is a useful creative process in the engineering domain, especially when you want to conceptualise an invention or solve a problem. ►

There are **two key points** to learn in this handout. In order to understand the steps for conducting FD, first, you need to recall the vocabulary of *functional concepts* which can be used to construct the whole concept of the intended device. Second, there must be clear *organisation* of all these functional concepts in a defined flow of relationships. ►

I. Kinds of Concepts

The intention of an inventor is reflected in the way the artifact's functions are being specified. To do this, inventors need to explore as clearly as possible, *how* he wants to achieve his goals and *what* exactly the target artifact's functions are. You also need to anticipate problems which might occur as a certain function is chosen. ►

1. *THE 'WHAT' FUNCTION (what goals to achieve)*

- Also called functions, sub-functions or supplementary functions which you want the device to perform. A function is an assumed role of a particular component.
- A 'what function' is **not** the name of the component which is going to perform the function (which is an agent). An operand is the thing being processed by the device. Unlike an 'agent' which is the 'actor' or the 'doer', an operand is the thing which is being acted on. ►
- A 'what function' consists of *verb-operand* word combinations. The words are defined as follows:
  - i) VERB is an action which you would like the device to perform.
  - ii) OPERAND is the object that the action is going to act on. ►
- e.g.:

verb	operand
measure	temperature
convert	signals
expand	gas
weld	metal

►

2. *THE 'WAY' FUNCTION (how to achieve goals)*

- The 'way' functions are the possible techniques or ways and principles applicable to achieve potential device goals.
- Use gerunds (*verb*+…ing) to express techniques of function achievement. A statement of engineering-related principles will accompany the gerund. ►
- e.g. :

'way'	**principle**
digitising way	*analogue to digital conversion*
labelling way	*numeric symbols*
remote-sensing way	*satellite tracking*
identity-matching way	*database checking* ►

3. *PROBLEMS*

- Problems are the unintended behaviours you need to anticipate in the outcome of implementing certain functions. It is important to detect the causative chains of faults so as to avoid any product failure and to achieve a reliable design. ►
- It is the expression of a technical problem such as:

problems
over-heating
erosion
overloading
power hungry ►

II. Kinds of relationships in a hierarchy

Drawing tree structures can help you clarify your intended device. Here, the tree is upside down: the root is at the top while the branches are placed at the bottom.

When you want to define an invention, you want to find the alternative solutions which are available and explore them in as much detail as possible. This can help to find the root concept in the tree which might be missing. ►You can decompose the sub-concepts first even before you find the heading or the root, i.e.: work bottom-up. This will increase the chance to realise whether certain concepts can be grouped. Find a single concept to be placed at an upper branch at the later stage. The upper concept should glue all the sub-concepts together. ►

The number of ways to achieve this function is generally huge, while the number of functional concepts is relatively small. Therefore, we split the two up into different types of hierarchies. ►

First, tree diagram can be used to *define ideas* you recall, where you go from the most general to the most specific definitions. Second, there are tree diagrams for *deciding the parts* of a system that are going to be included. The following are explanations and examples of each kind of hierarchy. ▸

1. *IS-A HIERARCHY (for definition of idea).*

When you explore the relationships of certain concepts from the most general to the most specific, this means you are using an *is-a* hierarchy. This relationship is concerned with how to reach the most specific definition of a system. It can be used to explore the most general to the most specific ways of function achievement. ▸

e.g.:

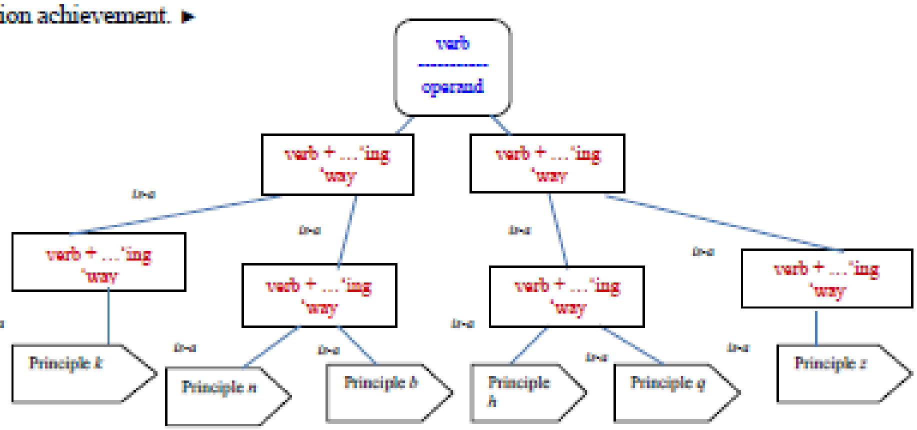


Figure 1: The structure of the *is-a* hierarchy of ways of function achievement. ▸

The following is the example of a *is-a* hierarchy for the function of 'kill creature'. There are missing words in the branches. Fill up the boxes with the given way functions or principles where appropriate.

ANSWERS:

- gradual killing way
- Injury/fracture
- Poison
- losing blood way
- Stop oxygen

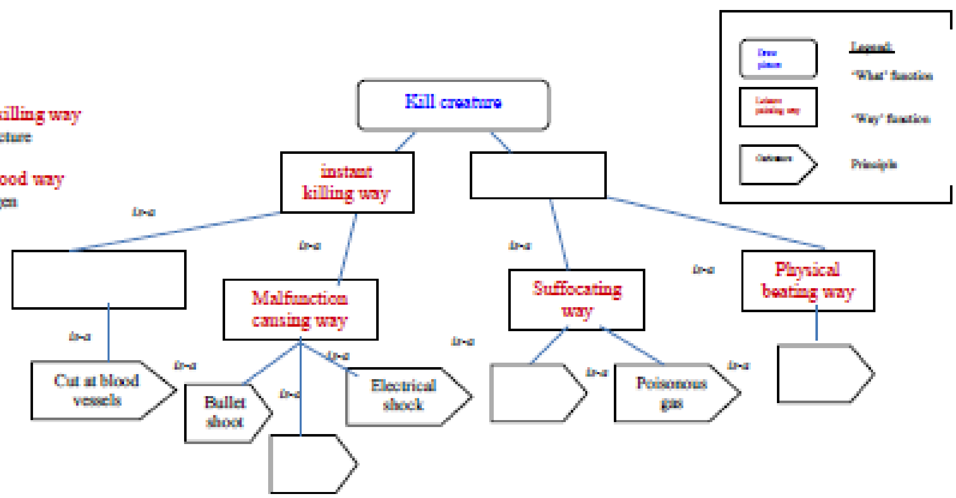


Figure 2: The full example of the *is-a* hierarchy of ways of function achievement. ▸

2. *IS-ACHIEVED-BY HIERARCHY (for deciding the parts of a system).*

Another hierarchy is the *is-achieved-by* tree hierarchy. It consists of a root function (called a macro-function) and a set or sets of sub-functions linked by the tree branches. The boxes at the branches of the tree contribute to the overall functioning of a macro-function. ►

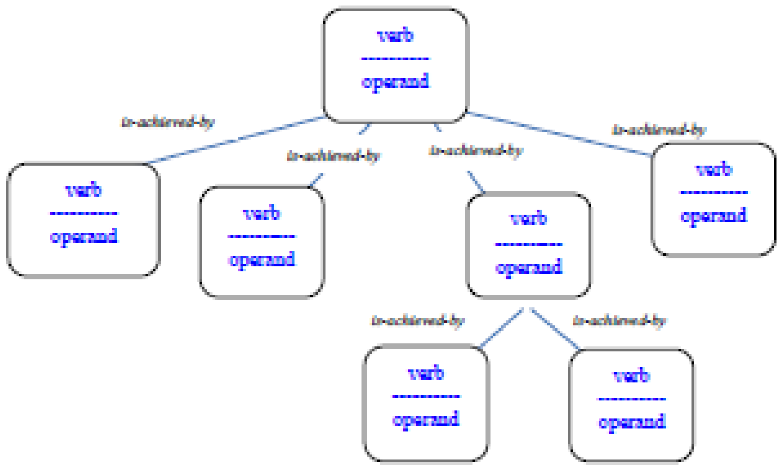
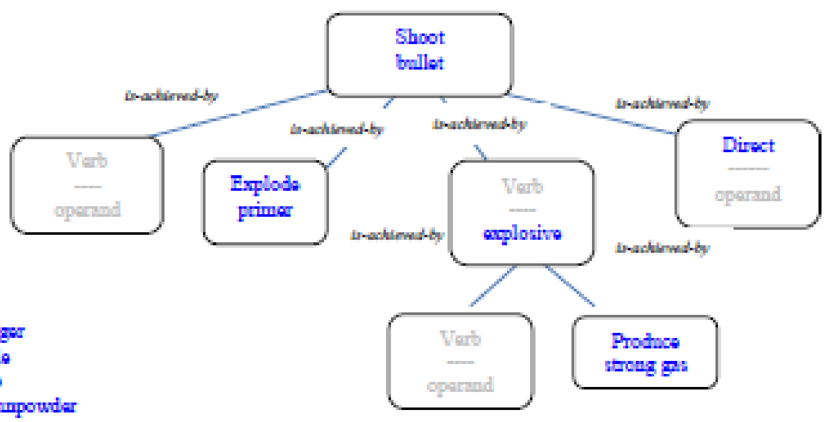


Figure 3: The *is-achieved-by* hierarchy of 'what' functions.

The following is the example of a hierarchy for exploring one of the principles (bullet shoot) to perform the instant killing way. Note that the root concept is changed into the verb-operand vocabulary so that it can fit the purpose of this *is-achieved-by* hierarchy, which is to find and expand on the parts contributing to one main function.

e.g.:



ANSWERS:

- pull trigger
- projectile
- generate
- ignite gunpowder

Figure 4: The sample *is-achieved-by* hierarchy of 'what' functions.

Handout 2:

PROCEDURE FOR EMPLOYING THE FUNCTIONAL DECOMPOSITION PROCESS

Imagine yourself trying to solve the following task:

"Invent a tool that can measure temperature".

As stated in Handout 1, you will follow the rule of verb + ..ing (gerund) for the 'way functions'. On the other hand, use verb-operand word combinations when you want to explore the relationships of 'what functions'. ►

The following table summarises the steps for conducting the functional decomposition process using tree diagrams:

STEPS	ACTIVITY	VOCABULARY	HIERARCHY
1	**Refine the question.**	verb-operand *e.g.: combine metal parts*	none
2	**Develop the *is-a* hierarchy of the ways of function achievement.**	verb + ..ing *e.g.:* *melting way; bolt and nut joining way*	*is-a* hierarchy (general to specific) ►
3	**Establish the *is-achieved-by* hierarchy of 'what functions'.**	verb-operand *e.g.: combine metal parts*	*is-achieved-by* hierarchy (a root function which composed of many sub-functions)
4	**Merge the information from all the previous steps to build a FD tree.**	verb-operand and verb + ..ing e.g.: see above	*is-achieved-by* hierarchy (a root function which composed of many sub-functions) ►

STEP 1: Refine the question.

Think of several 'what functions' to elaborate. They are hidden functionalities of the intended invention which can likely give new definitions for a particular device you want to invent. ►

For example, to invent a tool for measuring temperature can be defined as a tool that can i) sense heat and cold; or ii) a smart tool that digitises analogue data; or iii) a tool that can sense and show temperature changes through visible colouration/discolouration. Formulate a general statement. You then can expand your invention from here. ►

STEP 2: Build a tree to show ways of function achievement.

Find the alternative ways to achieve a desired function you have formulated in Step 1. Organise them in *is-a* relations of ways of achieving a function and their principles. ► The hierarchy can be very generic: use as much general knowledge as possible. Recall general principles related to your statement and at the same time think of several 'way functions' which you can use to group these principles.

Look at the following diagram for Step 2. Do you want to fill up the blank boxes of the root and branches of this tree? Use the suggested concepts at the bottom of this page to help.

e.g.:

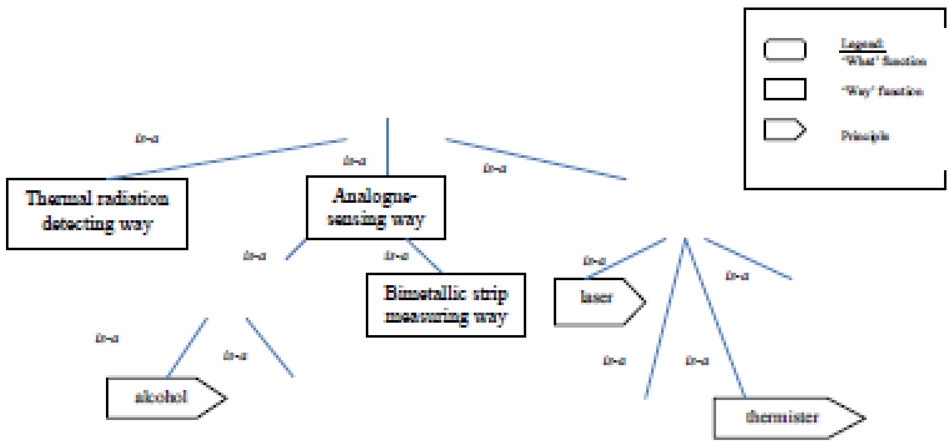
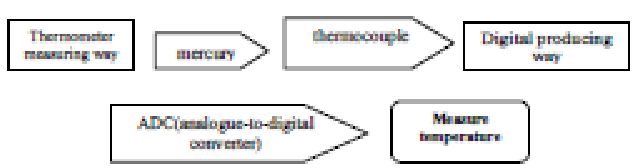


Figure 5: The *is-a* hierarchy of ways of function achievement. ►

ANSWERS:



STEP 3: Structure the tree of 'what' functions.

e.g.:

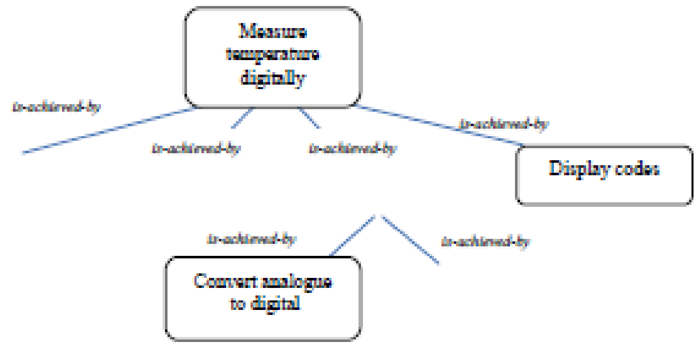
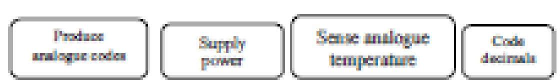


Figure 6: The *is-achieved-by* hierarchy of 'what' functions. ►

The above figure represents the *is-achieved-by* relations of 'what functions'. A device consists of the functional components or the parts that contribute to the higher level function. ► What is missing from the above tree diagram? Find the appropriate vocabularies and place them accordingly. Use the following verb-operand word combinations to complete the tree diagram.

ANSWERS:



STEP 4: Structure the complete FD tree.

In the FD tree, the 'what' and the 'way' functions are placed into one whole hierarchy. The problems and supplementary functions are also inserted. ►

e.g.:

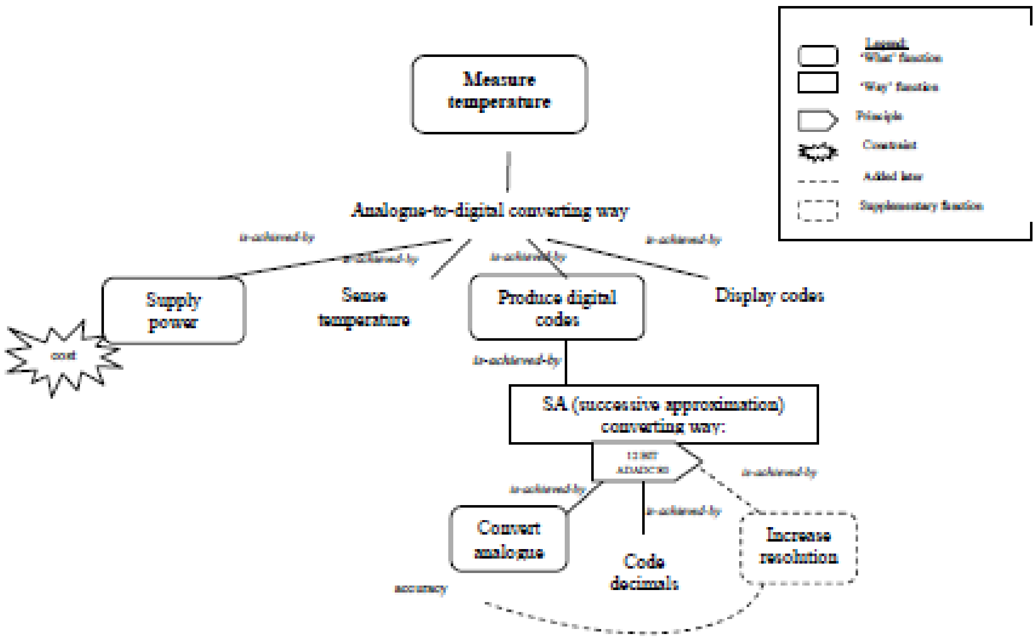


Figure 7: The FD tree. ►

Take into account what phenomena or problems could possibly occur by adding the problems at the related branches. Think about how to avoid these by adding supplementary functions. ►

Do you realise that there are five concepts at the tree branches which have not been put into the shapes? By referring to the 'legend', draw the appropriate shapes where those five concepts should be placed in.

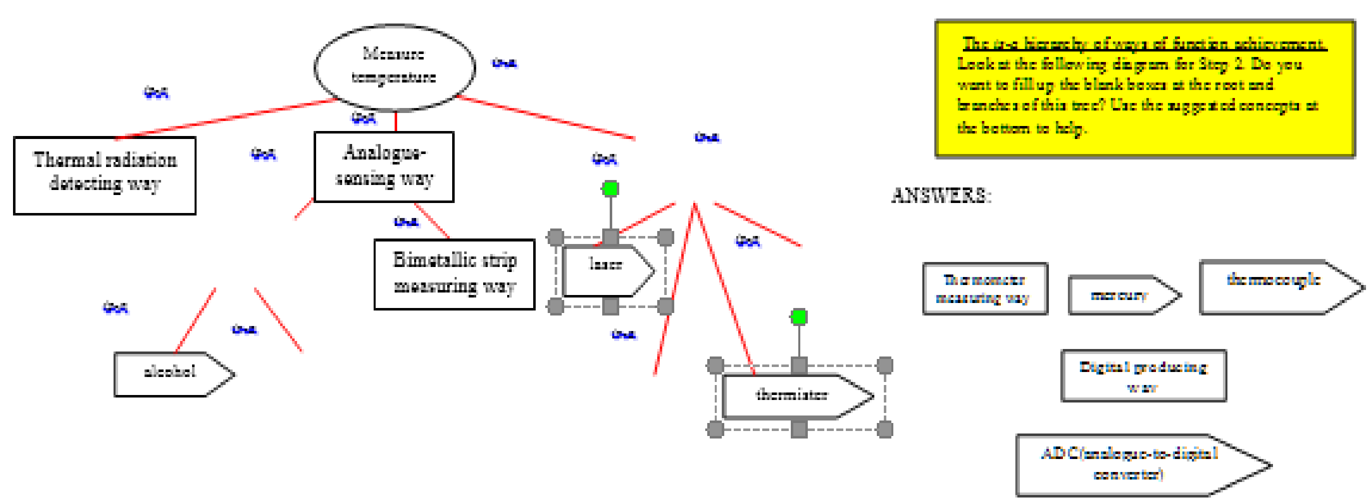
Look back and fit in new ideas into the FD tree. Be flexible.

1

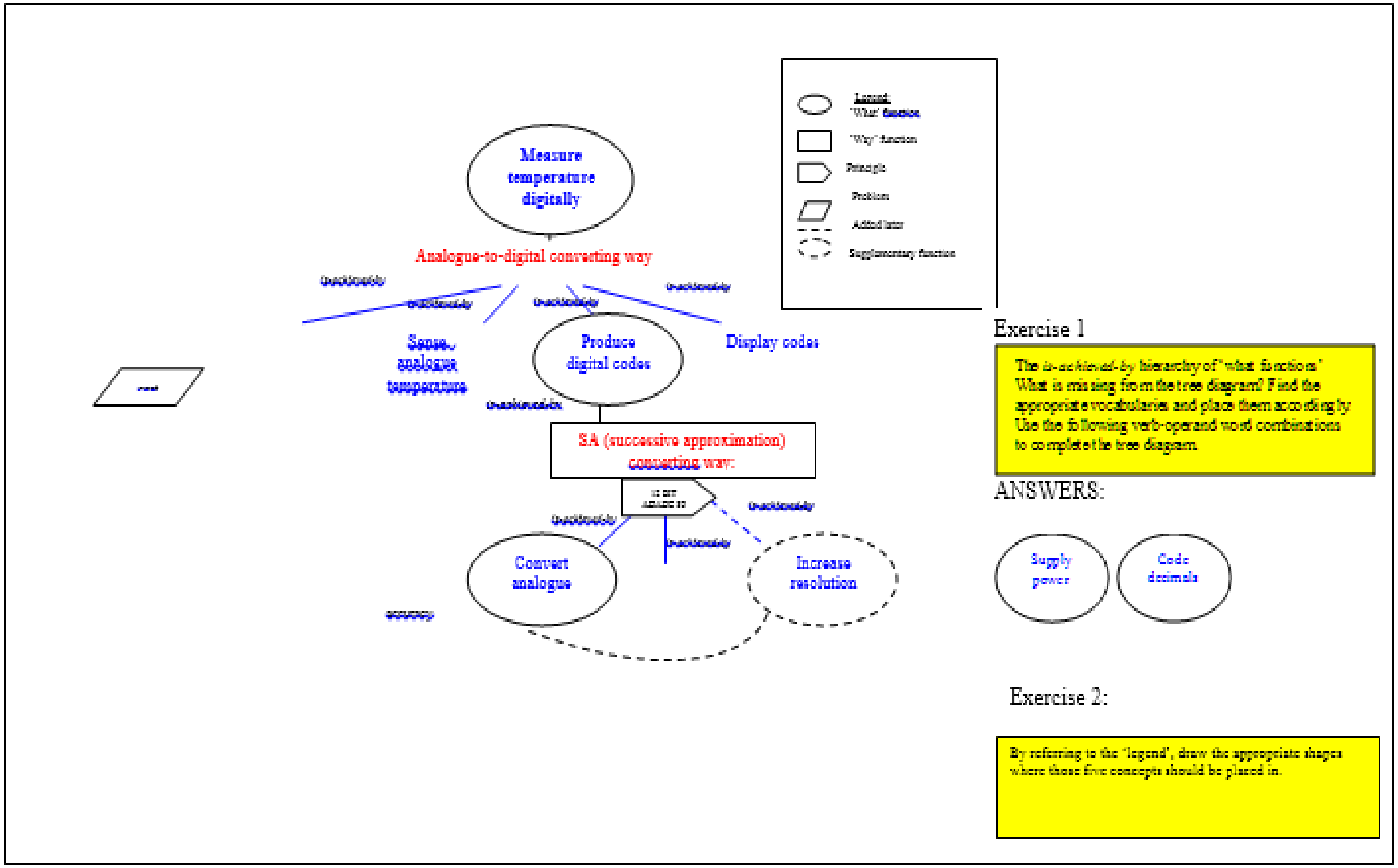
SHEET A

Invent an appliance that can measure temperature: Refinement of question:……………………………………………………………………………………

Box 1: Refine the question.



Box 2: Build a tree to show ways of function achievement.



Box 3: Structure the tree of what function and complete the tree.

(E) THE MATERIAL FOR THE COMPARISON/CONTROL GROUP

(CPS-Creative Problem Solving, Divergent-Convergent Thinking)

Handout 1

Please generate as many explanations as you can as you follow this module (pages 1 - 9). As a reminder, pause when you see this sign ( ) and try to explain the particular statement you have just read.

HOW TO ENHANCE INVENTIVENESS USING CPS METHOD

- Inventiveness can be enhanced by adopting Creative Problem Solving (CPS) as a way of thinking and behaving. CPS is a process, method, or system for approaching a problem in an imaginative way and resulting in effective action.

- The ground rules for CPS are as follows:

For Effective Divergent Thinking:

1. Defer judgment
2. Look for lots of ideas
3. Accept all ideas
4. Take time to rephrase or reorganize your data
5. Seek combinations

For Effective Convergent Thinking:

1. Be deliberate
2. Be explicit
3. Avoid premature closure

4. Develop affirmative judgment

5. Don't lose sight of your goals

- Figure 1 is the flowchart that shows the guided steps for a conducting creative problem solving.

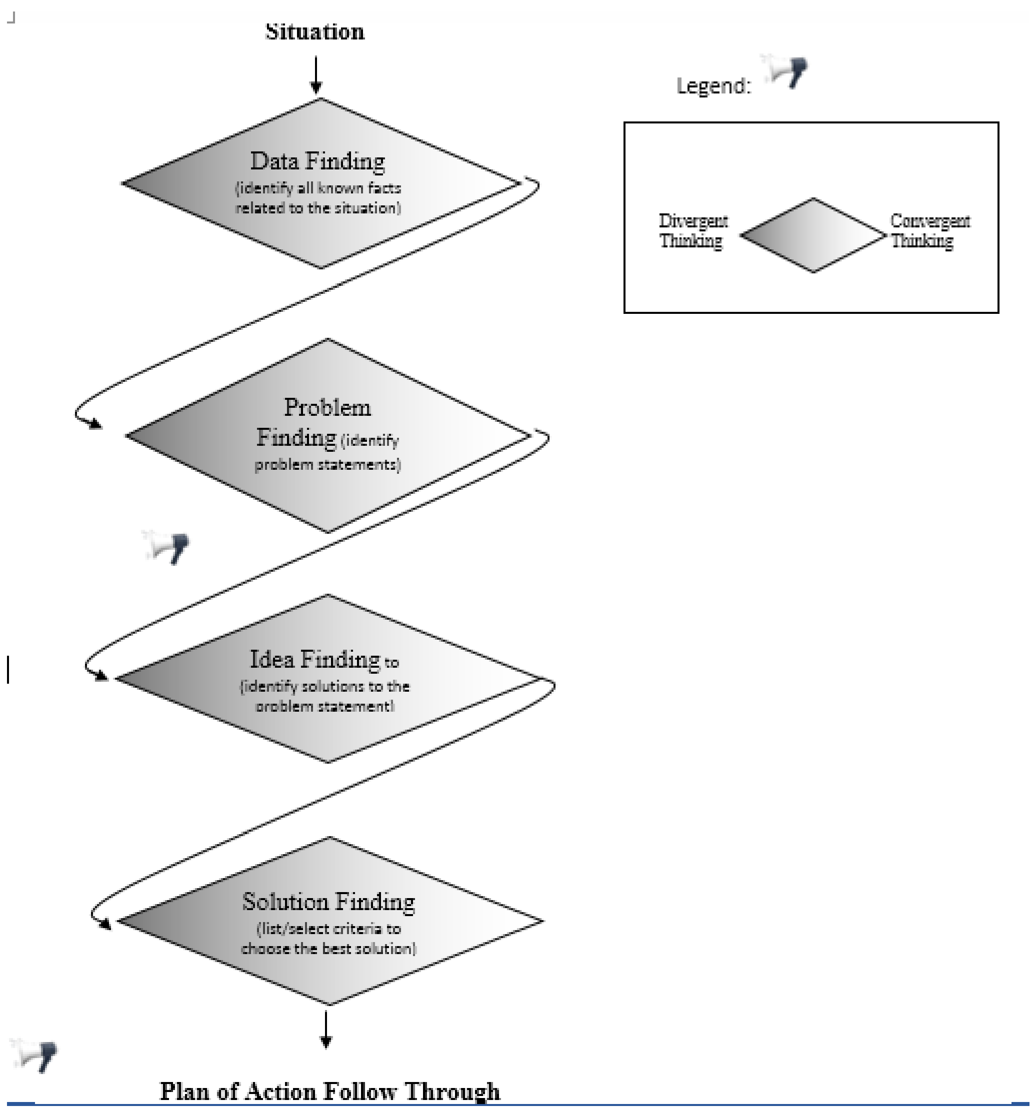


Figure 1: The steps for conducting CPS.

Handout 2

WORKED EXAMPLE ON HOW TO CONDUCT CPS

Let us say that the objective of your intended invention is to invent a device that can measure temperature. Study the following topic 1 to 4 for strategies to conduct data finding, problem finding, idea finding and finally solution finding in solving inventive tasks. As explained in the flowchart on page 2, each step will be composed of part A for divergent thinking; and part B where you will think convergently.

1. DATA FINDING

1 A: Divergent thinking

- Ask yourself who is involved? What is involved? What are some examples of the problem? What causes the problem? When will it happen? Where does it happen? How does it happen? Why does it happen?
  e.g.:

Who? *Everybody talks about weather and seasonal change. Scientists understand the interactions and changes of chemical substances by conducting experiments and measuring the change of temperature.*

What? *Temperature keeps changing. Some means of detecting this change is available in the market. Weather can be told and generalized in terms of temperature.*

Cause? *The change in temperature is caused by natural or artificial heating and cooling processes.*

When? *Climate change, or when heating and cooling treatment is conducted.*

Where? *At home, broadcasting/ TV station, science lab.*

How to be accurate? *Use appropriate electrical parts like analog digital converter.*

What facts are lacking?

How errors in measuring the correct temperature happen?

What is the range of temperature the device is suppose to measure?

1 B: Convergent thinking

- Apply convergent thinking to judge and select the most important facts.
- You can circle most significant facts and those that provide a key to your situation. For example, in this page, the above three data are circled for you.
- Write the most important and relevant data:

e.g.: Detect change of temperature

Range of temperature

Accuracy of the device

2. PROBLEM FINDING

2 A: Divergent thinking

- Based on the data you have found, determine what you want to accomplish in more specific terms. Formulate the problems in several ways. Brainstorm and avoid prejudgments.

- Begin each statement with the phrase "In What Ways Might I…" (IWWMI) or "How Might I…" (HMI...).

e.g.: HMI increase the accuracy of mydevice?

HMI reduce errors in the device?

HMI convert the temperature into digital display in Fahrenheit or degree Celsius?

IWWMI increase the accuracy of the critical component, the sensor?

IWWMI display the temperature automatically and promptly?

IWWMI incorporate all the device components for an effective thermometer?

HMI reduce the cost of the thermometer?

2 B: Convergent thinking

- The above calls for variety of statement of problems you want to base your future work on. Choose the most appropriate statement for the current context.

- Rewrite the selected problem statements. Here is one example of problem statement:

  IWWMI increase the accuracy of the thermometer, and at the same time reduce the cost of the device?

- Create your own statement of problem for the device you want to invent. Be focused on the actual problem you **want** to address.

  ……………………………………………………………………………………………
  ……………………………………………………………………………………………
  ……………………………………………………………………………………………
  ……………………………………………………………………………………………
  …………………………………………………………………….

3. IDEA FINDING

3 A: Divergent thinking

- Again, divergent thinking, combined with deferred judgment, is critical in this step. Your goal is to generate lots of ideas for answering the problem you have already stated.

- Let your divergent process create ideas. Start listing them below--continue on additional sheets of paper. RECORD ALL IDEAS. Create more ideas in the space provided.

  e.g.: Use more modern and accurate sensors

  Avoid heating of the device

  Increase the sampling rate of Analog Digital Converter (ADC)

  More accurate display of the Binary-Coded Decimal (BCD)

  Decrease the errors in BCD

Use high quality sensors

Placement of the thermometer -handy

Packaging of the thermometer - simple

……

………(Please ask for extra paper if you need so).

3 B: Convergent thinking

- Think carefully about which from the above list of ideas are the most important for the development of a quality thermometer. Using your convergent skills, review all your ideas and choose the ideas that seem to have the **greatest** potential.

……….

4. SOLUTION FINDING

4 A: Divergent thinking

- Your ideas affect cost, time, reliability, quality, morale, customers, legality, safety, company practices and approvals, feasibility, timeliness, and ease of implementation. Any or all of these, as well as others, can be considerations for criteria.

- Create a preliminary list of factors or criteria that will be used to evaluate your ideas. Write the list below.

e.g.: Moderate cost for a quality thermal sensor

Moderate cost for ADC to increase sampling rate

Readability of the display even for customers with eye-vision problem, or to be readable even in a dark site

Aesthetical value

Durability

Customer-friendly: Light-weight and handy for easy carriage

Producer-friendly: Available power source-battery

4 B: Convergent thinking

- Select the most critical criteria.

e.g.: Moderate cost for a quality thermal sensor

Moderate cost for ADC to increase sampling rate

Readability

Handy and attractive design

Use batteries

Now, summarise your idea(s) you are going to implement below while considering the above criteria. Describe your invention. Include initial sketches of the device below.

e.g.: This invention is called the 'digital thermometer'. What makes this invention so original is its high accuracy and clear display. The thermometer is equipped with modern thermal sensor and more sampling rate of ADC. At the same time it is affordable for customers. It uses available and cheap batteries as power source. The design of the thermometer is handy and eye-catching.

(F) PROCEDURE AND EXAMPLE USED FOR USING SELF-EXPLANATION METHOD FOR LEARNING A NEW STRATEGY

General remarks: Self-explanation process including generating inferences to fill in missing information, integrating information within the study materials, integrating new information with prior knowledge, and monitoring and repairing faulty knowledge. Prompting, an external cue that is intended to elicit the activity of self-explaining will be given by the experimenter if participants stop explaining for more than 30 s. examples of prompts are included.

Kinds of statements that will be coded:

- A **meta-cognitive statement**. It is an assessment, made by the student, of his or her own current understanding of the line of text or example step.
- A **self-explanation inference**. It is an identified pieced of knowledge generated...that states something beyond what the sentence explicitly said.

Instruction and Prompts

Here are the instructions to self-explain, taken from Chi et al. (1994):

"We would like you to read each sentence out loud and then explain what it means to you. That is, what new information does each line provide for you, how does it relate to what you've already read, does it give you a new insight into your understanding of how the circulatory system works, or does it raise a question in your mind. Tell us whatever is going through your mind–even if it seems unimportant."

These prompts were reworded to be used in Hausmann & VanLehn (2007):

- What new information does each step provide for you?
- How does it relate to what you've already seen?
- Does it give you a new insight into your understanding of how to solve the problems?
- Does it raise a question in your mind?

Handout for Self-explainers

* Explanations don't just tell ‘what’ something is or describe it -they tell the ‘how’ and ‘why’ about it.

* Explanations should be in our own words-not just repeating an explanation we have heard and memorized.

* When we explain something we often use information we already have to make what we are explaining clearer (like comparing the new information to something we already know about.

*Explanations often connect two things or ideas or link a procedure and an idea together.

The difference between description and explanation is as follows:

Description: Describing something or telling what happened (telling the "what")

Explanation: Explaining something or explaining what happened (telling the "why" and "how" of it)

Example:

Description of the circulatory system

The circulatory system is made up of the heart, veins, arteries, and blood. Some of the arteries and veins are small, and some are large. The heart pumps blood through the arteries and veins.

Explanation of the circulatory system

We need a circulatory system in our bodies to move the blood around to all parts of the body because the blood carries oxygen, which is food for the cells of the body. All parts of the body need the oxygen to grow and function. The circulatory system is just a way of getting that oxygen moved around. The tubes the blood moves in are the arteries and veins. The arteries and veins are all connected, like highways and roads, so they can transport blood to any place in the body. Near the heart the arteries and veins are large because they have a lot of blood to carry, and as they get closer to one part of the body or to a cell they become much smaller (like freeways, highways, streets, roads, and dirt paths). They can also be seen as being like branches of a tree that get smaller as they get closer to the leaves because they don't have so much to carry to only one leaf. The heart is a pump and it pumps the blood so that it keeps moving around in the network of arteries and veins. The heart pumps by squeezing in and then releasing over and over and over (like making a fist and relaxing it).

(G) FORMALISM FOR PROTOCOL CODING

The content codes can be divided into six major design elements, while the rest of other ideas which do not fall under design elements are coded as ‘miscellaneous’. The following seb-section elucidates what actually are design elements in general as compared to the non-design elements. Then, after that, the definition of each code will be explained in detail.

The difference between design element and non-design elements

Design elements are desired, potential or actual ideas that constitute a design or invention. They are the several aspects involved when a designer develops an invention idea (see the following figure). All interrelated ideas surrounding an invention mentioned during the conceptualization of the device are design elements. It helps characterise the device.

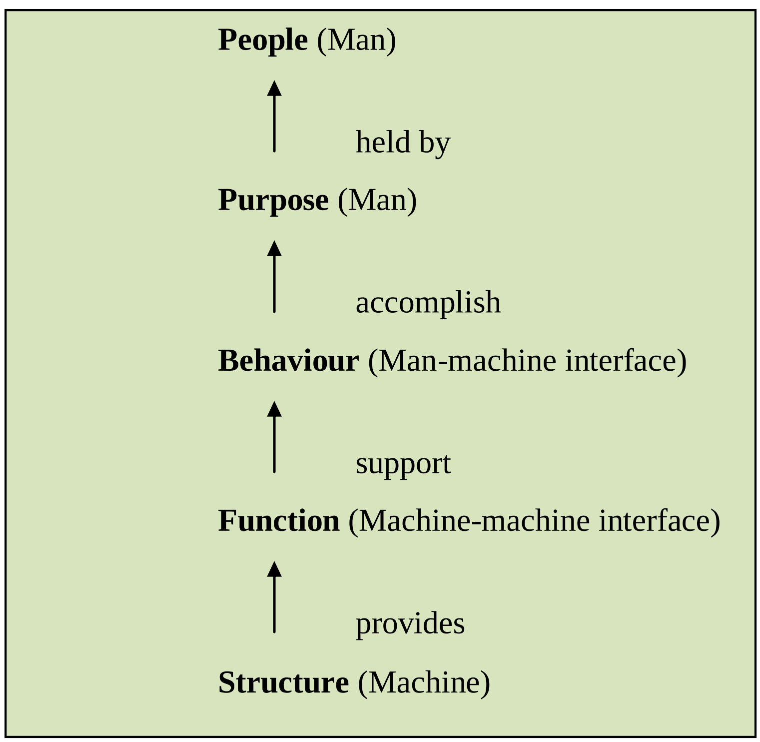


Figure: Elements or aspects of design development (adapted from Goel, 1995 p.242)

Goel (1995) proposed the idea that there is a pre-requisite to the problem solving stage which is called problem structuring process. ‘Function’, ‘behaviour’ and ‘structure’ are basic elements of design when designers conduct design or inventive problem solving. ‘People’, ‘purpose’ and ‘resource’ are other important elements of design which must be mentioned during the process of problem structuring processes of initial design. They should be included as design elements because ideas can change as these three elements change. In other words, the three elements directly affect the decision making process when designing takes place.

Non-design elements are normally used for supporting design ideas. They are not about the device features and do not directly lead to the decision making process. Coded as ‘miscellaneous’ for the purpose of analysing the protocols of this research, non-design elements involve statements about **facts** or supporting evidence for proposing an idea. These statements do not contribute in making design decisions but are mentioned for the purpose of clarity of one’s explanation of ideas (e.g.: comparing the current status of technology). As a test for the non-design elements, facts and evidences do not change as ideas change. Facts are not necessarily mentioned during conceptualization of an invention.

Examples:

“…room temperature will be different and human body will be different.”

“People will come and lock and unlock it.”

“Nowadays what we are using in the car is just like direct frequency which can be easily tracked by the thief.”

“I cannot listen to the person and to the radio at the same time right?”

“What should I do to turn on and what should I do to turn off the music?”

Designers often criticise the current idea by specifying which behaviour is undesirable and then that leads to what actually is desirable for the potential device. In the following example, the phrase “immediately cannot phone and contact the police” is a behaviour statement. However, this behaviour is not a design idea but it is considered a fact used for arguing over an idea. It is not an accepted idea for constructing the intended device.

“but people cannot anything..like they cannot…Hm..it is not fast….they can only be aware of it but immediately it cannot phone and contact the police”

Definition of content codes

For the definition, it is important to highlight that design elements are classified into problem structuring and problem solving. Problem structuring is a collection of statements that serve to solicit or generate information to structure the problem. It can be categorized into three aspects of element which are either information about 'people', 'purpose', or 'resource'. Problem solving statements are divided into 'function', 'behaviour' and 'structure' when the designer progresses on conceptualisation of the intended design using technological terms and schematic diagrams.

People statements deal with the users of the artefact. It is to answer the question of "who are our clients?"

"That will be very helpful for teachers."

"So the results of combination of groups could be accessed by lecturers…."

"The instrument is useful for teachers, students and researchers."

Purpose statements deal with the motives, intentions, and goals of the users.

"To check if a person is sitting or not."

"He can start listening to the song."

"And the advantage of this is there is very less chance of false alarm."

Resource statements consider resources, such as time, money, and people even though the statements do not specify the exact amount in numbers. It should just state the consideration of some relevant factors and how far these factors are taken into account.

"To reduce cost and power consumption."

"It should be of low cost."

Function codes are statements that have to do with the desired, potential, or actual functionality of the artefacts. Bradshaw's (1992) notion of function-space search matches the definition used for the current analyses. It involves machine-to-machine interfaces. Each component serves a particular functionality that affects the other interacting components in one way or another. In other words, the input/output/flow of device operation are functional statements.

"so this control will go into the music system."

"and this audio signal is again given to the speakers."

"I can say this, four blocks connected to the laptop."

"the results or… fit into, fit into the virtual learning environment."

"from microprocessor I can give to a control-like thing."

There are cases where vague functionality is mentioned without identifying the particular technology for realising that functionality. For example, in these statements, "*it senses the data"; "we can use technology to send a message to his mobile phone";* and *"games that you can use your olfactory and your mouth"* no technological term is mentioned. However, specific functional statements were highlighted.

There are also cases where a higher vocabulary of technological terms used known to be able to fulfil the intended functionality. Functional statement includes the first time a technology is proposed for informed/stated or uninformed purposes.

"I think some sensor can be kept over the seat."

"I can go for an ultrasonic stick for blind people..."

Normally, functional statements do not concern with how a particular device will look like. One example is, *"I can implement new things like just with the voice recognition system."* Function codes are also used for coding a proposed system. Sometimes an old system can be implemented in a new way for a device to become novel or inventive.

In the following examples, a 'film station' and a 'radio' a "brake" mean functionality and not a structure or object. To incorporate them in a furniture involves another process where it should coordinate with the functionality of a furniture and that the form of the film station and the radio is not known yet.

"We can put like film station (in the furniture)"

"...so we can also have radio (in the furniture)"

"and it must have a brake"

Function codes also explicate the performance of a machine, for instance, *"it needs to be wider range of transmission"* and *"image sensor can direct the movements and identify displays accordingly."* Furthermore, function statements present the specific performance designers want the device to achieve when a device is working appropriately.

"he can save up to ten channels."

"inbuilt in the projector"

"we don't have to have a separate screen"

In addition, a process done by a machine, such as *"there will be scanning going on there"* are also coded as function. In conclusion, function statements involve the machine performance including the input, functionality, and the measures of output of that functionality. The following shows how each segment is coded as one single function even though they are continuous statements. It shows the various kinds of functional statements.

E.g.:

Segment no.	Protocol	Code
12	*so I have to spread the rays.*	Fu
13	*So I have to amplify it and then,*	Fu
14	*keep it spreading it and I have to remove any obstacle.*	Fu
15	*and the sensor,*	*Fu*
16	*and the sensor must be amplified, so I must have amplifier,*	*Fu*
17	*the amplifier must be connected to an analogue to digital circuit,*	*Fu*
18	*from the sensor the signal is sent to the amplifier,*	*Fu*
19	*and then from the analogue to digital circuit*	*Fu*
20	*and then to the amplifier and then it is amplified,*	*Fu*
21	and then it sensed,	***Fu*

**Not behaviour because it involves machine-to-machine interface.

Behaviour statements specify the behaviour the artefact is supposed to encourage and support. It involves changes of object moving in space over time or change in properties. It differs from function codes in that it identifies the point at which the user interacts with a machine or equipment being used; a man-machine interface. It involves physical/observable behaviour of the device as the results of human contact, without saying how this can happen. Designer use behaviour statements to imagine the desirable machine's physical works.

"as the alarm starts the owner of the house will know easily."

"as the person presses a button on the remote the chair will produce some sound."
"so when the person stands up or moves away from the chair, automatically the music system should be stopped "

"so the machine will look at a specific locations, and try to recognize those handwriting or those prelearned answer."

"and if they match, it will say that this is the correct answer.

"and gives you the mark."

Behaviour statements also includes the limitations put by the designer as a consequence of having to specify which behaviour of interest.

"in radio mode I cannot make calls"

"even though alarm cannot protect"

"the owner should not be wrongly informed."

Another condition where behaviour statement is used is for indicating cause and effect relationships and even step-by-step actions of the user using the particular intended machine. For example:

"So.. people sit, start system, get the sign, the system is on, put the CD…"

The following denotes the vocabularies normally used for indicating a behaviour:

- If

"I can connect to my mobile if I am not in the home"

- If….then

"If the algorithm matches then it is the correct answer and if it does not match then it is not the correct answer."

- When/whenever

"When they press one, it will go to some person, a predefined person."

"When he presses the button the stick automatically comes out."

"Whenever a teacher moves from one class to another, he just have to insert the other chip of the class may be..say, class AS 01 and class AS 02..maybe when a teacher moves from class AS 01 to AS 02 just insert the chip of AS 02."

-As

"and it will alarm… buzz out as the distance is covered as you get an obstacle."

Structure statements have to do with the desired, potential, or actual form of the artifact. For example, *"It has only one number pad"* and "*we just need to introduce a button"* are structure statements. A generic component like "speaker", "earphones", "laptop" are object-oriented and therefore considered as structure statements.

Structure concerns the form, size, shape and materials of architecture of artefact.

"the material should be light and soft"

"the system should be fool proof, compact and stable and should have a good strength"

"I need to concentrate on things that can be felt"

If the intended device involves a display or details of a software as its final physical object, it can be coded as structure. For example:

"Twenty albums with hundred songs if you are going to play randomly, it is like you want to choose from this album, this album, this album, then it needs to read which album it is playing."

"And then they will have (in the screen)… I like giving presentations, I like just listening to things."

Where a particular component is positioned and how it is structured in the finished device also indicates structure. To indicate positions, designers use demonstrative pronouns such as here, this, these, there, that, those, etc. The labelling of parts normally during writing or sketching mode can be coded as structure as well.

"so these controls are actually available in the number pad."

"inbuilt in the projector"p10 "embedded inside"p34

Finally, the 'miscellaneous' statements do not fall into any of the other six categories of the content-analysis level.

(H) SAMPLES OF FINAL DESIGN DESCRIPTIONS

The Best For Task A

A(re)28

Product description:

"'BURGLAR ALARM"

1) Use magnetic fields or infra red beams on your compound walls and rear door steps. When these beams are intercepted use a switching device that switches on all the CCTV cameras.
2) Main point to be considered is to hide the CCTV cameras and not make them obvious. E.g: hide them in walls, statues, portraits.
3) Use accelerometers in locks and integrate them with GPRS
   (i) when a force above preset force is applied, the locks automatically open.
   (ii) When the locks open, send an alert SMS to police or house owner.
4) Have the doors fitted with child lock facility, which means door can be opened only from outside and not within.
5) Mix your valuables with the necklaces having GPS pendants (by chance if they escape from Step-4), this will track them down.
6) For cars, have an additional GPS system in the engine compartment in addition to the one inside.
7) Have a wireless system in tyres by which tyres get deflated when car is opened by force.

Product sketch:

-Nil-

The Best For Task B

B(re)29

Product description:

"WIRELESS PEN/CHALK HANDSETS"

1. wireless pen/chalk

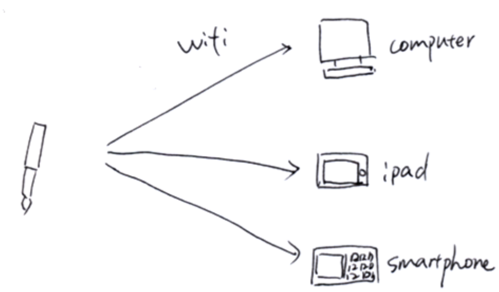
be used to record the notes written by teacher electrically and send them to the handsets of student by wireless.

2. handsets

can be computer/ tablet/ smartphone which has wireless interface, receive the notes and transfer them to electrical documents.

3. software on handsets
   1. should be adapted to different operation system or hardware
   2. easy to use

Product sketch:



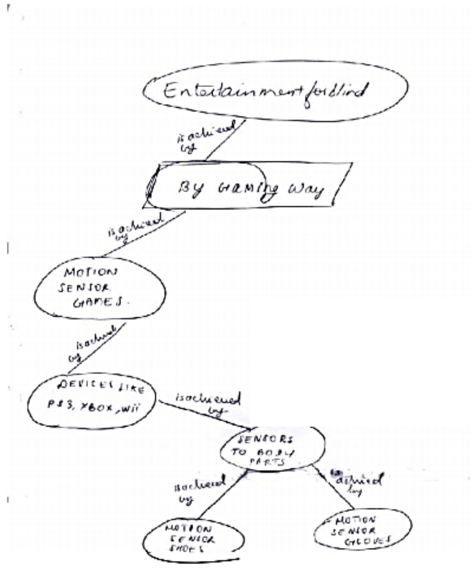
The Best For Task C

C(ost)28

Product description:

1. Blind people lack sufficient exercise.
2. Lack of exercise can cause health related issues.
3. Solution could be, like to make them move in the position without big movement.
4. Games based on motions are available. But what they require is simple, running and cycling games, where they know what they are doing.
5. For this we attach motion sensors to the shoes for legs and gloves for hands.
6. With these they get more entertainment and exercise as well.

Product sketch:



The Worst For Task A

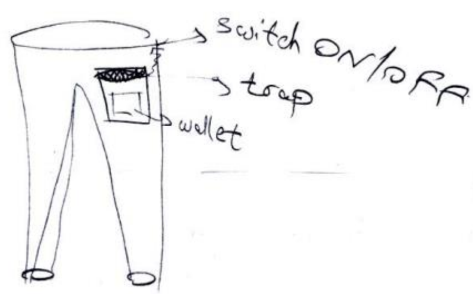
A(ost)8

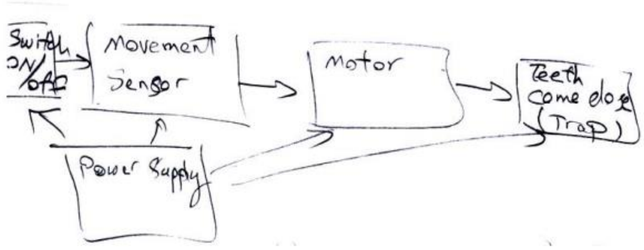
Product description:

"BACK POCKET TRAPPING DEVICE"

It is a device which can be fit into any space which is vulnerable to thefts, especially stealing with hands. If a hand enters your back pocket, the heat sensor would feel the sudden change in heat and that sends a signal to the trap to close. Also a switch is provided in the front pocket so the system can be turned off for the owner to access his pocket.

Product sketch:





The Worst For Task B

B(re)23

Product description:

1. OVERVIEW

These days there are a number of software and devices available in the market to help teachers and lecturers in the process of teaching and learning. Let us consider SNS or other services. But these are mainly for the young and older group of people. For the kids, we can see certain websites as well as other video applications but there has not been any significant advance in this domain. So, this incurs the need of a better software/device.

2. DESCRIPTION

The software mentioned in this draft is targeted towards kids of a school mainly but it also includes features for all age groups/standards in the school as well as the teachers. In addition, with the addition of few hardwares, the use could be extended to the disabled kids as well. A copy of this could be made available in the Internet so that it can be accessed from home.

3. SPECIFICATIONS

Programming Language: JAVA
Operating System : Windows XP/7/98
Database System : ORACLE

4. DETAILS

i) The initial page would provide two options:

Teachers login
Students login

ii) Teachers login page would lead them to a different page where they could do a number of jobs like registration, marking, etc.

iii) Students login would lead to a different page

1. Kindergarten
2. Standard I
3. Standard II

iv) For each link, there should be a different subset of applications. Let us take for example the kindergarten one.

1. Story
2. Poem
3. Alphabets
4. Basic Maths

The story page would lead to a list of stories available which could be played. A touch screen would encourage the little students to select it on their own. Similar approaches could be followed for other sections as well. *

5. ADVANTAGES

It would have a vast range of functionalities at a single place to use from.

Reference:
1. Story Telling Alice
* For a little senior group we might include applications like "Story Telling Alice" to teach children different programming languages.

Product sketch:

-Nil-

The Worst For Task C

C(re)9

Product description:

- Simple chair structure but needs to be flexible. It should be able to swing to and fro.
- Cushioning should be natural so that a blind should feel that it is safe and enjoyable.
- May include extra gadgets to help him while outing or traveling
- Gadgets for emergency calls.
- Both moving and still position settings should be there. This can be done by hydraulics and extra GPS will help out to find him.

Product sketch: