A Novel Approach to Quantifying Designer's Mental Stress in the Conceptual Design Process

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Abstract

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The objective of the present thesis is to quantify designer's mental stress during the conceptual design process, in which designers usually describe the design problem and design solutions using natural language, combined with sketches. In the process of solving a design problem, the design problem itself will evolve according to the design solutions generated at each step of the design. The design problem together with its solutions at each step is called a design state. Quantifying the designer's mental stress would assist in understanding the designer's creative and innovative design process, through which a design methodology can be optimized. In the present thesis, a cognitive experiment is used to study the quantification of the designer's mental stress. Subjects were invited to design a new litter-disposal system in a passenger compartment located in the trains of NS (Dutch Railways). In quantifying the designer's mental stress, the recorded design protocol data is firstly segmented into design states, each of which is then encoded into a Recursive Object Model diagram through linguistic analysis. The number of objects and relationships included in an ROM diagram is then used to quantify the designer's mental stress. The validation through the cognitive experiment shows that ROM is an effective encoding scheme. The analysis presented in this research shows that the designer's mental stress changes in a dynamic, nonlinear, and spiral manner along with the time.

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Dedicated to

My wife, Shu liu

My parents, brother and sister

For their constant love and unwavering support…

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Chapter 1
Introduction

1.1 Motivation

Over the last few decades, various design methodologies have been proposed to assist designers in generating quality designs in a more effective manner, such as systematic design methodology (Pahl and Beitz, 1988), TRIZ (Altshuller, 1984), axiomatic design (Suh, 1990), decision-based design (Allan and Mistree, 1997), artificial intelligence-based design (Gero, 2000b), and so on. There is no doubt that the existing methodologies have been greatly influencing the industrial product design process. However, a serious challenge is still faced in applying those design methodologies. This challenge arises because of two conflicting facts. On the one hand, any design methodology implies a set of well *structured logical* steps for solving a design problem. These design methodologies aim to deliver a design solution, which adds certain degrees of rigidity to the designer's thinking process. On the other hand, by contrast with the researchers who consider the structured design, there are other researchers who point out that design is a creative act, which is rooted in *flexibility and freedom* for exploring various avenues to achieve design goals (Akin and Akin, 1998; Dasgupta, 1994; Dorst and Cross, 2001; Wharton, 1999). Some attempts have been made to study design creativity in a design process. Dorst has indicated that creative design is a co-evolution process that looks for problems and solutions at the same time (Dorst and Cross, 2001). After studying the creativity in puzzles, inventions and designs, Akin has concluded that it is not feasible to search for a unifying theory of the creative process because creativity is domain dependent (Akin and Akin, 1998). Using the design of microprogramming as an example, Dasgupta points out that inventing is a goal-directed yet opportunistic act; thus the design agent's freedom and capacity to use his knowledge contribute significantly to the design creativity (Dasgupta, 1994). From the cognitive point of view, Wharton has characterized creativity as a focused mental process in which "we are not making something from nothing; rather, we are taking various existent elements and modifying them such that they interact in a new way" (Wharton, 1999). Thus, these design methodologies have not been widely accepted in general design practices. This contradiction between flexibility and structure is made even more complicated by an intrinsic nature of design: design solutions must pass an evaluation defined by design knowledge that is interdependently and recursively determined by the design solutions to be evaluated (Zeng and Cheng, 1991).

To develop a more effective design methodology that can be balanced between flexibility and structure, a great hope for resolving the contradiction in developing effective design methodologies lies in the thorough understanding of the designer's cognitive process such that the methodologies may either lead the designers to a better approach or assist the designers in their natural manner for delivering creative solutions. It is important to quantify the designer's cognitive processes, particularly the designer's mental stress. According to the Yerkes-Dodson law (Yerkes and Dodson, 1908) as shown in Figure 1, there is an inverted U-shaped curve correlation between performance and mental stress (Lundberg, 2002). An optimal level of arousal addresses the best performance for a given task, whereas the performance will decrease when the levels of arousal become too low or too high. The existence of correlation suggested by Yerkes and Dodson has been confirmed by other researchers (Bourne and Yaroush, 2003; Dyregrov, 2000; Gaillard, 1993; Gaillard, 1994). These researches have indicated that under the pressure of tight schedules, complex tasks, or other strong stress, people may be stressed out and their performance may thus degrade, or even fail. Modest levels of supra-optimal stress can be counteracted by the performer by increased effort, resource mobilization, or straining.

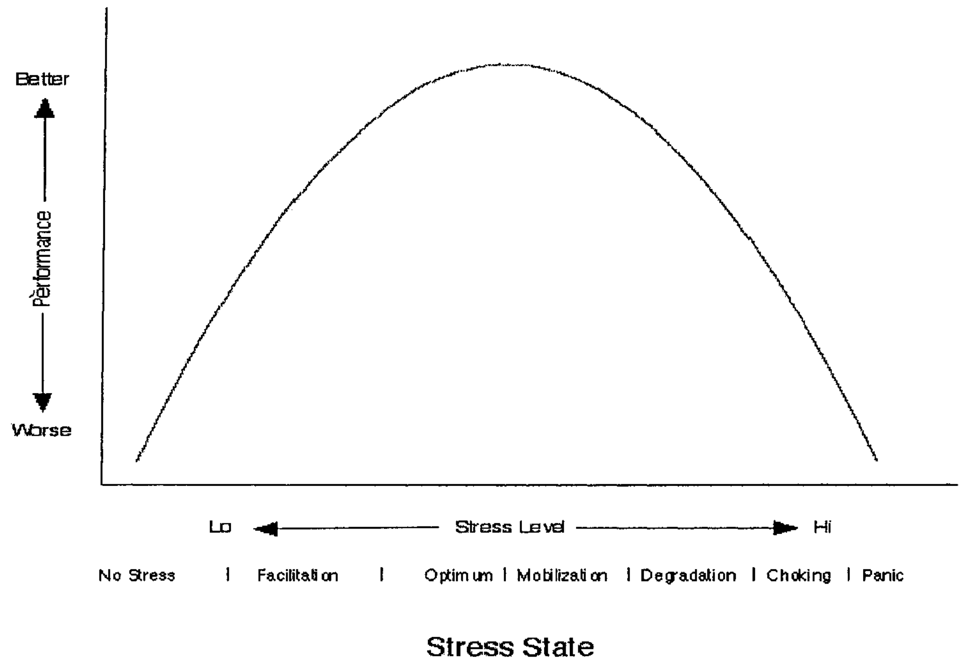


Figure 1 Graph of Yerkes-Dodson law (Yerkes and Dodson, 1908).

A design methodology can increase or decrease the designer's mental stress by providing a means to manage design tasks. A methodology may bring in the mental relaxation by helping designers release mental workload while it may also lead to designer's frustration if it is against the designer's conventional way of thinking and working. By contrast, a high-quality design methodology should be able to maintain mental stress within its optimal range, which aims to enhance the quality of designed product and to improve the efficiency of the design process, thus, it can lead designers to achieve an optimal solution.

1.2 Problem Statement and Objectives

However, there are three main weaknesses in the existing research:

(1) The investigation of mental stress is a result of an interdisciplinary study of the brain, but different disciplines (philosophy, psychology, artificial intelligence, neuroscience, linguistics) define the mental stress in different ways. Analysis of mental stress has become increasingly important for investigating designer's cognitive procedures. However, a concept of mental stress accorded with the domain of design has not yet been created.

(2) The observations and implications about designer's mental model and cognitive process are based on experiments or beliefs from cognitive science. There is no method to systematically reflect the nature and characteristics of a design process and to naturally accommodate a designer's cognitive activities.

(3) Encoding is an important and critical part to analyze subject's protocol data. Most of the current protocol studies devise the coding schemes according to specific design problems.

If the design problem is changed, the coding scheme will also be changed and therefore cannot be extended for other applications. As a result, experiments from different sources are not comparable, which brings a lot of subjectivity into the study.

To improve the applications of mental stress in the conceptual design process, the objectives of the present study are as follows:

(1) To describe a formal definition of the mental stress in domain of design using the axiomatic theory of design modelling;

(2) To represent the thinking of the design process using the protocol analysis;

(3) To find a generally encoding method to explain protocol data in different domain using the axiomatic theory of design modelling;

(4) To quantify the mental stress of designers during the conceptual design process using recursive object model (ROM).

1.3 Contributions

Two major contributions are presented in the present thesis:

(1) *Based on the axiomatic theory of design modelling and recursive object model, a general scheme is used to encode protocol data from a cognitive experiment.*

Traditionally, the encoding of protocol analysis is limited by specific design problems. Encoding is an important and critical part to analyze subject's protocol data. Most of the current protocol studies devise the coding schemes according to specific design problems. If the design problem is changed, the coding scheme will also be changed and therefore cannot be extended for other applications. As a result, experiments from different sources are not comparable, which brings a lot of subjectivity into the study.

The general encoding method, which was developed from the axiomatic theory of design modlling and ROM, can help researchers understand the characteristics of design process and does not depend on the specific design problems. The general encoding method focuses on abstracting the universal characteristic of design, but not the detail of design.

(2) *Based on the integrative application of protocol analysis, axiomatic theory of design modelling, and recursive object model, designer's mental stress is quantified for the conceptual design process.*

The quantification of the mental stress is shown in Figure 2. It is developed from the following three theories: protocol analysis, axiomatic theory of design modelling, and recursive object model. Protocol analysis (Ericsson and Simon, 1980) is used to identify the role of designer's thinking and reasoning in the design process. The axiomatic theory of design modelling (Zeng, 2002) is used to segment the protocol data. Recursive object model (ROM) (Zeng, 2007) is used to encode the linguistic analysis for the design process. All together these three theories and methods are used to quantify the designer's mental stress during the conceptual design process.

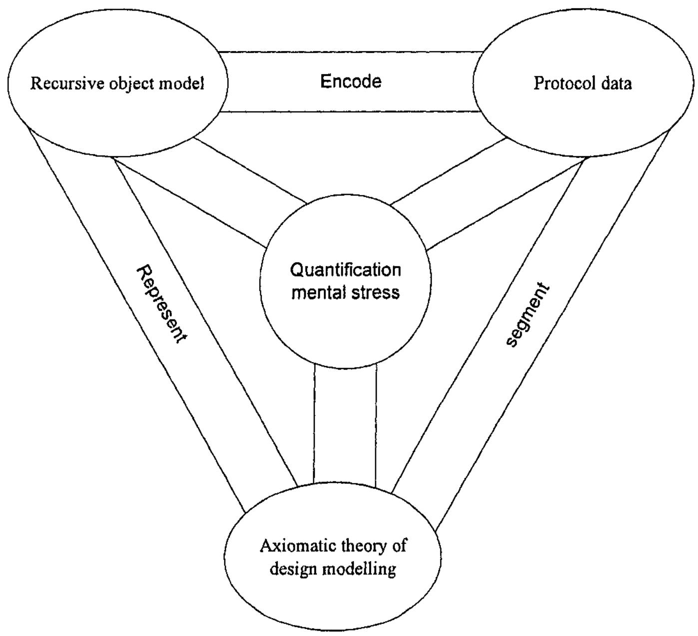


Figure 2 Quantifying mental stress based on three theories.

1.4 Organization of this Thesis

The rest of the thesis is organized as follows. Chapter 2 reviews the current cognitive studies of design and introduces existing cognitive science. Chapter 3 introduces the modelling tool used in the present research, which are the axiomatic theory of design modelling with the support of the recursive object model (ROM) and protocol analysis. Chapter 4 presents the experiment setting and data analysis method used in this research. A new approach is presented for quantifying mental stresses through ROM diagrams corresponding to protocol data in Chapter 5. Finally, Chapter 6 concludes the present thesis and lists some future research directions.

Chapter 2
Literature Review

This chapter provides a brief overview of the state of existing studies relevant to objectives of the present thesis. The topic of this thesis research includes two domains: design and cognitive science. The design paradigm seeks to extend the boundaries of human and organizational capabilities by creating new and innovative artifacts (Hevner et al., 2004). The cognitive-science paradigm is based on the idea that the study of human mind is in itself a worthwhile scientific pursuit (Varela et al., 1993). Both paradigms are foundational but not dichotomous. They are inseparable, positioned as they are at the confluence of people, organizations, and technology.

First, Section 2.1 reviews several well-known design theories. It should be noted that the axiomatic theory of design modelling is not discussed in this chapter but is discussed separately in Chapter 3 because the major methodology used in the present thesis is based on the axiomatic theory of design modelling. To present the relationships between design and cognitive science, Section 2.2 builds a bridge between them. Finally, Section 2.3 focuses on cognitive science, which includes the concept of mental stress, measurement of mental stress, theories of stress, and stress managements. Although this initial review is general in concept and limited in scope, it provides a basis for the consideration of factors that allow the quantification of mental stress in the conceptual design process.

2.1 Design

2.1.1 What is Design?

Design has been defined by previous researchers in different ways. In its widest sense, the term "design" has its roots in engineering and the sciences of the artificial (Simon, 1996). Minneman has defined design as a social activity (Minneman, 1991). Preliminary definitions that align design with the common usage are as the following: as a noun, the word design refers to the output of the design process and a specification or plan for making a particular artifact or for undertaking a particular activity (Galle, 1996; Gero, 2000c). In this discussion, a distinction is drawn between a design and an artifact—a design is the basis for, and a precursor to, the making of an artifact. As a verb, it refers to the action in design activities and the design process (Love, 2002; Zeng, 2004b). From this perspective, it follows that a "designer" is someone who is, has been, or will be designing: someone who creates designs. The noun and verb forms can be described as "a design" and "designing". Some typical definitions of design have been summarized as follows:

(1) Design is fundamentally a problem-solving paradigm. It seeks to create innovations that define the ideas, practices, technical capabilities, and products through which the analysis, design, implementation, and use of information systems can be effectively and efficiently accomplished (Denning, 1997; Tsichritzis, 1997).

(2) Engineering design is the process of applying various techniques and scientific principles for the purpose of defining a device, a process, or a system in sufficient detail to permit its physical realization (Taylor, 1959).

(3) Engineering design is a purposeful activity directed towards the goal of fulfilling human needs, particularly those which can be met by the technology factors of our culture (Asimow, 1962).

(4) Design is the process of inventing physical things that display new physical order, organization, form, in response to function (Alexander, 1979).

(5) ... the creation of a synthesized solution in the form of products, processes or systems that satisfy perceived needs through mapping between the relationships between the functional requirements (FRs) in the functional domain and the design parameters (DPs) of the physical domain, through proper selection of the DPs that satisfy the FRs (Suh, 1990).

2.1.2 Design Research Guidelines

It can be observed from the definitions above that design is inherently a problem-solving process. In addressing some of the characteristics of design research, Hevner has suggested that the fundamental principle of design research, from which seven guidelines are derived, is that knowledge and understanding of a design problem and its solution are acquired in the building and application of an artifact (Hevner et al., 2004). Table 1 shows seven basic guidelines that help explain the characteristics of design. That is, design research requires the creation of an innovative, purposeful artifact (Guideline 1) for a specified problem domain (Guideline 2). Because the artifact is "purposeful," it must yield utility for the specified problem. Hence, it is crucial to make a thorough evaluation of the artifact (Guideline 3). Novelty is similarly crucial since the artifact must be "innovative," solving a heretofore unsolved problem or solving a known problem in a more effective or efficient manner (Guideline 4). In this way, design research is differentiated from the practice of design. The artifact itself must be rigorously defined, formally represented, coherent, and internally consistent (Guideline 5). The process by which it is created, and often the artifact itself, incorporates or enables a search process whereby a problem space is constructed and a mechanism posed or enacted to find an effective solution (Guideline 6). Finally, the results of design research must be communicated effectively (Guideline 7) both to a technical audience (researchers who will extend the results and practitioners who will implement them) and to a managerial audience (researchers who will study the results in context, and practitioners who will decide if they should be implemented within their organizations).

2.1.3 Design Theory and Methodology

After reviewing what are common design properties, this section is a short introduction to some well-known design theories and methodologies. A design theory addresses the nature and models of the design process, of design objects, and of design knowledge. It can be applied to improve the design process. Design methodology research is concerned with (a)

Table 1 Design-science research guidelines (Hevner et al., 2004)

Guideline	**Description**
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

understanding design decision-making, (b) methodological systematization of design processes and/or activities, (c) design modelling and representations, and (d) design analysis and simulation. Typical achievements in these two research aspects are the following:

(1) *Systematic design methodology* (Hubka, 1984; Hubka and Eder, 1988; Pahl and Beitz, 1988). The systematic design methodology defines the step-by-step procedures for completing a design task: (a) product planning and clarification of task, (b) conceptual design, (c) embodiment design, and (d) detailed design.

(2) *Axiomatic design* (Suh, 1990). Axiomatic design perceives the design process as mapping between four domains: customer domain, functional domain, physical domain, and process domain. Those mapping must obey the two axioms in the methodology.

(3) *Decision-based design theory* (Allan and Mistree, 1997). Decision-based design theory views the designing as a decision-making process, which includes a series of decision.

(4) *AI-based design theory* (Gero, 2000a). AI-based design theory includes three major issues: (a) Representation of products in different levels, (b) design knowledge, and (c) users' requirements.

(5) *Science-based design theory* (Zeng and Gu, 1999a; Zeng and Gu, 1999b). Science-based design theory aims to establish some fundamental principles and theories for engineering design. It includes two fundamental parts: laws and languages.

(6) *Environment-based design* (EBD) (Zeng, 2004b). Different from traditional design methodologies, which are largely based on the understanding that a generic design process comprises analysis, synthesis, and evaluation, Zeng presents the environment-based design methodology which includes the following three main stages: environment analysis, conflict identification, and concept generation (Zeng, 2004b).These three stages work together to progressively and simultaneously generate and refine the design specifications and design solutions. The EBD methodology is illustrated in Figure 3. The objective of environment analysis is to find out the key environment components, in which the product works, and the relationships between the environment components. From the environment implied in the design problem described by the customer(s), the designer will introduce extra environment components that are relevant to the design problem at hands. The results from this analysis constitute an environment system. One of the key methods for environment analysis is linguistic analysis. Following the environment analysis, conflicts should be identified among the relations between environment components. At the third stage of EBD, a set of key environment conflicts will be chosen to be resolved by generating some design concepts. This process continues until no more unacceptable environment conflicts exist.

The environment based design is a few things. First, it is a prescriptive model of design (which is a design methodology) that guides designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. Secondly, it is a

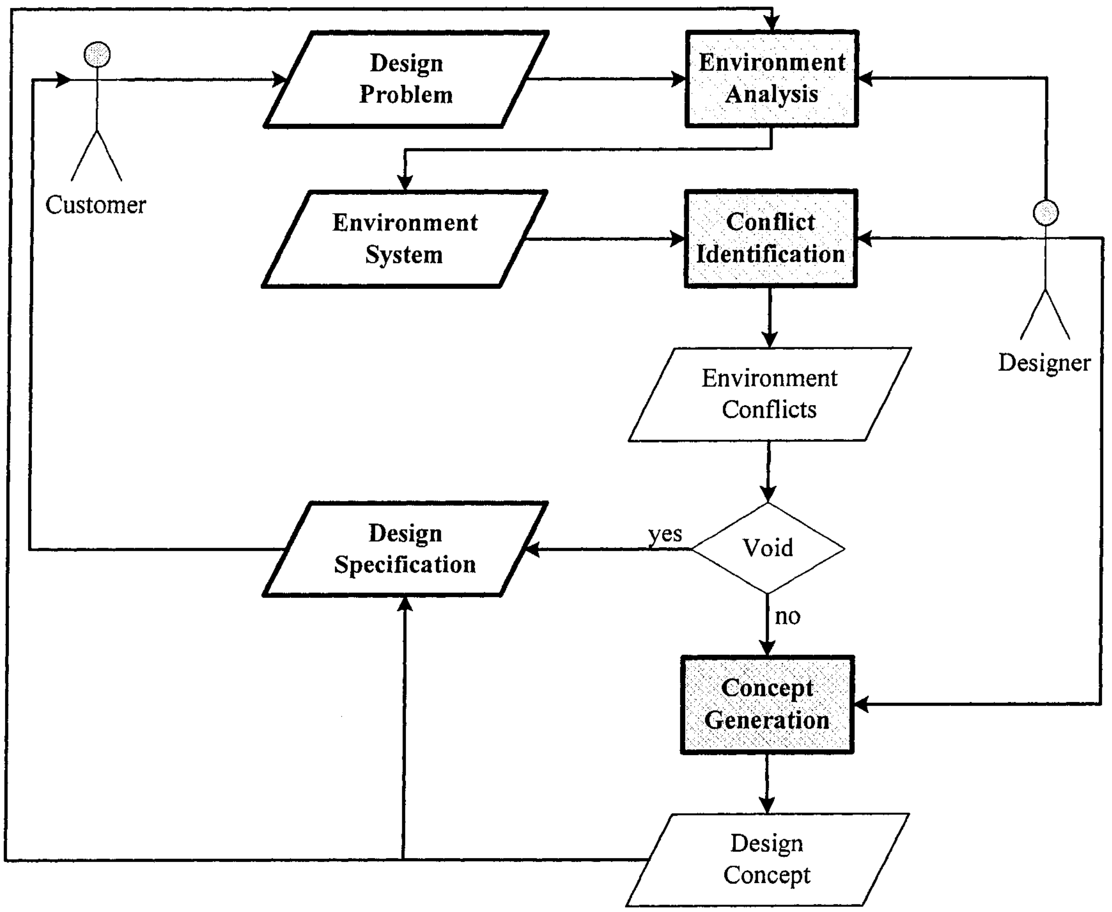


Figure 3 Environment-based design: process flow (Zeng, 2004).

descriptive model of the natural design process that illustrates how designers conduct a design task.

2.1.4 Design Process

The design process varies from product to product and from industry to industry. French has argued that the design process includes the processes of conception, invention, visualisation, calculation, marshalling, refinement, and the specifying of details. All of these processes determine the form of a product (French, 1998). Ullman has summarized in a generic diagram the activities that must be accomplished for all projects. This diagram is shown in Figure 4 (Ullman, 2002). In this framework, any product must go through five phases.

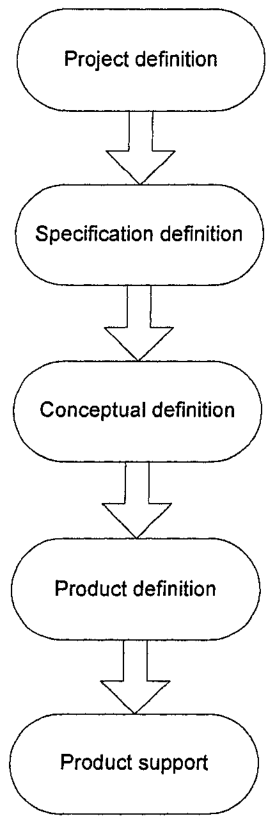


Figure 4 Ullman's generic design process in all projects (Ullman, 2002)

Pahl and Beitz have done research into the traditional design process. Their model is different from that of Ullman. Theirs is shown in Figure 5 (Pahl and Beitz, 1999). In this model, a product design process is divided into five phases, which are the following:

clarification of the task, concept generation, embodiment design, detail design, and physical evaluation. Obviously, Ullman's model pays more attention to needs analysis; Pahl and Beitz's model emphasizes the generation of solution and evaluation.

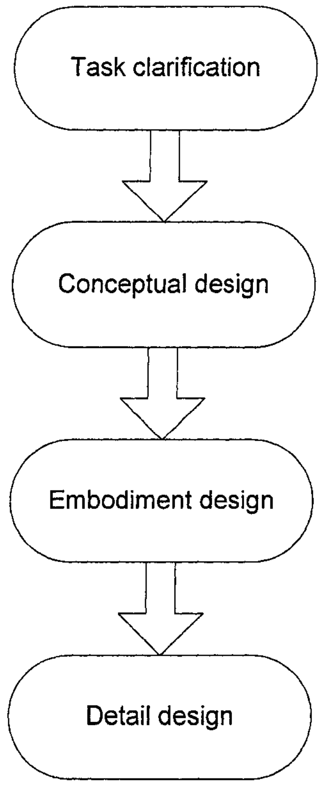


Figure 5 Pahl and Beitz's traditional design process (Pahl and Beitz, 1999)

Since the present research focuses on the conceptual design, a key part of the entire design process, the present section will mainly review the research results related to process.

A design process usually begins with requirements. These requirements may come from brand-new needs or existing designs. In the case of the requirements of an existing design, the designer hopes he/she can meet the update need, i.e. can generally optimize the existing design. Ideally, the stage in which the determining requirement is ascertained should be of successively increasing precision, of gradual crystallisation or hardening. It ends with a set of specifications that enable the thing designed to be made. Then, the earlier stages differ in character somewhat from the later ones since the earlier ones have greater flexibility than the later design stages. These earlier stages, where there are still major decisions to be made, are called "conceptual design". The conceptual design has the following feature (French, 1998):

(1) The solution to the given design problems can not be used an instruction for accurate implementation and /or manufacturing;

(2) Carrying to a point where the means of performing each major function has been fixed, as have the spatial and structural relationships of the principal components;

(3) A high-quality conceptual design should be sufficiently worked out in detail so that it can be supply approximate costs, weights, and overall dimensions, and the feasibility should have been assured as far as circumstances allow;

(4) A high-quality conceptual design should be relatively explicit about special features or components but need not extend much detail.

2.2 Design and Human Beings

Design is inherently one of the most characteristic of human-related activities. It includes recognition, creativity, and ingenuity. Humans are typically involved in design in three major forms: (a) as originators of universal design knowledge (design philosophers, design scientist and/or theoreticians, designers), (b) as design problem solvers (design methodologists, designers, design system developers), and (c) as targeted benefiters (users, consumers, undertakers, students) (Horvath and Vergeest, 2000).

Research into human assets has been centered on design psychology, cognition, epistemology, marketing, aesthetics, and ergonomics. One of the main research issues is to clarify the relation of the human being to design as a socialized, creative, knowledge intensive industrial activity (Horvath, 2001). *Design psychology* has become concerned with mental processes and behavioral characteristics of individuals and groups influenced by the design activity or affected by the products of designing. *Design cognition* has presented results in the areas of knowing, perceiving and conceiving of design knowledge, but also in understanding of intuitions, hypotheses, feelings and beliefs regarding design. In the *design epistemology* domain, research has been concerned with the nature and methods of human acquiring (learning), possessing (sorting and storing) and utilizing (processing and applying) general design knowledge. The main objective of *design marketing* research has been to investigate humans as targeted customers, to comprehend their needs, behavior as well as habits, and study the trends in product manifestation. As for *design aesthetics* research, studies have dealt with the ways and elements of achieving beauty in design by examining form giving, materialization and decoration, as well as by looking at the emotional reactions to aesthetic impressions. In *design ergonomics* studies have been conducted to increase comfort, safety, efficiency and the convenience of use by exploring and optimizing the physical and informational connections between humans, products and environments.(Horvath and Vergeest, 2000).

In the domain of design, understanding cognitive process is instrumental in improving the qualities of conceptual design. The mental load response can be used in a number of ways to assist the designer and operator of contemporary systems (Gopher and Donchin, 1986; Hancock and Chignell, 1988). As a diagnostic tool, mental load can help the ergonomist to distinguish between the efficiency of competing designs. Mental load can also be used to provide insights into specific job characteristics (Kantowitz, 1987). Some researchers have attempted to discover designer's cognitive model during the design process. By focusing on the increase of the germane cognitive load, Kirschner aims at further improving instructions by making designers take advantage of otherwise unused working memory during learning (Kirschner, 2002). Dong attempts to quantify coherent thinking by using a latent semantic analysis in a conversation mode, and this measurement also reveals patterns of interrelations between an individual's ideas and the group's ideas (Dong, 2004). Stempfle and Badke-Schaub have investigated the cognitive processes of design teams during the design process by studying three laboratory teams solving a complex design problem (Stempfle and Badke-Schaub, 2002). Fuchs-Frohnhofen, et al. have analyzed the user's mental models in the work setting and have generated variants of human-machine interfaces matching the user's mental models by using a methodology incorporating the taxonomy of mental models (Fuchs-Frothnhofen et al., 1996).

2.3 Stress and Cognition

Mental stress is the intensity of information imposed by environment on the brain (Zhu *et al.*, 2007) . It is traditionally the research topic of cognitive science (Bourne and Yaroush, 2003). To develop a more effective design methodology, it is important to identify the designer's cognitive processes. The term cognitive science was coined by Christopher Longuet-Higgins in his 1973 commentary on the Lighthill report, which concerned the then-current state of Artificial Intelligence research (Lighthill, 1973). Cognitive science is the interdisciplinary study of mind and intelligence, embracing philosophy, psychology, artificial intelligence, neuroscience, linguistics, and anthropology. The history of studying cognitive science can be traced back to the Ancient Greeks (Clark, 2001; Dawson, 1998).Though of differing opinions, philosophers such as Plato articulated the point of view that the mind relates to the realm of abstract ideals. By contrast, Aristotle developed the point of view that the mind is what the brain or body does (Clark, 2001; Dawson, 1998).

2.3.1 What is Mental Stress?

Stress is a descriptive term used in interdisciplinary researcher to cover conditions of a physical, biological, philosophy, and psychology sort that typically cannot be controlled by organisms, and that often strain organisms beyond their powers to adapt (Black., 1991). Stressors are environmental and cognitive events, among other things. Stressors can also be physical or psychological. An example of an internal psychological stressor is intense worry about a harmful event that may or may not occur. (Lyle E. Bourne, 2003). For human beings, sources of stress that have been found include, but are not limited to, extreme temperatures, loud or noxious noises, physical diseases, sleep deprivation, extreme heavy or prolonged work loads, time pressures, social pressures, and negative emotions. Stress can come from non-work stress or can be created by the task itself and can arise from these.

Mental stress refers to the synthesis of processing encoded information of brain, which include thinking process, learning process, and so on. There are three models of mental stress: object-based model, subject-based model and relationship based model. An *object-based model* treats stress as a function of external influences such as demanding workload, heat/cold, and time constraint (Stokes and Kite, 1994). However, it ignores individual differences and neglects entirely the role of emotion By contrast, a *subject-based model* holds that stress is a composite of response patterns (heart rate, blood pressure, and body temperature) that result from exposure to a given stressor (Pollock *et al.*, 1979a) More recently, a third approach has emerged, which defines mental stress as an interaction between an individual and his or her working environment. This is the *relationship model.* It emphasizes the relationships between the mental workload, the designer, and the brain. Mental stress is the intensity of information imposed by environment on the brain. (Zhu et al., 2007).

2.3.2 Measurement of Mental Stress

Measurement is the process observing and recording the observations that are collected as part of a research effort. In the cognitive design, the measurement of mental stress can be classified according to three methods: the neuro-physiological measures of stress, the self-report measures, and the performance or behavioral measures.

(1) Neuro-physiological Measures of Stress

To measure the physiological reactions to stress, the following procedures have been most frequently used. Researchers have measured a variety of peripheral responses, including the heart rate (HR), the blood pressure (BP), the respiratory rate, perspiration, eye gaze, electroencephalogram (EEG), magnetic resonance imaging (MRI), the digestive system and so on. For example, Cacioppo has tested peripheral responses associated with stressful situations, including but not limited to, the increases in the heart rate (HR), blood pressure (BP), respiratory rate, perspiration, and inhibition of digestive and sexual functions (Cacioppo, 1994). Andrew analyzed the brain image to find the relationships between the orientation of the face and the eye gaze (Bayliss et al., 2004). Gevins and Smith have described an initial evaluation of a new method for assessing transient states of cognitive impairment associated with intoxication or fatigue: neural network pattern recognition applied to features of the electroencephalogram (EEG) recorded from the subjects performing a standardized task. (Gevins and Smith, 1999).

As mentioned in regards to physiological reactions to stress, it should be noted that the strength of a stressor can be determined only by measuring the subjective and physiological response of an individual since individuals may vary widely in their response to stressful circumstances.

(2) Self- report Measures

Matthews et al. have developed a broader index known as the Dundee Stress State Questionnaire (DSSQ), which provides the first comprehensive multi-dimensional assessment instrument for transitory states associated with stress, arousal, and fatigue (Matthews et al., 1999).

The Profile of Mood States (POMS) is a self-report measure of mood states. It has six subscales: tension, depression, anger, vigor, fatigue and confusion. POMS has these advantages: extensive reliability and validation testing (Pollock *et al.*, 1979a; Shacham, 1983).

The most successful self-report measures of stress focus on three processes: commitment to the task, feelings of cognitive overload, and self-assessment of success.

(3) Performance or Behavioral Measures

The behavioral performance assessment should supersede the physiological assessment or the self-report as the primary exposure criterion, although these other measures still provide important supplementary information. For instance, Hancock and Vasmatzidis have proved that hot conditions can give rise to cognitive decrements (such as performance on tracking tasks) that may result in unsafe behaviors before harmful physiological responses are manifested (Hancock and Vasmatzidis, 1998). Another example is the Standardized Tests for Research with Environmental Stressors Battery (STRES Battery). STRES has been widely used by the Advisory Group for Aeronautical Research and Development (AGARD) (Draycott and Kline, 1996). The STRES Battery comprises seven tests: reaction time, mathematical processing, memory search, spatial processing, unstable tracking, grammatical reasoning, and dual task (unstable tracking with concurrent memory search). To evaluate the stressors, the performances of participants are compared under controlled conditions to determine the effects of stressors such as sleep deprivation, fatigue, monotony and boredom, illnesses, hypoxia, temperature extremes, and alcohol and other drugs.

In conclusion, the available methods for measuring mental stress in natural conditions today have several limitations, such as the lack of comprehensive valuations. Thus, the development of a robust measurement method would facilitate the recordings of physiological and behavioral processes in the studies of mental stress.

2.3.3 Theories of Stress

In general, the assumptions behind theories of stress differ. Some theories emphasize the biological effects of stress, treating stress as a by-product of biological processes. In this area, some of the contributors are the automatic neurological and/or hormonal changes that are triggered by an event. Van Gammert and Van Galen have employed the concept of neuromotor noise to explain the activation side of stress effects (Gemmert et al., 1997). Others assign major performance control functions to plans, appraisals, analyses, and other cognitive phenomena. Hammond claims that the Cognitive Continuum Theory (CCT) provides a new orientation for the field of stress and cognition. He highlights four points: (a) environmental events and cognitive events share equal and joint billing in the determination of behavior, (b) stressors should always be examined in relation to cognitive activities, (c) disruptions of homeostasis should be differentiated into endo-versus exogenous and the current cognitive mode should be recognized (intuitive/analytical), (d) leaders and followers should be taught to be alert to and to accept the need for cognitive change (Hammond, 2000).

No theory that I have reviewed completely elucidates the stress process, but these theories are useful adjuncts to any further attempts at theoretical explanation.

2.3.4 Stress Managements

Stress may have adverse or beneficial effects on human performance. Stress levels vary with people and situations. How can we effectively deal with stress? Some people seem to be more successful than others. But it is possible to train anyone to manage stress in a more successful manner. Training programs, often called stress management programs (SMPs), have been primarily developed by clinical psychologists. SMPS can assist people to control and to reduce mental stress. Among the most common procedures are progressive muscle relaxation, meditation, biofeedback, and cognitive-behavioral skills training. The most effective SMPs are those that depend on relaxation and the acquisition of cognitive-behavioral coping skills. De Jong and Emmelkamp found that many SMPs can be effectively administered by paraprofessionals, thus reducing the expense that might otherwise be incurred in these training programs (De Jong and Emmelkamp, 2000). Moreover, the viewers who experienced more serious life stressors benefited most from a televised stress management program (Jason et al., 1989).

2.4 Summary

In this chapter, literature about the current situation and future trend of design, design and human beings, and cognitive science are reviewed to arrive at the possibility of quantifying a designer's mental stress in the conceptual design process. As the main focus of this research, these issues were reviewed in nine subheadings: definition of design, guidelines of design, design theory and methodology, design process, design and human beings, definition of mental stress, measurement of stress, theories of stress, and stress managements.

Chapter 3
Experiment and Modelling Tools

In the present thesis, Recursive Object Model (ROM), which is derived from the axiomatic theory of design modelling, is utilized as a main tool to quantify the designer's mental stress in the conceptual design process. To facilitate the presentation of the research results introduced in the present thesis, protocol analysis, axiomatic theory of design modelling and ROM will be briefly reviewed in this chapter. As mentioned in Section 1.4, these three theories and methods have been integrated as shown in Figure 2.

3.1 Protocol Analysis

Protocol analysis is a psychological research method that elicits verbal reports from research participants. Newell and Simon pioneered and championed the use verbal protocols. They proposed computational models that could reproduce the observable aspects of human performance on well-defined tasks through the application of explicit procedures (Newell and Simon, 1972). Protocol analysis has been used to studying thinking in cognitive psychology (Crutcher, 1994), cognitive science (Ericsson and Crutcher, 1991; Ericsson and Simon, 1980), and behavior analysis (Austin and Delaney, 1998). It has found further application in the design of surveys and interviews (Sudman et al., 1996), and educational psychology (Renkl, 1997).

Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. The central assumption of protocol analysis is that it possible to instruct subjects to verbalize their thoughts in a manner that doesn't alter the sequence of thoughts mediating the completion of a task, and can therefore be accepted as valid data on thinking. Cognitive tasks have provided information about "what we are thinking" by verbally describing what is going through mind while performing the task. This type of data is referred to as a *verbal protocol.* (Ryan and Haslegrave, 2007a; Ryan and Haslegrave, 2007b; Suwa and Tversky, 1997) .

Traditionally, in protocol analysis, subjects are trained to think aloud as they solve a problem, and their verbal behavior forms the basic data to be analyzed. The process of protocol analysis is shown in Figure 6. The first step of a protocol analysis is to obtain, and then transcribe, a verbal protocol. The next step is to take the protocol and use it to infer the subject's problem space (i.e., infer the rules being used, as well as various knowledge states concerning the problem). The third step is to create a problem behavior graph, which reflects state transitions as subjects search through the problem space in their attempt to solve the problem. Finally, the problem behavior graph is used to create a computer simulation (typically created as a production system) that will solve the problem (Ericsson and Simon, 1980) . By comparing, in detail, the behavior of the simulation to the verbal protocol, one can validate the assumptions that led to the program's creation. In turn, the program provides a rich description of an individual's processing steps, and transitions in knowledge, during the problem-solving process.

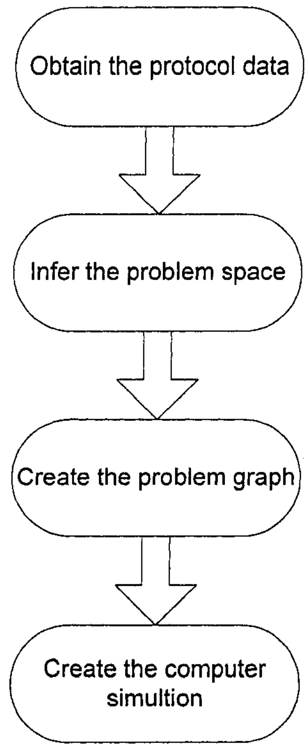


Figure 6 Protocol analysis processes.

In this research, protocol analysis is used to identify the role of designer's thinking and reasoning in a design process. This method is to study subjects' mental processes in the performance of tasks by recording their spontaneous thinking aloud and subsequently segmenting the running commentary into the discrete atomic mental operations that the subjects have used in the accomplishment of the tasks.

3.2 Axiomatic Theory of Design Modelling

Axiomatic theory of design modelling is a logical tool for representing and reasoning about object structures (Zeng, 2002). It provides a formal approach that allows for the development of design theories following logical steps based on mathematical concepts and axioms. The primitive concepts of universe, object, and relation are used in the axiomatic theory of design modelling, based on which two axioms are defined in the axiomatic theory of design modelling.

3.2.1 Axioms

An axiomatic system contains a set of primitive concepts and axioms. Axioms are also called postulates. Primitive concepts are usually informally described and left undefined. Axioms are self-evident truths that can be taken as the basis for inference. They often look simple and trivial (Zeng, 2002).

Design is an activity in which products are created that can function in a desired manner. Design involves both nature and human thought. Nature is where the products are supposed to function while human thought is where the design ideas are generated. All objects appearing in the design process are called design objects, which include design requirements, design solutions, and design knowledge. These objects reside in nature and human thought as well. The design process deals with the relations between these objects. Hence, the modelling of design depends on the assumptions underlying the nature of design objects and the design thought process. The following two groups of axioms address assumptions for this theory.

(1) Predicate symbols: $\supseteq$ (inclusion), $=$ (identity), $\neq$ (inequality)

(2) Operation symbols: $\cup$ (union), $\cap$ (intersection), $\otimes$ (relation), $\oplus$ (structure)

The logical symbols used in the axiomatic theory have the same meaning that they have in other branches of mathematics and logic (Van Dalen et al., 1978). Auxiliary symbols are self-evident in the context. Predicate and operation symbols will be described or defined based on the axioms of objects.

3.2.2 Axioms of Objects

Axiom 1. Axiom of the Universal Object

Everything in the universe is an object.

In this axiom, universe and object are two primitive concepts. Informally, universe is the whole body of things and phenomena observed or postulated. An object is any element that can be observed or postulated in the universe. This axiom looks trivial and simplistic. However, it makes this theory different from set theory where concrete and abstract objects are distinguished by set and element. In our theory, the universe is the only abstract concept, which sets the boundary for the discourse of our discussion. Every other object is treated as the same in that it is an object in the universe. This brings convenience into the uniform representation of design objects in the evolutionary design process.

Axiom 2. Axiom of Object Relation

There are relations between objects in the universe. Symbolically,

$$A \sim B, \ \forall A, B, \tag{1}$$

where A and B are objects. A~B is read as "A relates to B". A relation of one object to itself is called the relation on the object itself.

In this axiom, relation is an aspect or quality that connects two or more objects as being or belonging or working together or as being of the same kind. Relation can also be a property that holds between an ordered pair of objects. This axiom has many implications. Obviously, different types of relations will lead to different concrete axiomatic systems. Corollary 1 defines an inclusion relation between two objects:

Corollary 1 Every object in the universe includes other objects. Symbolically,

$$A \supseteq B, \ \forall A \ \exists B, \tag{2}$$

where B is called a sub object of A. The symbol $\supseteq$ is inclusion relation.

Corollary 2 Every object in the universe interacts with other objects. Symbolically,

$$C = A \otimes B, \ \forall A, B \exists C, \tag{3}$$

where C is called the interaction of A on B. The symbol $\otimes$ represents interaction relation. Interaction relation is idempotent but not transitive or associative. Based on the Corollaries 1 and 2 above, a new operation can be developed as follows:

Definition 1 Structure operation, denoted by $\oplus$, is defined by the union of an object and the interaction of the object with itself.

$$\oplus O = O \cup (O \otimes O), \ \forall O, \tag{4}$$

where $\oplus O$ is the structure of object O.

The structure operation provides the aggregation mechanism for representing the object evolution in the design process.

3.2.3 Two Theorems of Design

The following two theorems are derived following logical steps from the axiomatic theory of design modelling:

(1) *Theorem of recursive logic of design.* A design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution that is to be evaluated (Zeng and Cheng, 1991).

Based on this theorem, a design process is composed of a series of design states defined by both product descriptions and product requirements, as is shown in Figure 7 (Zeng et al., 2004).

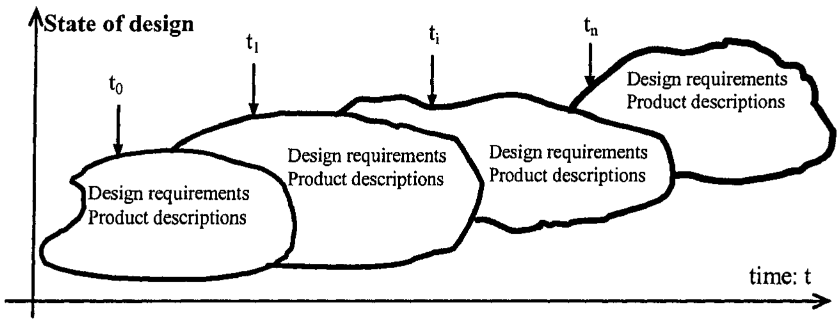


Figure 7 Evolution of the design process (Zeng et al., 2004).

(2) *Theorem of environment-based design.* A design process continues until no undesired combined conflicts exist in an environment system.

This theorem can be illustrated in Figure 8.

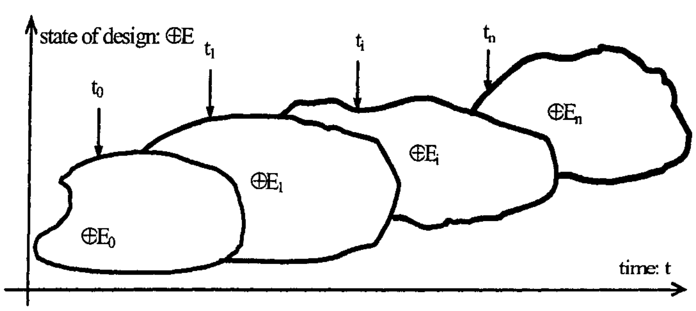


Figure 8 Environment based design: mathematical model (Zeng et al., 2004).

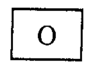
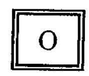
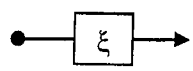
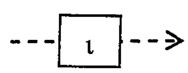
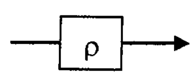
3.3 Recursive Object Model (ROM)

In engineering applications, design states are usually described by using natural language. It is not feasible to ask designers to describe design states in the form of mathematical formulation proposed in the axiomatic theory of design modelling. Hence, it is essential to have a graphic language to represent the objects and relations for the designers to formulate their design process, based on which a step-by-step process can be developed to formalize a design problem described by natural language into this graphic language.

ROM is a graphic representation of linguistic structure, derived from the axiomatic theory of design modelling (Zeng, 2006). Through the lexical, syntactic, and structure analysis of natural language descriptions of a design process, the formalization process decomposes the description of a design problem and solutions into environment components, and then reveals their inherent relations. The graphic symbols proposed in the ROM are sufficient to represent all the linguistic elements in the technical English.

The recursive object model (ROM) is comprised of two kinds of objects: object and compound object; and three kinds of relations: constraint, connection, and predicate. They are summarized in Table 2.

Table 2 Symbols in ROM

Type	Symbol	Graphic Representation	Description
Object	Object		Everything in the universe is an object.
	Compound Object		It is an object that includes at least two objects in it.
	Constraint Relation		It is a descriptive, limiting, or particularizing relation of one object to another.
Relations	Connection Relation		It is to connect two objects that do not constrain each other.
	Predicate Relation		It describes an act of an object on another or that describes the states of an object.

Chapter 4
Experimental Design and Procedure

In this chapter, an experimental study is reported for understanding designer's cognitive process. As introduced in Chapter 3, the cognitive experiment is implemented based on three theories and methods: protocol analysis, the axiomatic theory of design modelling, and ROM. This chapter is organized as follows: Section 4.1 describes the experimental design. The collection of the verbal protocol data and its transcription comes from Shenji Yao. It should be noted that, the details of these will be introduced in her Ph.D. thesis. Section 4.2 proposes a new encoding scheme for analysis for analysis the protocol data from the experiment.

4.1 Experimental Design

In this study, subjects were assigned a design task in which they need to look for conceptual solutions. Each individual subject's design activities were recorded and analyzed for quantifying the designer's mental stress during the design process.

4.1.1 Selection of Subjects

In this study, the criteria for selecting the subjects include educational background, engineering design experience, and language ability. A subject should have basic training in engineering design and understand what is expected in performing a design task. The subject should also be able to express their thoughts in English reasonably well, though fluent

English as a native speaker is not required. Chapter 5 discusses the influences of non-standard English on the research results. Human research ethics approval for the study has been received from University Human Research Ethics Committee.

Seven graduate students with various cultural backgrounds and engineering experience (5-10 years) volunteered as the subjects in this study. They are from mechanical engineering, electrical engineering, and computer engineering, respectively. All the subjects signed a consent form prior to taking part in the study.

4.1.2 Materials

The design problem used by Dorst and Cross (Dorst and Cross, 2001) was adapted for this study. It was chosen because it is feasible, realistic and challenging enough for the anticipated subjects in our study. The problem was rephrased to be more easily understood by our subjects, who have diverse backgrounds. The subjects were presented a pre-prepared description of the design problem as follows:

Design a litter-disposal system for passenger compartments in a train. This system should be convenient for the passengers to deposit their garbage and for the cleaners to collect the garbage.

The structure of the passenger compartment is shown on the thesis to the subjects as shown in Figure 9

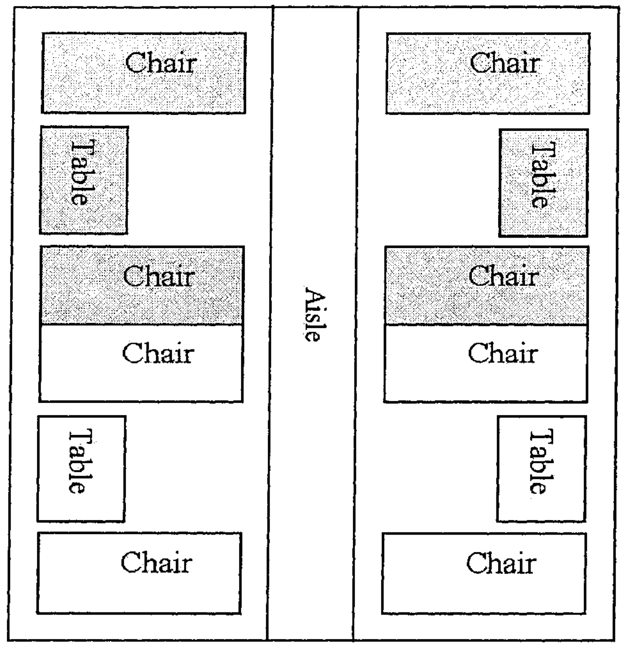


Figure 9 Design problem.

4.1.3 Experimental Design and Procedure

The objective of this study is to quantify the designer's mental stress during the design process. One requirement is that the information determining the designer's mental stress must be recorded as accurately as possible. Various approaches may be needed to record the information. Another requirement is that the experiment must not interfere with the designer's mental process so that the designer's mental stress is not influenced by the adopted experimental approach.

Therefore, the experiment in this study is composed of two sessions: design session and interview session. In the design session, the experimenter will present the pre-prepared problem description to the subject and will answer any questions from the subject regarding the procedure of the experiment. The subject will then work alone on the design task in a quite room. S/he can use references or Internet to find the required information to solve the design problem. The subject is asked to sketch or write anything in a free sketching system installed in a WACOM Tablet as shown in Figure 10, which gives the user a direct point-and-draw-on-screen; hence, the subject could design as if s/he were designing by using a pencil and a piece of paper. The text and the sketch created by the subjects on the tablet screen are recorded by the software My Screen Recorder as shown in Figure 11. That screen recording system was used to record everything that the subject did during the design process, which can be used to analyze the design process. This natural interface does not add any extra mental workload to the designer (Zeng, 2004c).The experiment setting is shown in Figure 12. During the design session, the researcher will generate a list of questions about the subject's decision making process by observing the subject's actions.

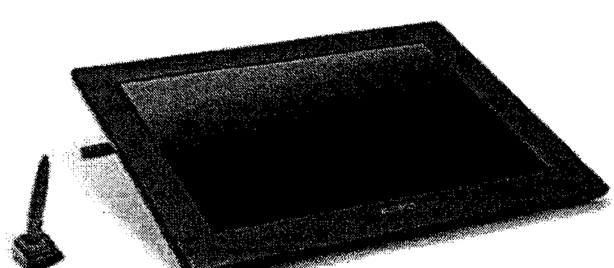


Figure 10 WACOM tablet and grip pen.

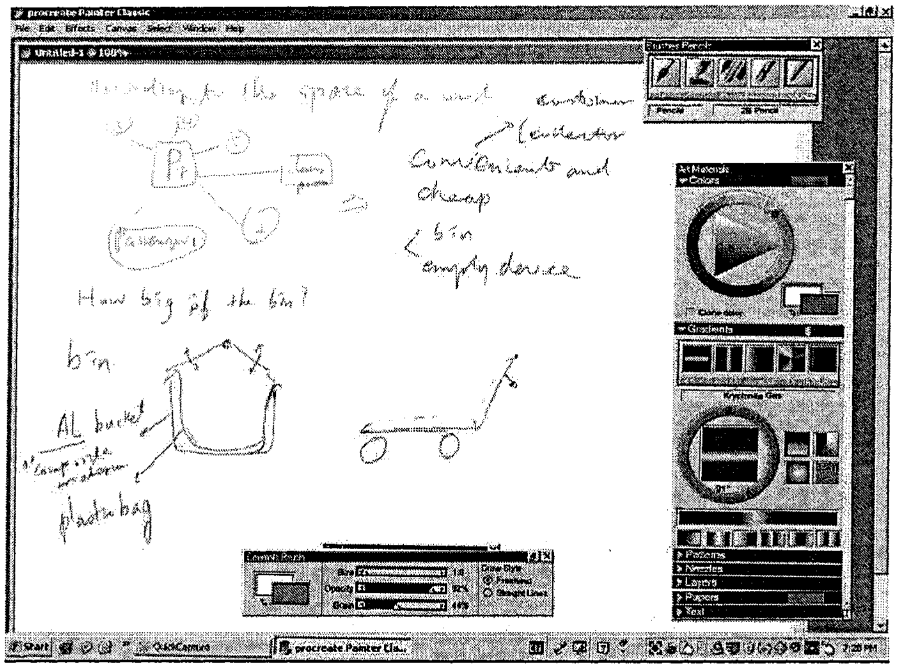


Figure 11 The interface of My Screen Recorder.

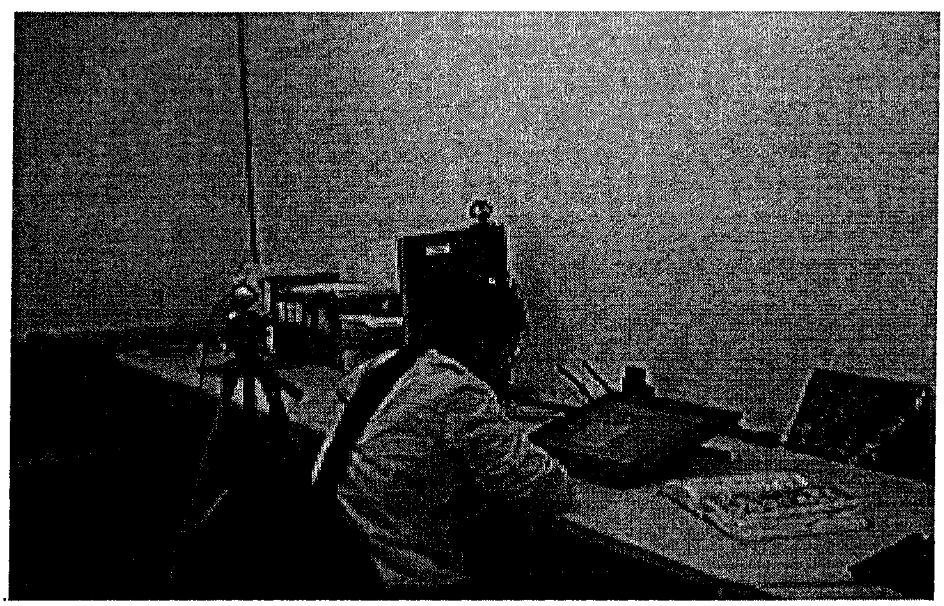


Figure 12 Experiment set-up.

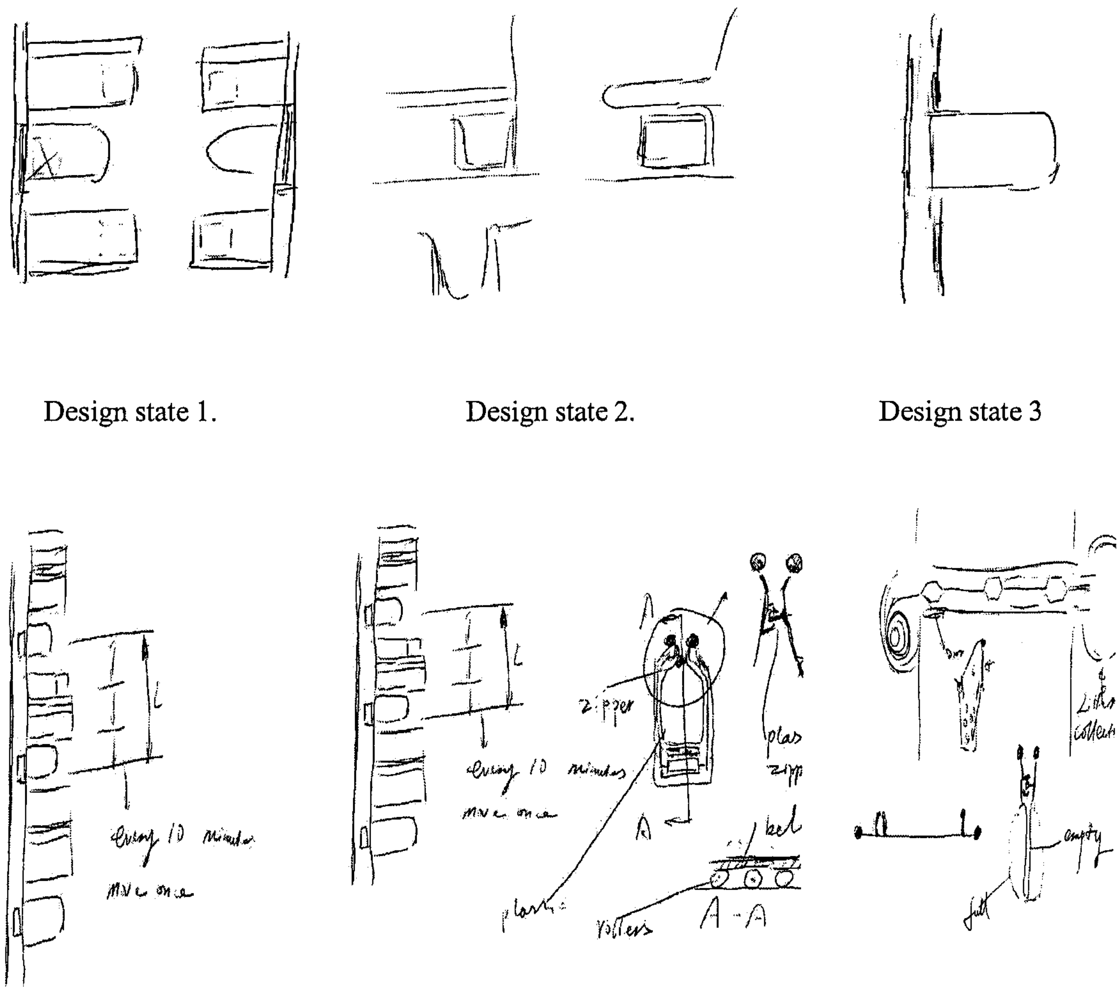
In the interview process, the researcher will ask the subject those questions prepared during the design session and seek the explanation about the subject's thought process. The recorded audio, video, screen activities will be shown to the subject as memory cue for her/him to answer the questions. The answers will be recorded and are used to analyze the trend of change of the subject's mental stress during the design process. Figure 13 shows five consecutive states of the design during a subject's design process.

Table 3 gives some sample questions and answers in the interview session. A method for asking questions during the design process can be used for this purpose (Wang and Zeng, 2007).

All the information collected from the video, audio media and screen recording video during the two sessions is organized for protocol analysis.

4.1.4 Processing and Analysis of Protocol Data

Since design is a creative act full of style, randomness, and flexibility, the protocol data corresponding to the design process will be unstructured. The analysis of experimental data, however, requires that the data be organized in a structured manner. In the literature, the data processing consists of three tasks: transcription, segmentation and encoding (Ericsson and Simon, 1980). The transcription process is to transform verbal protocol data into text documents. The objective of segmentation is to break the transcribed text into segments. Encoding is an important and critical part to analyze subject's protocol data. Most of the current protocol studies devise the coding schemes according to specific design problems. If the design problem is changed, the coding scheme will also be changed and therefore cannot be extended for other applications. As a result, experiments from different sources are not comparable, which brings a lot of subjectivity into the study.



Design state 1. Design state 2. Design state 3

Design state 4-1. Design state 4-2. Design state 5.

Figure 13 Design sketches.

Table 3 Examples of interview session

Design State	Time	Sample questions	Sample answers
1	00:26:50–00:30:00	Please watch the Video shown in the Tablet. How did you start this project?	First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin.
		What were you thinking in this process? (pointing at the video)	I just draw a garbage bin very simply. I think the garbage bin is put here.
2	00:30:45–00:39:20	Why did you put the garbage bin under the seats?	It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables.
3	00:39:30–00:45:16	How did you get this new design?	Now I suddenly got an idea. When the garbage passes through the channel, how to pack the garbage? I cannot let the garbage pass on the belt directly. How to design? I suddenly think about the plastic zipper on the plastic bag.
4	00:47:30–00:51:38	What were you drawing? (pointing at the video)	Then I consider whether I should install one garbage window for every seat. But I consider installing it symmetrically, which is good for the whole programming design.
5	01:05:50–01:07:11	You thought the garbage bin should be flexibility?	Now I consider the plastic bag, namely garbage bag for the whole compartment.

Because of this contradiction between the aforementioned two facts, most existing protocol analysis in design research is domain and researcher dependent. In this study, the concept of design state is used to organize unstructured design protocol data into structured records, based on which logical analysis can be made.

4.1.4.1 Transcription of Verbal Protocol Data

We transcribe all the verbal protocol data provided by subjects during the interview stage into text documents. However, these documents may contain some vague and inconsistent information due to insufficient presentation from the subjects of their cognitive process. To solve the problem, we add some annotation to explain their non-verbal intentions to make the transcript more consistent. We assigned three operators to do cross-checking to ensure the accuracy and consistency of the transcript and produce the final formalized transcript.

4.1.4.2 Segmentation of Protocol Data Based on Design States

The objective of segmentation is to break the transcribed text into segments, which are further encoded with a coding scheme. In our study, the protocol data is segmented in terms of the concept of design state proposed by Zeng (Zeng, 2004a), based on which a design process is characterized by a series of design states as shown in Chapter 3. As mentioned in Section 3.2.3, a design process is characterized by a series of design states, so each transcript is divided into separate design states. Hence, the design state is defined as the structure of environment. A new state of design can be defined as the structure of the old environment (E_i) and the newly generated design concept (S_i).

$$\oplus E_{i+1} = \oplus(E_i \cup S_i) = (\oplus E_i) \cup (\oplus S_i) \cup (E_i \otimes S_i) \cup (S_i \otimes E_i). \qquad (5)$$

$$B_{i+1} = (E_i \otimes S_i) \cup (S_i \otimes E_i). \quad (6)$$

The following paragraph is an example for segmentation.

Original text: *"First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin. Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the position of the coach car. Now I consider the convenience for the cleaners to pick up the garbage bin. Cleaners walk along the aisle. Then I think of putting the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. This place (under the seats) is not convenient for picking up. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle."*

Segment 1: *First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin*

s1=a garbage bin

e1= Φ

b1= Φ

Segment 2: *Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the structure of the coach car.*

e1=coach car, location of the garbage bin, e2=s1=garbage bin

s2= Φ, s2=s2$\cup$s1=garbage bin

B2= considering the structure of the coach car when a garbage bin is put there

Segment 3: *Now I consider the convenience for the cleaners to pick up the garbage bin. Cleaners walk along the aisle.*

e1=cleaners, e2=table, e3=aisle, e4= s2=garbage bin

s3=the location of the garbage bin: to put the garbage bin under the table

b1=how cleaners can pick up the garbage bin conveniently;

b2=cleaners walk along the aisle;

b3=garbage bin is put under the table.

segment 4: *Then I think of putting the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. This place (under the seats) is not convenient for picking up. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.*

e1=passenger, e2=seats, e3=table, e4=s3

s4=the location of the garbage bin: to put the garbage bin under the seats

b1=the location of putting garbage bin under the table affects the movement of passenger's legs;

b2=the only place is under the seats considering seats, tables.

Each segment above includes environment components and the relations between those components, as was implied in Eq. 5. Table 4 shows the components included in each design state. Other segments are identified in the same way.

Table 4 Design states

Segment	Environment	boundary	New concept	Content
1	e1= Φ	b1= Φ	s1=a garbage bin	*First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin.*
2	e1=coach car, location of the garbage bin, e2=S1=garbage bin	b2= considering the structure of the coach car when a garbage bin is put there	s1=garbage bin s2=s2∪s1=garbage bin	*Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the structure of the coach car.*
3	e1=cleaners, e2=table, e3=aisle, e4= garbage bin	b1=how cleaners can pick up the garbage bin conveniently; b2=cleaners walk along the aisle; b3=garbage bin is put under the table.	s2=garbage bin s3=the location of the garbage bin: to put the garbage bin under the table	*Now I consider the convenience for the cleaners to pick up the garbage bin. Cleaners walk along the aisle.*
4	e1=passenger, e2=seats, e3=table, e4=S3	b1=the location of putting garbage bin under the table affects the movement of passenger's legs; b2=the only place is under the seats considering seats, tables.	s4=the location of the garbage bin: to put the garbage bin under the seats	*Then I think of putting the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. This place (under the seats) is not convenient for picking up. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle.*

4.2 Encoding by ROM

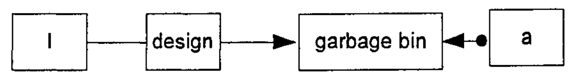
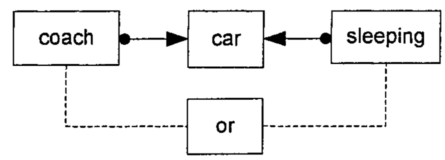
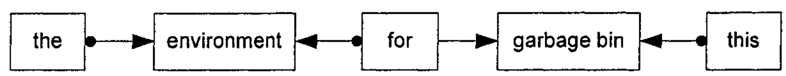
Encoding is an important and critical part to analyze subject's protocol data. The encoding scheme in the present thesis is developed based on the concept of design state comes from the axiomatic theory of design modelling (Zeng, 2002) and ROM (Zeng, 2007). The graphic symbols proposed in the ROM are sufficient and necessary to represent all the linguistic elements in technical English (Zeng, 2007). Therefore, ROM is used to collect, organize, and interpret protocol data, especially analyze the characteristics by inferring from multiple object relationships. The designer's description using natural language will be transformed into ROM diagram, which enables us to systematically code the designer's decisions transforming the design from one state to another. The ROM diagrams provide a foundation for quantifying the designer's mental stress.

As mentioned above, three major relations are implicated by ROM. Table 5 shows examples of ROM diagram for some protocol data.

The ROM diagram of the following example is shown in Figure 14 and Figure 15 .

Example 1: *For the first requirement, we try to measure this requirement. How can we measure the size? It should accommodate 4-6 people. We can measure it by volume. If it is 2 liters for the volume, it can accommodate 6 people. If 10 liters, the volume can accommodate 10 people, something like that.*

Table 5 Examples of ROM diagram

Natural Language	ROM
I design a garbage bin	
coach car or sleeping car	
the environment for this garbage bin	

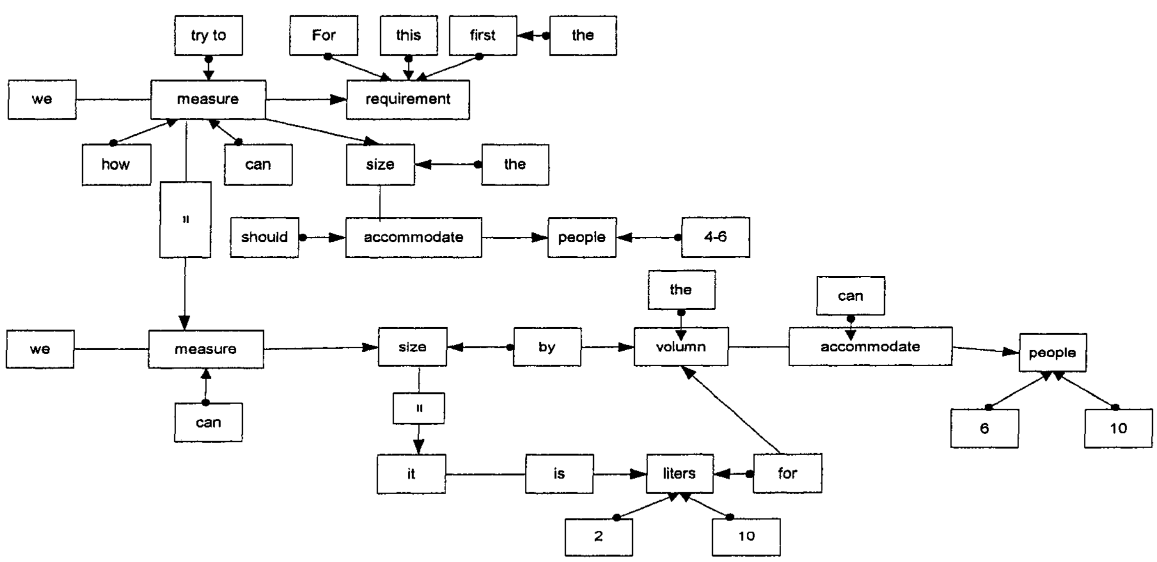


Figure 14 Example 1 of ROM diagram.

Example 2:*It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats.*

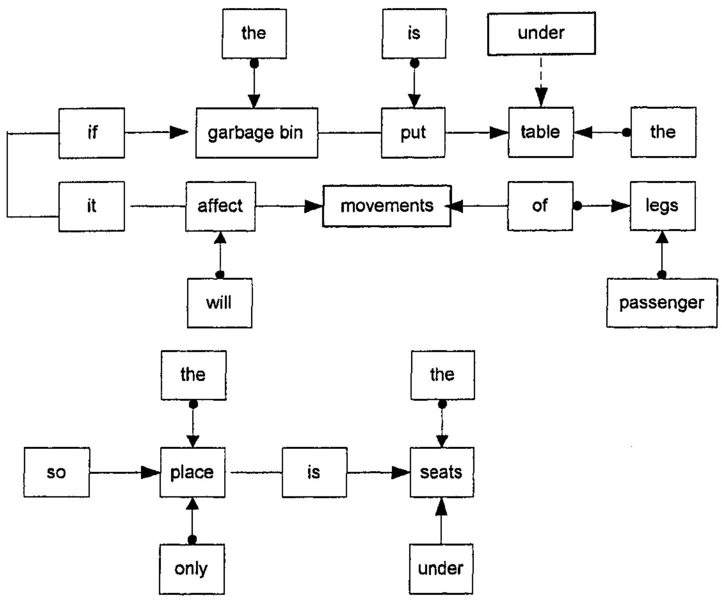


Figure 15 Example 2 of ROM diagram.

When using words in a natural language to describe a design process, it always has inherent sequence. There are eight major types of words in English grammar: noun, verb, adjective, adverb, pronoun, determiners, preposition, and conjunction. All the words are objects and can be coded with a sequence. Hence, we define a serial number to identify the sequence of words being used in a text. The serial number is represented by a capital alphabetical letter plus Arabic numerals. However, in many cases, multi-relationship exists for one object. In order to differentiate the relationship, each one is given a number respectively. The rules for defining the relationships are shown in Table 6. Furthermore, mental stress is quantified by estimating the result from ROM.

Table 6 Encoding eight major types of words

Part of Speech	Example	Numbering
noun	environment	N+number
verb	think	V+number
Link verb	is	L+number
adjective	red	J+number
adverb	then	D+number
pronoun	I	P+number
determiners	the	A+number
preposition	for	T+number
conjunction	or	C+number

The ROM diagram with the serial number of each object is shown in Figure 16 and Table 7 :
Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the structure of the coach car.

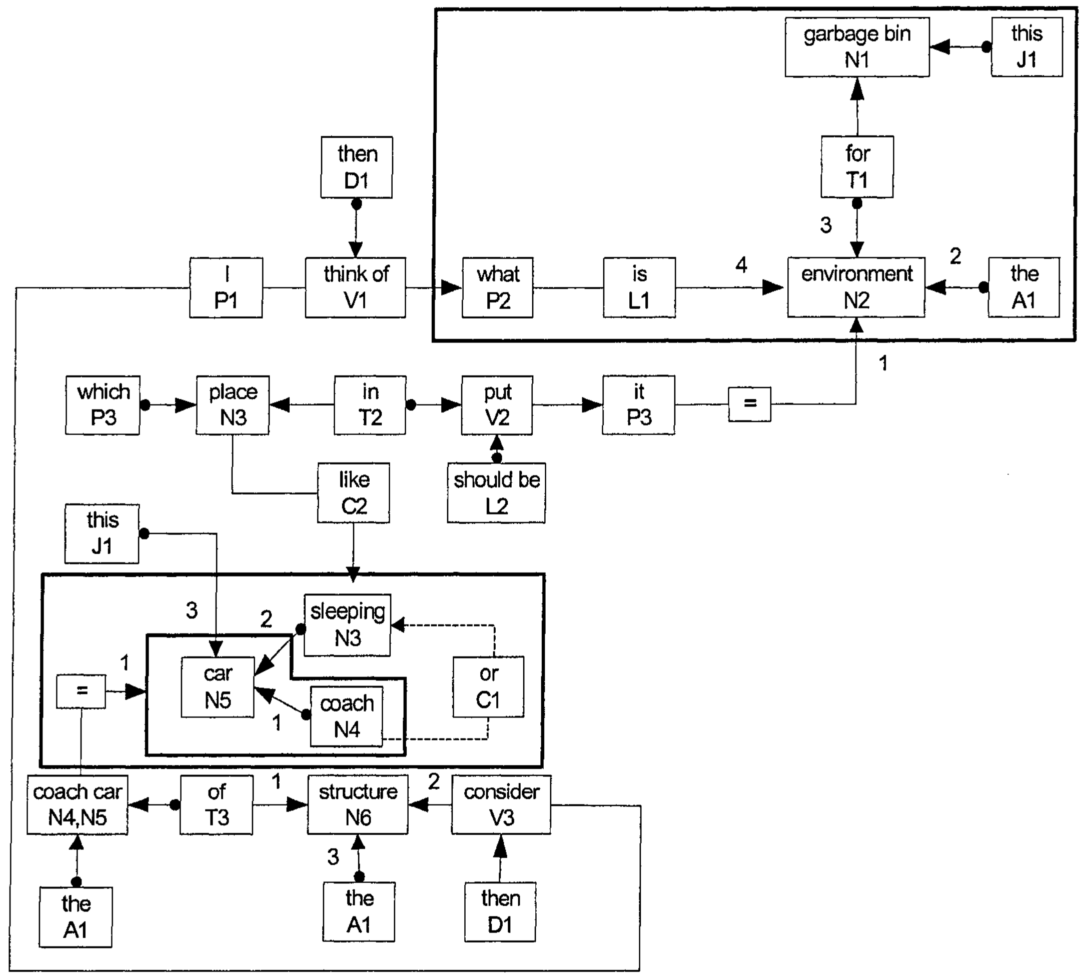


Figure 16 Example of code objects.

Table 7 Example of encoding major types of words

Part of Speech	Example	Numbering
noun	garbage bin	N1
	environment	N2
	place	N3
	coach	N4
	car	N5
	structure	N6
verb	think of	V1
	put	V2
	consider	V3
link verb	is	L1
	be	L2
adjective	this	J1
adverb	then	D1
pronoun	I	P1
	what	P2
	which	P3
determiners	the	A1
preposition	for	T1
	in	T2
	of	T3
conjunction	or	C1
	like	C2

4.3 Summary

This chapter described the implementation of the proposed theories and methods presented in Chapter 3. The cognitive experiment of designing a new litter-disposal system was used to verify those theories and methods. The cognitive experiment consists of two sessions: design session and interview session. All information collected from the video, audio media and screen recorder during the two sessions was organized and transferred to protocol data. Then, the protocol data was segmented into different design states by using the axiomatic theory of design modelling (Zeng, 2002). After that, the protocol data in each state were encoded into ROM diagrams, which are used to quantify the mental stress. Details of the quantification methodology are discussed in the next chapter.

Chapter 5
Quantification of Designer's Mental Stress

Since the verbal protocol is now encoded into ROM diagrams, the designer's mental stress should be able to be quantified from the encoded ROM diagrams. In this chapter, Section 5.1 analyzes the mental stress based on the axiomatic theory of design modelling and ROM. The quantification of designer's mental stress, which is quantified with the multi-relationship of objects based on ROM diagram, is proposed in Section 5.2. Section 5.3 provides the discussions. It should be noted that the analysis results presented in present chapter are preliminary. More comprehensive analysis is required to correlate different factors appearing in this process.

5.1 Analysis of Mental Stress Using Axiomatic Theory of Design Modelling and ROM

In this study, the mental stress is defined as the intensity of information imposed by environment on the brain. For the discussion of mental stress, the first step is to identify where the mental stress comes from. The quantification of the designer's mental stress is based on the observations presented in Figure 17. In general, after a task is assigned to an agent, the agent will produce a result. In the context of design, the task can be replaced by a design problem, the agent can be replaced by designer(s), and the result can be replaced by solution. The overall design task is characterized by delivering a design solution for a given design problem. Any design problem can be seen as a mental workload for a designer. A design solution is a result of the designer's performance. Intuitively, the stress level is in direct proportion to workload and inverse proportion to the subject's mental capacity. The more workloads assigned by the environment, the more mental stress may be exerted on the designer's brain. That is the reason why some designers may find a design problem easy whereas the others may find it difficult. This feeling of the easiness or difficulty of the problem is the mental stress of the designer faced with the design problem.

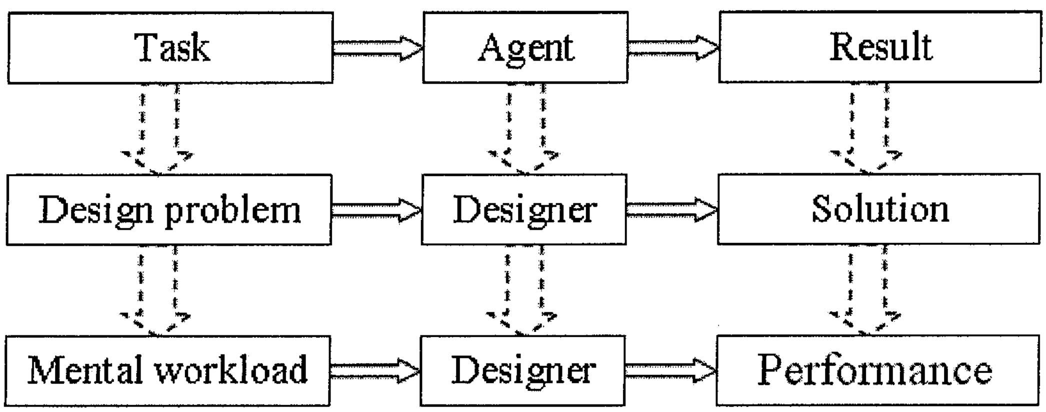


Figure 17 Analysis of mental stress.

It can be seen from Figure 17 that the designer's mental stress can be viewed as the designer's response to a given design problem. This response may be reflected through different psychological, physiological, linguistic and other parameters. It is noticed that what the designer describes in the experiment is indeed what s/he thinks and feels about her/his mental process during the design process. In this study, it is assumed that the complexity of the designer's description of the design process can be taken as an indication of his/her mental stress. This complexity of description can be quantified by the complexity of the structure of the ROM diagram corresponding to the text for the description.

Experiments based on EEG signals and eye gaze movement patterns are being conducted in the design lab (CIISE) to validate and verify the effectiveness of quantifying the mental stress through the ROM diagram of description texts. The quantitative results from this quantification approach conform to our intuitive understanding of the design process.

Figure 18 shows how to analyze mental stress using the axiomatic theory of design modelling. Mental stress is the physical reaction of the brain to the workload imposed by the environment. Different environments impact brain in different ways whereas different brains react differently to the same environment.

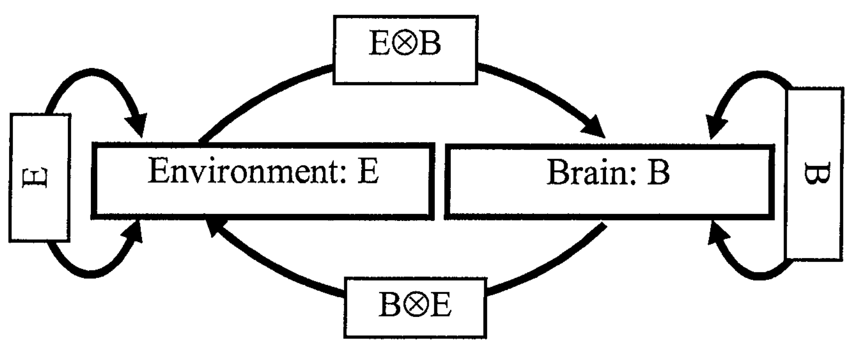


Figure 18 Analysis of mental stress using the axiomatic theory.

The mental stress can be represented by the following equation.

$$M \subset B \otimes E, \tag{7}$$

⊗: Interaction operation,

M: Mental stress,

E: Environment, and

B: Brain

Figure 19 shows how mental stress may be related to ROM, which indicates the feasibility of using ROM to quantify mental stress. Mental stress is related to natural language, just like EEG, eye gaze movement, heart rate, and so on. Language is a symbol system that human beings used to describe the universe. By common agreement among its users, its symbols (letters and words) usually stand for ideas in the mind or objects in the environment (Turner, 1971; Zeng, 2007). The symbols in a language may also fulfill certain structural functions in the language pattern so that ideas and objects can be combined to form more complex meanings (Turner, 1971). Bradac, et al argued that mental stress is directly related to the language intensity of sources (Bradac et al., 1978).

As mentioned in Chapter 3, the graphic symbols proposed in the ROM are sufficient and necessary to represent all the linguistic elements in technical English language. Since the relationship is the most important foundation in ROM diagram, based on the abductive logic we assume that the relationships of ROM diagram have a mapping with the mental stress.

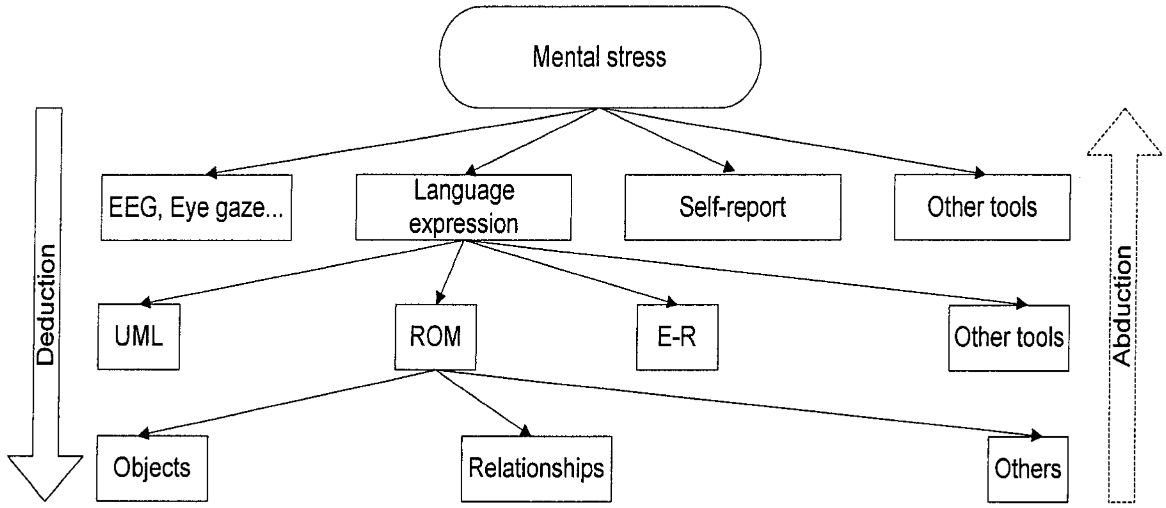
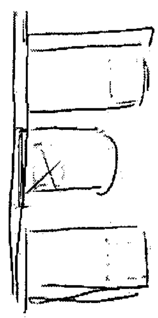
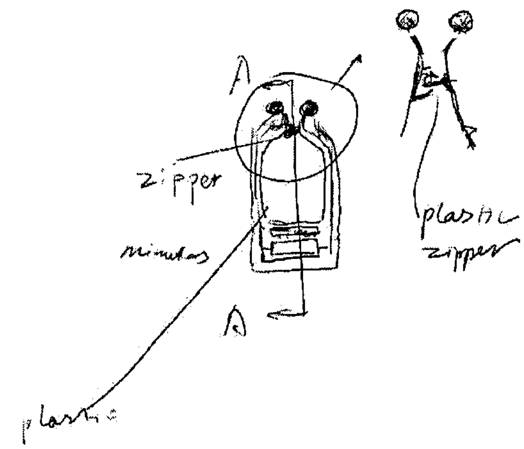


Figure 19 Relationship between mental stress and ROM.

In the following, we will use two sentences to illustrate the assumption above. The two sentences, both having 30 words, are picked up from one subject's protocol data. The first sentence belongs to the first design state and the second sentence belongs to the fourth design state, corresponding to the sketches shown in Figure 20. It can be seen from the complexity of the sketches that the first design state may be related to less mental stresses than that in the fourth design state.



Design state 1



Design state 4

Figure 20 Two sketches in different design states.

The following text is extracted from our protocol data:

One sentence of design state 1*: Now I consider the convenience for the cleaners to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table.*

One sentence of design state 4: *Now I consider the plastic bag, namely garbage bag for the whole compartment. I need to consider how to put the garbage bag and how to collect the garbage bag.*

The environment components and their mutual relationships imply the designer's mental stress; therefore, the identification of environment components and their relationships behind the description above could be useful for quantifying the designer's mental stress. The following lists all those objects by using the axiomatic theory of design modelling:

For the sentence of desig state one:

e_1=cleaners, e_2=table, e_3=aisle, e_4=S_{i-1}=a garbage bin,

$E_i=e_1 \cup e_2 \cup e_3 \cup e_4$,

s_i=the location of the garbage bin: to put the garbage bin under the table,

$S_i=S_{i-1} \cup S_i$=the location of the garbage bin is specified to be under the table,

$b_1=R(e_1, e_4)$= cleaners pick up the garbage bin,

$b_2=R(e_1, e_3)$=cleaners walk along the aisle,

$b_3=R(e_2, e_4)$= garbage bin is put under the table,

$B_i=b_1 \cup b_2 \cup b_3$.

For the sentence of desig state four:

e1=plastic bag, e2=compartment, e3=garbage bin,

b1=considering how to put the garbage bag in the system,

b2=considering how to collect the garbage bag.

The ROM diagrams of the two sentences are shown in Figure 21 and Figure 22, respectively. The designer's mental stress behind the ROM description is analyzed in Table 8. The objects of sentence one include 5 nouns and 5 verbs. There are 14 objects whose number of relationships is less than 4. Compared to sentence one, the objects of sentence two include 3 nouns and 4 verbs; the number of objects with less than 4 relationships is 13. The factors of ROM, which includes object with less than 4 relationships, show that the mental stress is inversely related to the number of objects and relationships included in a ROM diagram. However, intuitively, the number of objects and their relationships in a ROM diagram may contribute to the mental stress positively. Therefore, the object with less than four relationships to it may not contribute to the designer's mental stress.

From Table 8, the significant differences between the two sentences are the number of objects with more than 3 relationships to it. Sentence one has two such objects, which are "garbage bin" and "cleaners". The maximum number of relationships is four, which is related to the word "garbage" and "cleaners". The total number of relationships is 8. In contrast, sentence two has two such relationships, which are related with the word "consider" and "bag". The total number of relationships is 14.The maximum number of relationships is seven which is related to the word "bag".

It should be noticed that we have ignored the auxiliary words such as "the" and "how". Based on the case study, the mental stress is directly related to multi-relationships. Therefore, it is possible to use multi-relationships of ROM to quantify designer's mental stress.

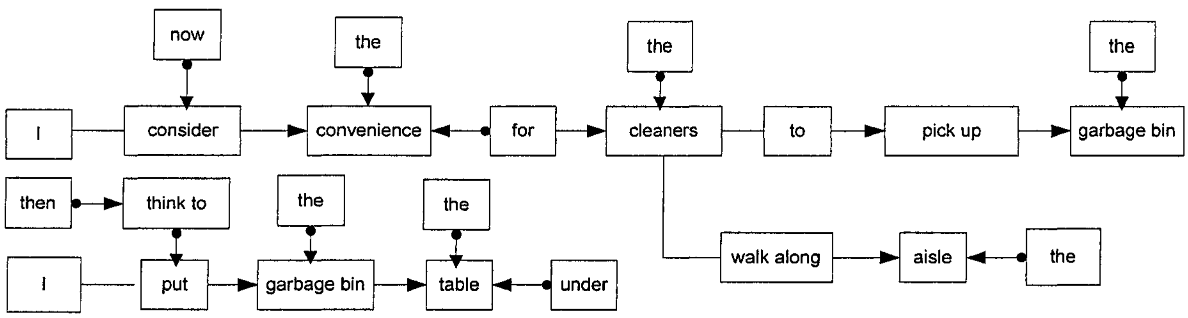


Figure 21 ROM diagram of a sentence in one subject's design state one.

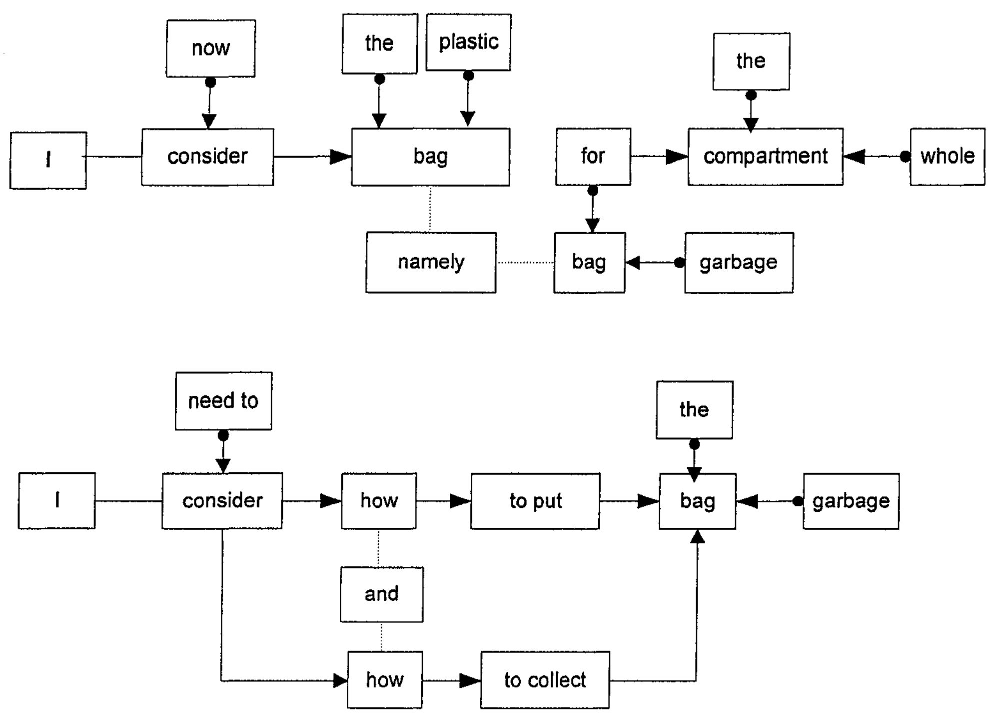


Figure 22 ROM diagram of a sentence in one subject's design state four.

Table 8 Statistical data of two ROM diagrams

	Noun	Verb	1 Relationship	2 Relationships	3 Relationships	≥ 4 Relationships
Sentence one	convenience cleaners garbage bin aisle table	consider pick up walk think to put	then now under	I to pick up walk along consider for think to	put table aisle convenience	the garbage bin (4) Cleaners (4)
Sentence two	plastic bag compartment garbage bag	consider put collect need to	now plastic whole need to	for and namely garbage to collect to put I	compartment the	How Consider (6) Bag (8)

5.2 Quantification

This section presents some of the results from our protocol data analysis based on the method introduced in Chapter 4 and section 5.1 of this thesis.

5.2.1 Statistical Analysis

Table 9 summarizes the statistical data derived from each encoded ROM diagram corresponding to a design state that was segmented from individual designer's protocol data. It has nine columns. The first four columns are the subject number (S_n), the index for design states (D_s), the number of nouns (N_n), and the number of verbs (N_v), respectively. Seven subjects' design states, whose numbers are either 5 or 6 in this study, are obtained based on the segmentation of the protocol data. The numbers of nouns and verbs are identified in each design state.

The fifth column lists all the stress relationships, which are represented by an array (n_r, n_o). A stress relationship is the relationship to an object that has more than three relationships on it. The array (n_r, n_o) means that there are no objects that has nr relationships.

The sixth one is the total number of stress relationships (R_t) in a ROM diagram. The relationships are quantified by summing up the total number of the relationships as follows:

$$R_t = \sum n_r \times n_o. \qquad (8)$$

Table 9 Statistical data of different design states

S_n	D_s	N_n	N_v	N_r: (n_r, o_r)	R_t	ρ_r	Time	Duration
1	1	31	29	(2,4), (1,8)	16	3.75	00:26:50–00:30:00	00:03:10
	2	72	57	(4,4), (2,5), (1,7), (1,8),(1,9), (1,16), (1,17), (1,24)	107	1.21	00:30:45–00:39:20	00:08:35
	3	77	35	(2,4), (1,5), (1,8), (1,12), (1,14)	47	2.38	00:39:30–00:45:16	00:05:46
	4	186	117	(4,4), (1,5), (1,6), (1,7), (1,9), (1,11), (1,12), (1,31), (1,59)	156	1.94	00:47:30–00:51:38	00:04:08
	5	39	21	(2,4), (1,5),(1,14)	27	2.22	01:05:50–01:07:11	00:01:21
2	1	10	13	(1,6)	6	3.83	00:08:00–00:09:30	00:01:30
	2	28	20	(1,4), (1,6), (1,7), (2,8)	33	1.45	00:09:40–00:12:08	00:02:28
	3	30	30	(2,4),(1,20)	28	2.14	00:12:30–00:15:19	00:02:49
	4	14	17	(1,4), (1,5),(1,11)	20	1.55	00:15:30–00:17:20	00:01:50
	5	11	16	(2,4), (1,7)	15	1.80	00:19:00–00:31:30	00:12:30
3	1	48	30	(5,4), (2,5), (3,6), (3,7), (1,12), (1,17), (1,49)	147	0.53	00:09:55–00:17:35	00:07:40
	2	85	83	(6,4), (4,5), (3,7), (2,8), (1,10), (3,12), (1,13), (1,15), (1,19), (1,58)	256	0.66	00:19:55–00:26:45	00:06:50
	3	55	51	(6,4), (1,5), (3,6), (2,7), (3,8), (1,9), (1,10), (1,11), (1,12), (1,52)	179	0.59	00:27:20–00:34:35	00:07:15
	4	198	153	(11,4), (10,5), (6,6), (4,8), (3,9), (5,10), (3,11), (2,12), (3,13), (3,15), (1,17), (2,18), (1,20), (1,21), (1,30), (1,44),(1,45), (1,88)	681	0.52	00:35:20–01:17:42	00:42:22
	5	64	44	(5,4), (2,5), (3,6), (3,7), (4,8), (2,11), (1,13,), (1,41)	213	0.51	01:18:00–01:25:33	00:07:33
4	1	101	59	(7,4), (6,5), (3,6), (6,7), (1,9), (1,10), (1,16), (1,43)	196	0.82	00:20:10–00:30:22	00:10:12
	2	82	60	(11,4), (7,5), (5,6), (1,7), (2,8), (1,11), (1,16), (1,21), (1,43)	223	0.64	00:31:00–00:36:23	00:05:23
	3	97	67	(5,4), (8,5), (3,6), (6,7), (1,8), (1,17), (1,19), (1,20), (1,33), (1,42)	259	0.63	00:37:10–00:45:01	00:07:51
	4	174	111	(7,4), (7,5), (8,6), (2,7), (2,8), (1,9), (2,10), (3,12), (1,13), (1,16), (1,19), (1,23), (1,25), (1,41), (1,56)	445	0.64	00:45:55–01:01:20	00:15:25
	5	57	44	(3,4), (4,5), (1,6), (1,7), (1,10), (1,12), (1,25), (1,28)	120	0.84	01:02:00–01:07:10	00:05:10
	6	79	59	(5,4), (3,5), (1,6), (1,7), (5,9), (1,12), (1,17), (1,18), (1,19), (1,28)	187	0.74	01:08:10–01:19:01	00:10:51
5	1	35	29	(2,4), (1,6), (1,9), (1,13), (1,16), (1,20)	72	0.89	00:03:50–00:12:20	00:08:30
	2	85	24	(4,4), (7,5), (2,6), (2,9), (1,11),(1,12), (1,13)	113	0.96	00:12:59–00:19:00	00:06:01
	3	87	25	(4,4), (7,5) (1,6), (2,7), (1,52)	123	0.91	00:19:09–00:24:00	00:04:51
	4	35	24	(5,4), (1,5),(1,6), (1,7), (1,8),(1,13)	59	1	00:24:01–00:27:00	00:02:59
	5	60	22	(7,4), (1,5), (1,6), (1,7), (1,9), (1,11), (1,20)	86	0.95	00:27:01–00:29:00	00:01:59
	6	84	30	(10,4), (1,6),(1,7), (1,8),(1,10), (1,11), (1,13), (1,31)	126	0.90	00:29:01–00:33:42	00:04:41
6	1	26	20	(4,4), (2,5), (1,7), (1,8), (1,19)	68	0.68	00:41:16–01:19:09	00:37:53
	2	40	22	(3,4), (2,5), (2,7), (1,10), (1,11), (1,13), (1,16), (1,22)	108	0.57	01:26:50–01:32:10	00:05:20
	3	27	19	(5x4), (1,5), (1,6), (1,7), (1,9), (1,10)	57	0.81	01:33:30–01:57:32	00:24:02
	4	75	73	(3,4), (2,5), (3,6), (1,7), (1,8), (1,10), (1,12), (1,13), (2,14), (1,16), (1,17), (1,19),(1,21), (1,29), (1,40)	260	0.57	01:42:05–01:57:32	00:15:27
	5	34	51	(1,4), (5,5), (4,6), (1,8), (1,9), (1,10), (1,11), (1,17), (1,42)	150	0.57	01:57:44–02:23:40	00:25:56
7	1	22	12	(2,4), (1,5), (1,6)	19	1.79	00:04:02–00:11:21	00:07:19
	2	48	20	(7,4), (4,5), (1,6), (2,8), (2,12)	94	0.72	00:12:13–00:18:43	00:06:30
	3	28	18	(4,4), (2,5), (2,6), (1,7), (1,9), (1,19)	73	0.63	00:19:01–00:24:52	00:05:51
	4	91	63	(11,4), (1,5), (2,6),(3,7), (1,8), (2,9), (1,10), (2,11), (1,12), (1,13), (1,14), (1,16), (1,17), (1,38)	250	0.62	00:25:04–00:38:54	00:13:50
	5	46	13	(4,4), (1,6), (1,7), (1,8), (1,9), (1,11), (1,12)	69	0.86	00:39:35–00:42:53	00:03:18

The seventh column is the density of the relationships, which is denoted by ρ_r and calculated by the following equation:

$$\rho_r = \frac{R_t}{N_n + N_v} \qquad (9)$$

The parameter ρ_r represents mental stress Rate-Of-Change by dividing index by the summation of numbers of nouns and verbs in each design stages.

The last two columns are the amount of time that the subject spent in each design state and duration of each state, respectively. Each design state has a start time and an end time in the format of hh:mm:ss, and the duration of each state is calculated by subtracting a start time from an end time in the same format.

5.2.2 Overview the Designer's Mental Stress

Figure 23 shows the quantification of the designer's mental stress. The levels of their mental stress are sorted from low to high in the following order: 2, 5, 1, 7, 6, 4, and 3. Subject 4 has 6 design states whereas the others have 5 design states. Design states are shown on the X axis. The Y axis represents the subject index. The Z axis shows the mental stresses calculated from multiple relationships.

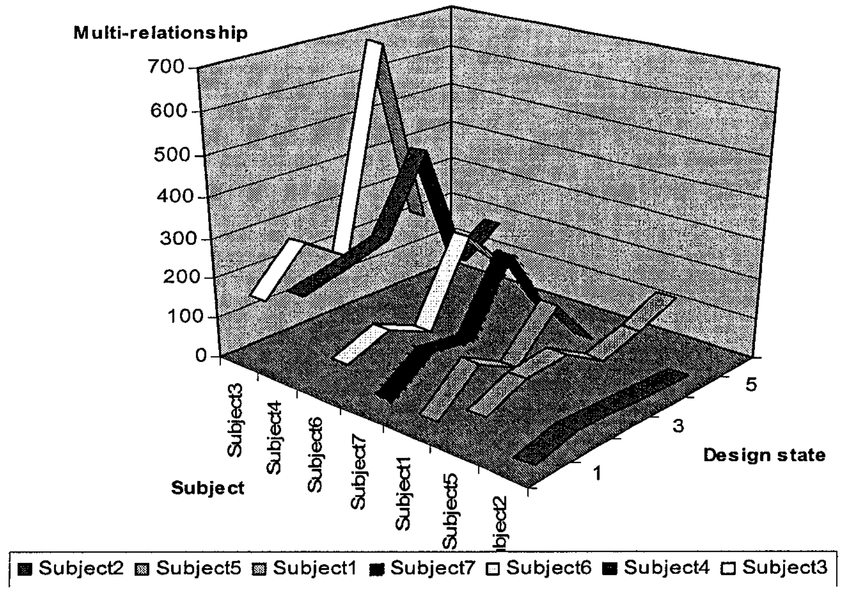


Figure 23 Quantification of designer's mental stress.

5.2.3 Analysis of Individual Subject's Mental Stress

Each individual subject's mental stress can be related to his/her design activities. Based on Table 9 we can plot the trend of the numbers of verbs, nouns, and multi-relationships with respect to design states (time) for each subject. Figure 24 shows such a trend for subject 1. In stage 1(from 26:50 to 30:00), the subject was trying to understand the design problem and the subject's mental stress was relatively low. In stage 2 (from 30:45 to 39:20), the subject had developed a preliminary design idea, which was to place the garbage bin under the passenger seat or under the table. However, the subject realized that it was not good to put the bin aside or inside because one has to install a lot of garbage bins in every block. Therefore, the subject rejected this design idea and was to get ready for the new design, which explains the decreasing of the mental stress in the stage 3(from 39:30 to 45:16). Then the suject started a new design by using a conveyor belt under the window to automatically collect the garbage rather than using a bin. In this stage (from 47:30 to 51:38), the mental stress is higher than those in the other states because of the high density of information that he had to consider. In stage 5 (from 1:05:50 to 1:07:11), the subject finalized the design and finished the design process.

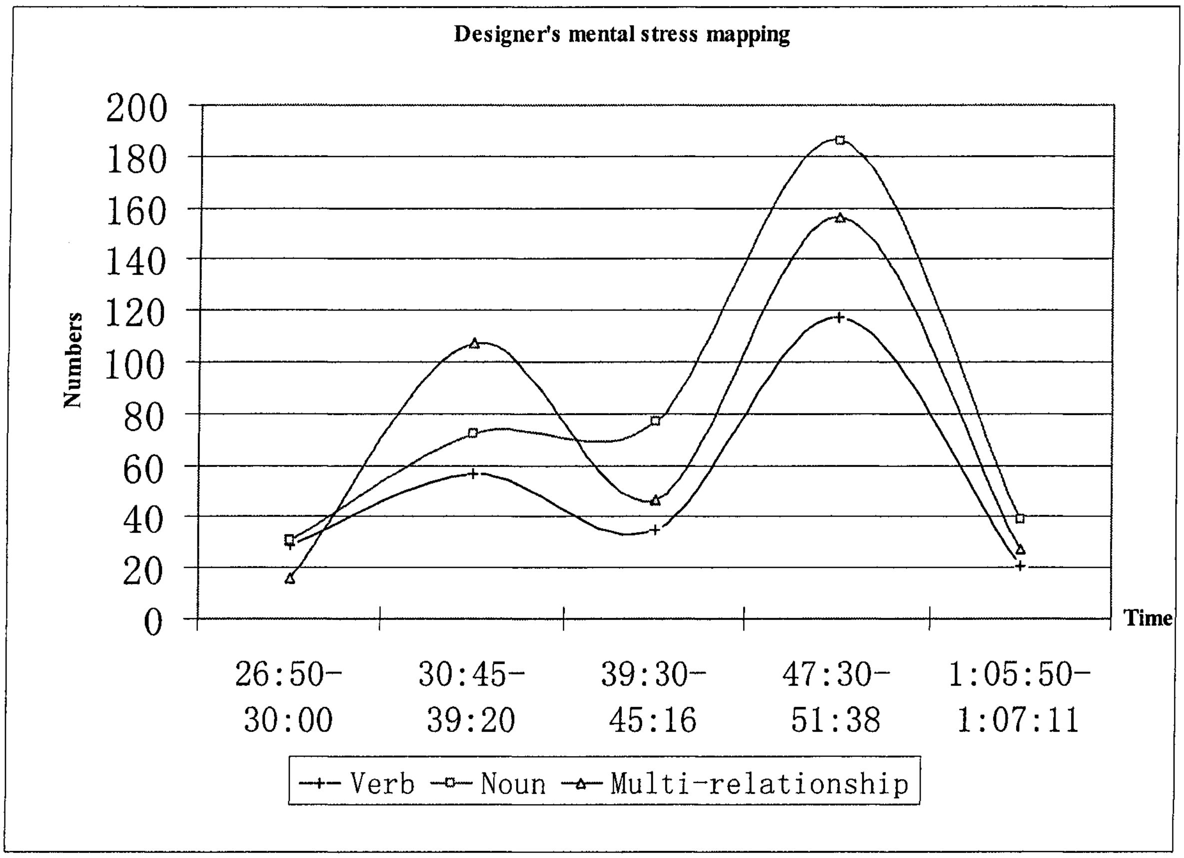


Figure 24 Mental stress mapping of subject 1.

5.2.4 Comparisons of Stresses between Two Subjects

The comparisons of mental stresses between two subjects are shown in Figure 25. There is a significant difference between the maximal mental stress of subject 3 and the minimal mental stress of subject 2 among the seven participants. As for duration, Subject 2 only used only 23 minutes to finish the design; however, subject 3 used almost 1.4 hour. The total index of subject 3 (index=1476) is 14.47 times larger than that of subject 2 (index=107). Similarly, the total number of nouns, verbs of subject 3 in each design state is about 3-6 times of those of subject 2.

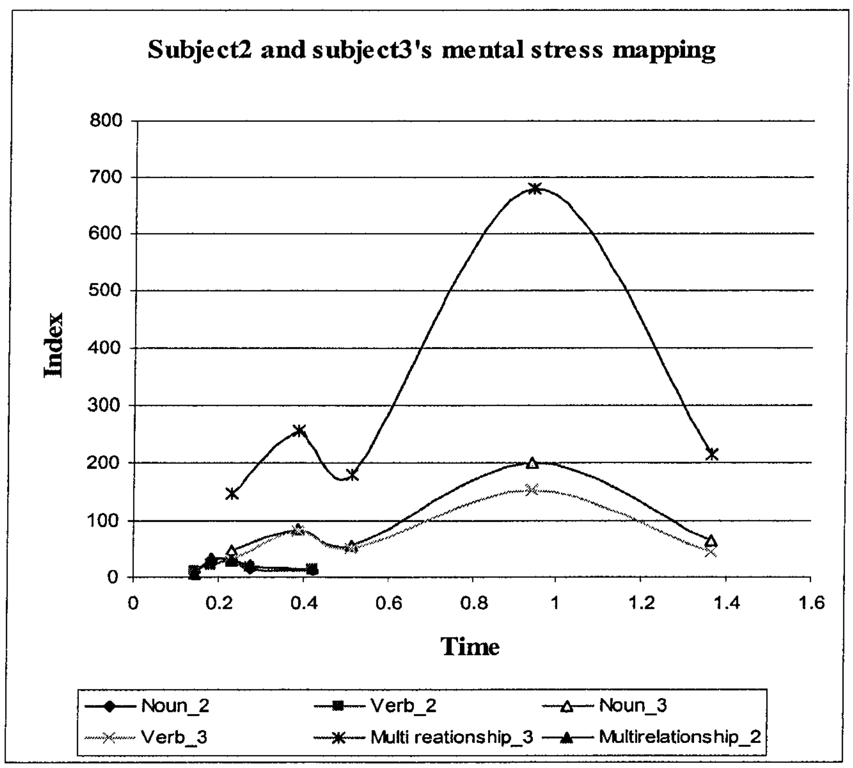


Figure 25 Comparisons of two subjects' mental stress.

5.2.5 Three-Dimensional Models

We present a direct, stereoscopic, easy-to-understand 3D image for tracing mental stress. There are three most typical mental stress trend graphics in Figure 26: Subject 2's mental stress changes smoothly; Subject 1's mental stress shows a medium change; Subject 3's mental stress oscillates the most.

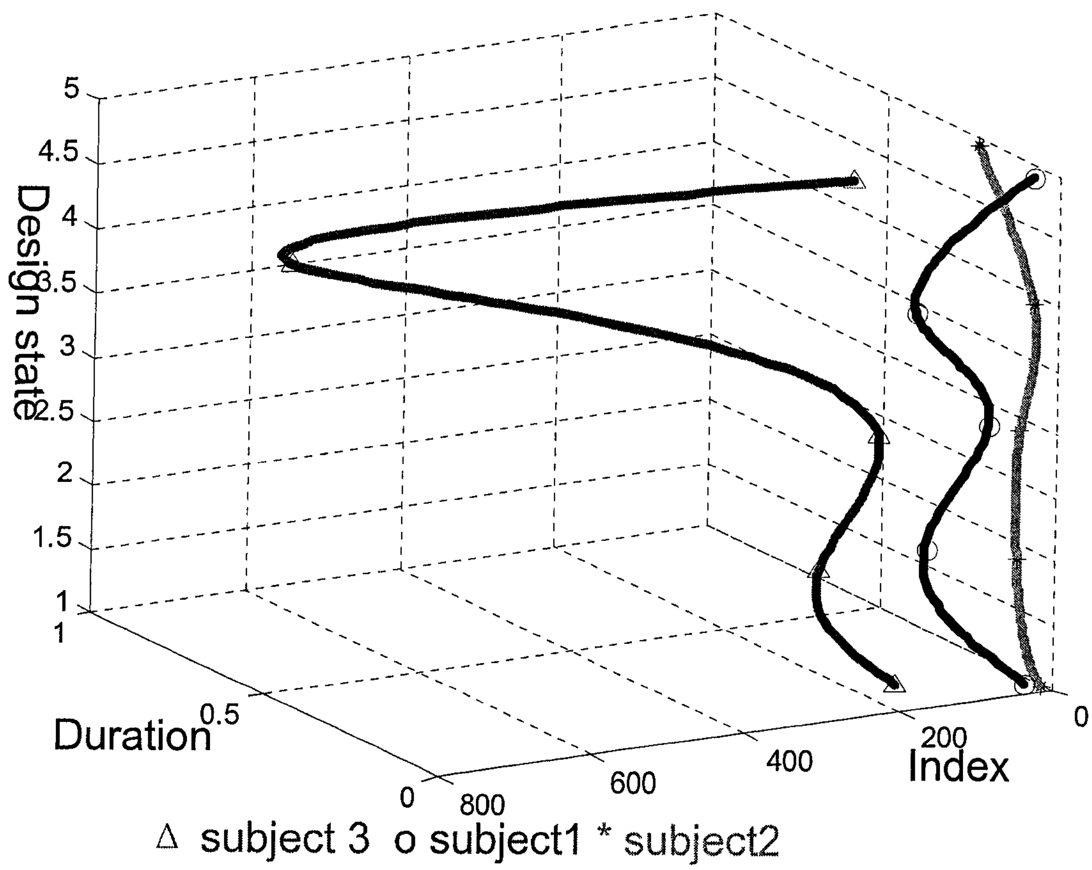


Figure 26 Three-dimensional image.

Figure 27 is a parallel projection, the X-Y plane. The X coordinate means subject's index or multi-relationship. The Y coordinate is explained as the design state's duration. The front view of the X Z-projection is shown in Figure 28. Segmentation of the three-dimensional images projection is plotted in the X-Y projection and the X-Z projection. The designer's mental stress shows a spiral, recursive and evolutionary trend.

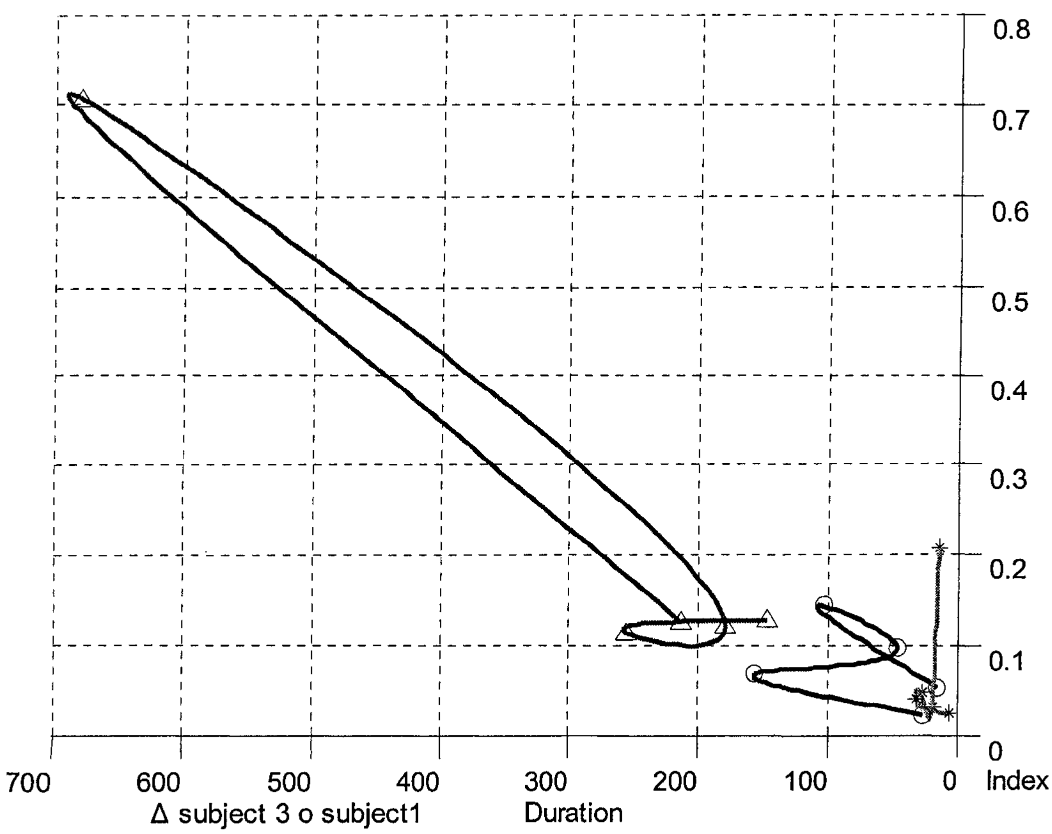


Figure 27 Projection X-Y plane.

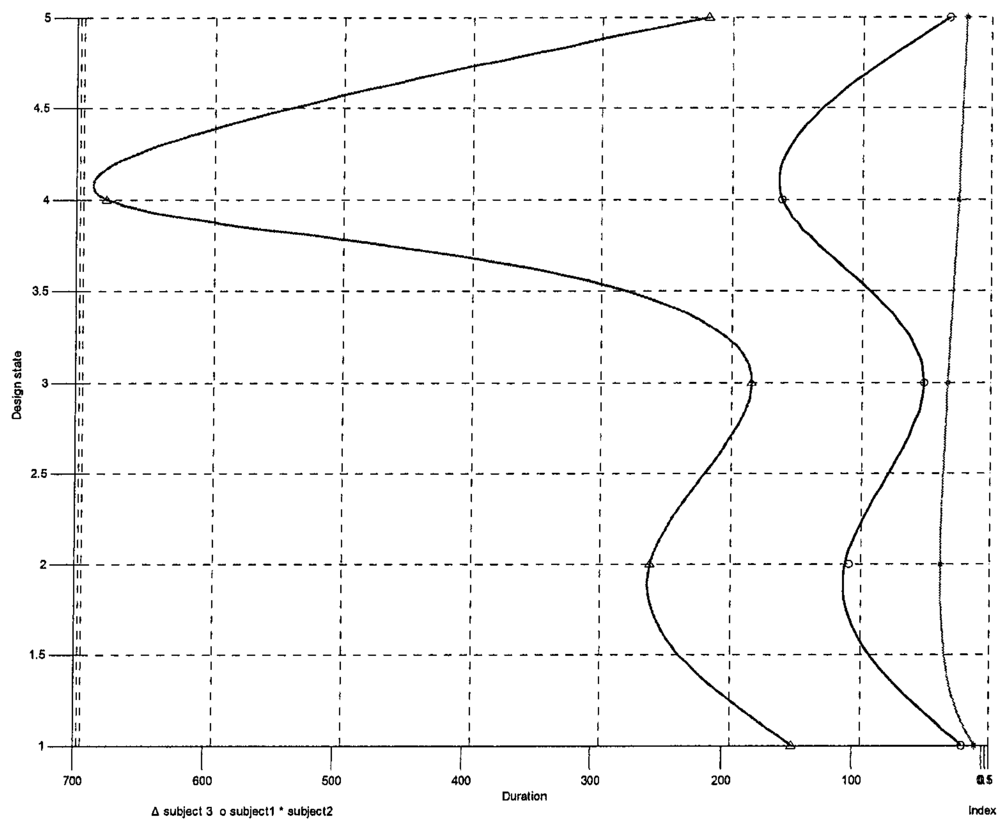


Figure 28 Projection X-Z plane.

5.2.6 Divergent Thinking of Mental Stress

As the number of multi-relationship and the size of vocabulary are usually proportionally related, the more a subject talks, the more vocabulary might be used. In this case only measuring multi-relationship of objects is not enough to quantify the designer's mental stress. The concept of mental stress density is proposed. The parameter ρ_r represents mental stress Rate-Of-Change (ROC) by dividing index by the summation of numbers of nouns and verbs in each design stage. The ROC indicator is a very simple but effective quantifying factor that measures the percent change in mental stress from one design state to the next.

The ROC of the seven participants' mental stress is shown in Figure 29 . To conveniently compare the mental stress using ROC, the means of ROC in each participant have been calculated. The seven subjects' mental stress is sorted from low to high level in the following order: Subject 1 (the mean ROC is 0.496), subject 2 (the mean ROC is 0.524), subject 5(the mean ROC is 0.96), subject 7 (the mean ROC is 1.264), subject 4(the mean ROC is 1.413), subject 6 (the mean ROC is 1.596), and subject 3 (the mean ROC is 1.802). The order of mental stress, which is sorted by the ROC, is different from section 5.2.2. In the future, we will identify which statistics is the best match the fact by associating with EEG, eye gaze and heard rate.

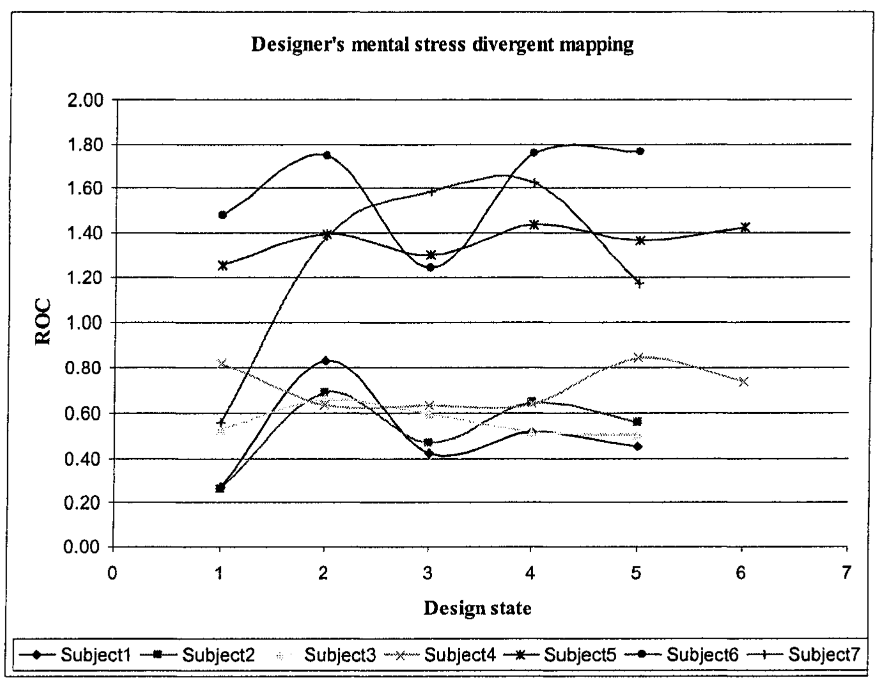


Figure 29 Divergent thinking.

5.3 Discussions

5.3.1 Number of Subjects

There are two issues concerning the determination of the number of subjects in our study. The first issue concerns the category of subjects in terms of knowledge level, experience/expertise level, and cultural difference((Kantowitz;Pollock *et al.*). Usually the experience level (expert versus novice) and the knowledge level may be of interest. The second issue is the number of subjects (also referred to as the sample size). Generally speaking, the sample size is dependent on the design of the experiment (Montgomery, 2001). In a design study, usually the response cannot be represented by a crisp value.

Table 10 gives some examples about how many participants are chosen in the ergonomic domain. Given the fact of complexity in human factors-related experiments, Kotval determined the number of subjects in his study using eye movement parameter by simply surveying about 181 published papers in the area of eye movement study (Kotval, 1998). He found that 13 subjects was the best number, and that number was indeed used for his experiment design. Paquet used five male college students to simulate 3 of 6 construction job tasks (Paquet et al., 2001). Ryan presents concurrent and retrospective verbal protocol methods, which were used to collect thoughts from 18 participants during a manual handling task involving the repeated transfer of loads between locations at two tables (Ryan and Haslegrave, 2007). To explore the interplay between designers' representations and their design activities in the investigate of engineering students' use of external representations, Cadella selected four students (two seniors and two freshmen) from the original dataset (Cardella et al., 2006). This method was used due to the difficulty in determining the sample size for a human factors study using standard principles in statistics (Montgomery, 2001).

Table 10 Number of participants in literature

Authors	Number of participants	Year
Kotval	13	1998
Paquet et al., 2001	5	2001
Ryan and Haslegrave	18	2007
Cadella	4	2006

5.3.2 Linguistic Noises in the Quantification of Mental Stresses

Language is a system of conventional spoken or written symbols used by people in a shared culture to communicate with each other. A language reflects and affects the way of thinking. Related languages become more differentiated when their speakers explain the same fact (see Britannica Concise Encyclopedia). That may lead to serious problems, even the subjects suffer a same mental stress, but the results from the ROM quantification of mental stress may still be different, since ROM depends on the number of relationships of the words to measure mental stress. However, it is reasonable to assume that each individual has the same language habit. In the present research, we focus on the trend of change of multi-relationships. Therefore, linguistic noises, which come from the individual habits of using a language, can be eliminated.

To test the assumption above, we treated the synonymies as the same word. Table 11 and Figure 30 show the comparisons of statistical results of subject 5: one method is by using the index of original analysis and the other method is by using synonymy analysis. The correlation coefficient between these two methods is 0.8994, which means the language noise can be removed by ROM in this case.

Table 11 Comparison of language habits

Design state	Index of original analysis	Index of synonymy analysis	Correlation coefficient
1	72	85	0.8994
2	113	105	
3	123	140	
4	59	74	
5	86	92	
6	126	168	

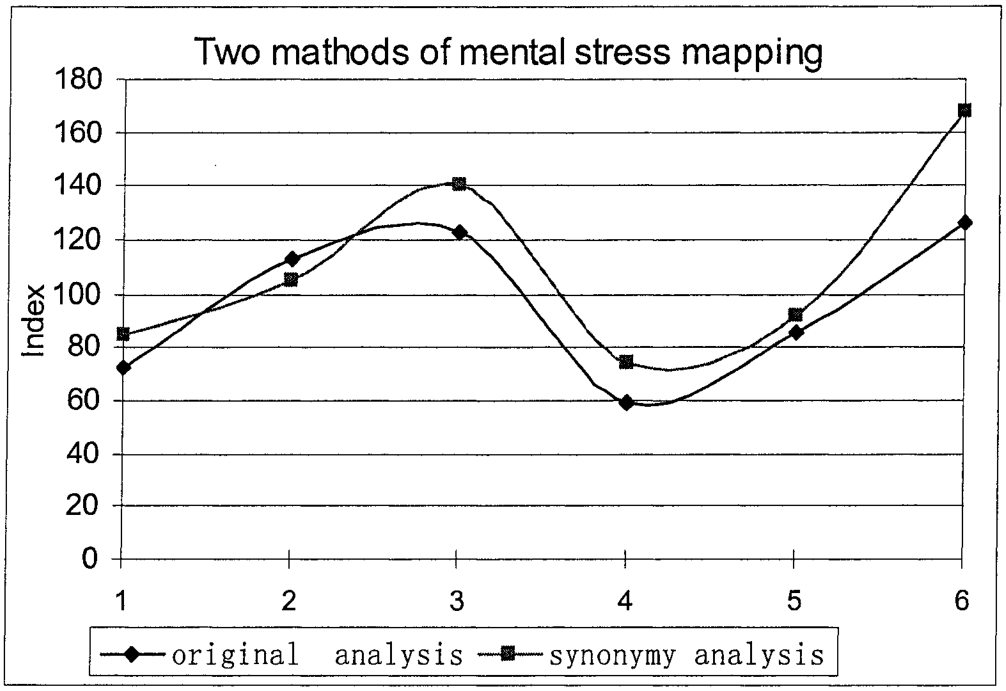


Figure 30 Influence of linguistic noises.

5.4 Summary

This chapter analyzes the designer's mental stress based on the axiomatic theory of design modelling and ROM. Mental stress is a physical reaction of the brain to the workload imposed by the environment. Different environments impact brain in different ways whereas different brains react differently to the same environment. To quantify the designer's mental stress, we explored the relationship between the mental stress and the designer's language expression, which can be represented by using ROM object relationships.

Detailed statistic analysis of the design processes from 7 participants is made to calculate the number of objects and the relationships between these objects. Individual subject's performance is evaluated by calculating the numbers of verbs, nouns, and relationships. Comparison is made between two subjects. Based on the analysis, we may conclude that the bigger the quantity of relationships the higher the mental stress. An index named ROC is proposed to calculate the density of mental stress.

Chapter 6
Conclusions and Future Work

6.1 Overview

The objective of this thesis is to quantify the designer's mental stress during the conceptual design process. Quantifying the designer's mental stress would assist the effort of understanding the designer's creative and innovative process. In this thesis, Recursive Object Model (ROM) is used as a formal tool to represent the designer's mental state in each step of the conceptual design process. During the conceptual design process, designers usually describe the design states using natural language, combined with sketches. The description based on natural language is transformed into ROM diagram through linguistic analysis. A cognitive experiment, which is to design a new litter-disposal system in a passenger compartment located in the trains of NS (Dutch Railways), is conducted to study the designer's thinking process. The ROM is used to analyze and quantify the designer's mental stress based on the protocol data collected in the experiment.

6.2 Conclusions

The present thesis presents a formal definition of mental stress using the axiomatic theory of design modelling. The mental stress is defined as the intensity of information exerted on human brain by environment. A new scheme based on the recursive object model (ROM) is proposed to encode protocol data collected from cognitive experiments. Designer's mental stress is quantified based on the ROM diagrams corresponding to the protocol data from different design stages. Our analysis shows that the designer's mental stress changes according to the difficulty levels of the design task. It also has impacts on the designer's performance. This research shows that ROM is an efficient and effective tool for processing protocol data in cognitive experiments.

6.3 Future Work

Our future work will focus on using Neuro-physiological measures in our on-going experiment, such as Electroencephalo Graph (EEG), eye gaze, heart rate, etc. The results from these measurements will be compared with the results obtained using the present method.

As for the analysis of the result, semantic analysis may be needed to be a supplement to the present methodology of quantifying mental stress.

Publications

Zeng,Y., **Zhu, S.**, and Yao, S. (2007), Quantification of designer's mental stress in the conceptual design process, *Applied Ergonomics* (under review).

Zhu, S., Yao, S. and Zeng, Y.,(2007) A novel approach to quantifying designer's mental stress in the conceptual design process, IDETC/CIE 2007, Las Vegas, Nevada, USA.

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