Evaluation of mental stress during cognitive activities through HRV data and kinesics study

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ABSTRACT

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Yao Tang

Many studies have been conducted to test and improve existing design methods, which can be used for engineering production and development. In order to improve the usability of design methods, the present thesis proposes a new approach to quantify the human mental stresses during the design activities. Two sets of experiments are implemented for this study. Kinesics analysis is used to quantify the designer's mental stresses during the design activities. Meanwhile, heart rate variability (HRV) analysis has been performed to verify the results from kinesics study.

The present thesis initiates the research that employs the kinesics study in the quantification of the mental stresses.

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LIST OF ACRONYMS

CWT	Color-word test
ECG	Electrocardiogram
EEG	Electroencephalograph
FFT	Fourier transform
HF	High frequency
HR	Heart rate
HRV	Heart rate variability
LF	Low frequency
NN interval	Normal-to-normal interval
PSD	Power spectral density
RR interval	R peak to R peak interval
TLX	NASA Task Load Index
ULF	Ultra low frequency
VLF	Very low frequency

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The present thesis aims to propose a new approach for quantifying human mental stresses during the cognitive activities through his/her body language, i.e., kinesics. Heart rate variability (HRV) is employed to support the present method.

In the past five decades, study of design science has attracted enormous attention thanks to the modern engineering development. Design science was accepted by engineers as the rules during the engineering lab work. Many studies have been performed in the interest of determining the design rules and many efforts have been concentrated on the utilization of design science on engineering production and development. With the view of study in human factors in design science, the present thesis proposes a new approach to quantify the human mental stresses during the cognitive activities. Considering the complexity of the design process, independent cognitive experiments are employed in the experiment. For the first experiment, participants have been asked to design a litter-disposal system for passenger compartments in a train carriage. Kinesics analysis has been exploited to quantify the participants' mental stresses. In the next experiment, Stroop color word test (CWT) has been employed in the experiments. Kinesics analysis has also been exploited to quantify the participants' mental stresses. Meanwhile, HRV analysis has been performed to understand the mental state of the participant, in addition to prove the conclusion of kinesics study.

1.2 BACKGROUND AND APPLICATION

The study of mind can go back to the Ancient Greeks [1, 2]. Philosophers such as Plato and Aristotle tried to explain the mind and its operation from different perspectives. Plato said: "the mind relates to the realm of abstract ideals". Aristotle said: "the mind is what the brain or body does". Mental stresses are considered to be an elevation in a person's state of arousal or readiness of the mind. This mental response, which is caused by some stimulus or demand, determines human behavior. Yerkes and Dodson [3] developed the Yerkes-Dodson (Y-D) law in 1908, which shows that there is a U-shape correlation between arousal and performance. According to the Y-D law, the medium level stress addresses to better performances. Sweller is known for formulating an influential theory of cognitive load [4]. Peter Nixon, a British cardiologist, presented his research result in 1979 (Figure 1) [5].

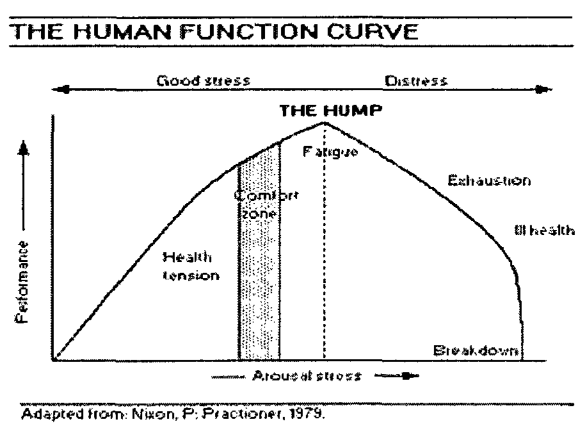


Figure 1. The human function curve [5]

We can observe from the figure, initially, the increased mental stresses produce increased performance. The "optimal" stress involves functional amounts of arousal contributing to effective task performance. Once the stress over a point (the hump), more stress produces decreased performance. Cognitive load theory (CLT) can provide guidelines to assist in the presentation of information in a manner that encourages learner activities that optimize intellectual performance. It is based on a cognitive architecture that consists of a limited working memory and an unlimited long-term memory. According to the theory, limitations of working memory can be circumvented by coding multiple elements of information as one element in cognitive schemata, by automating rules, and by using more than one presentation modality.

In the domain of design, some researchers have attempted to discover designer's cognitive model during the design process. Kirschner [6] focuses on the increase of germane cognitive load, which aims at further improving instructions by making designers take advantage of otherwise unused working memory capacity during learning process. Dong [7] 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. Stempfle and Badke-Schaub [8] study on three laboratory teams solving a complex design problem to investigate the cognitive processes of design teams during the design process. Fuchs-Frohnhofen, et al. [9] use a methodology incorporating the taxonomy of mental models to analyze the user's mental models in work setting and generate variants of human-machine interfaces to match them.

There are several ways to measure mental stresses. On the one hand, one can tell how stressful s/he feels under certain situation. NASA Task Load Index (TLX) is such a tool for assessing the subjective rating score of mental workload [10]. The NASA Task Load Index is a method for providing an overall workload score based on a weighted average of ratings on six subscales, namely, mental demands, physical demands, temporal demands, own performance, effort, and frustration [10]. This method gives a scale of the workload that is proportional to mental stresses.

So far, there is no standard method for quantitatively evaluating mental stresses. Researchers are still seeking the relationships between mental stresses and other parameters.

1.3 PROBLEMS

The major issue of this study is to abstract the information to quantify mental stresses based on the human behavior. We assume that human behavior is the actual output of the human mental world. These behaviors can be presented in the physiological parameters which are controlled by the body autonomic nervous system. The nonspontaneous behavior, such as body movements and linguistic communication, are generated after thinking process. Meanwhile, the spontaneous behavior such as, blink and yawn, happens without any planning. Thus, we believe that the mental stresses are represented by the nonspontaneous behavior. Following this lead, we have found that, the participants trend to have less movements when they have a higher mental work load. With the development of the research, spontaneous behavior has been realized to be equally important. Therefore, the mental stresses are believed to be described by both spontaneous and nonspontaneous behaviors.

In order to find the transformation function of mental stresses and human behavior, experiments have been performed. Considering the complexity of the design process, independent cognitive experiments are employed in the experiments. Kinesics analysis has been exploited to quantify the participants' mental stresses. Nevertheless, the result can only be verified according to the restating of the participants. Scientific test and verification to the kinesics analysis are necessary. For that reason, HRV analysis has been performed to understand the mental state of the participant, in addition to prove the conclusion of kinesics study.

1.4 THESIS OUTLINE

The historical review including the existing research results in mental stresses, human body language, and the heart rate variability is given in Chapter 2.

Research approaches are explained respectively in Chapter 3 and Chapter 4. The final chapter describes the research result and gives the conclusion of the present research.

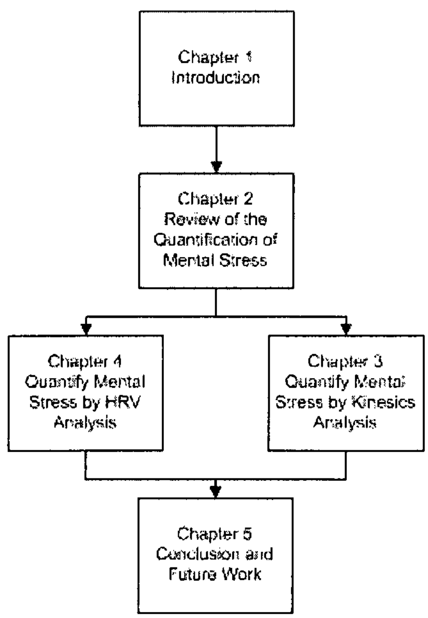


Figure 2. Thesis organization

CHAPTER 2

LITERATURE REVIEW

2.1 MENTAL STRESS

Over the last few decades, various design methodologies have been proposed to assist designers in generating quality designs in an effective manner [11-16]. There is no doubt that the existing methodologies have been greatly influencing the industrial product design process. However, a big challenge is still faced in applying those design methodologies, which lies in two contrasting facts. On the one hand, design is a creative act, which is rooted in the flexibility and freedom for exploring various avenues to achieve design goals [17-19]. On the other hand, any design methodology implies a set of well structured logical steps for solving a design problem. This contradiction between flexibility and structure, also can be considered as the contradiction between freedom and logic 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 [15].

To develop an effective, structured and logical design methodology that can accommodate flexibility and freedom, it is important to quantify the designer's cognitive processes, particularly the designer's mental stresses. According to the Yerkes-Dodson law [20], there is an inverted U-shaped curve correlation between performance and mental stresses. An optimal level of arousal addresses the best performance for a given task whereas performance will decrease when levels of arousal become either too low or too high. Their research indicated that under the pressure of tight schedule, complex tasks, and/or other intensive tasks, people can be stressed out; as a result, their performance may degrade or even fail. Modest levels of supra-optimal stresses can be counteracted by the performer through increased effort, resource mobilization, or straining [21-24]. A design methodology, as a means to manage design tasks, can increase or decrease the designer's mental stresses. Thus a design 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 [15].

Therefore, a good design methodology must be able to enhance the designer's performance by keeping the designer's mental stresses within an optimal range. For this purpose, it is essential to model the relationship between designer's mental stresses and performance. As the first step of this modeling, the designer's mental stresses and performance must be quantified. However, the quantification of designer's performance is not the focus of this present thesis and will be discussed elsewhere. The objective of the present thesis is to quantify designer's mental stresses during the conceptual design process.

To the authors' best knowledge, no results have been reported in the literature regarding the quantification of designer's mental stresses. Most of the reported work is focused on understanding general cognitive processes in design, particularly on the roles of sketches in the conceptual design process [25]. Through fluid gestures and smooth hand-eye coordination during the sketching process, designers not only attempt to capture their flow of thoughts but also use their sketches to generate new ideas and images in their minds [26]. This visual thinking provides mental relaxation and helps in generating fresh new ideas. It reduces the cognitive load on engineers during conceptual design and encourages the free flow of creativity. 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 [27]. 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 [7]. 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 [8]. 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 [8].

Despite the progress in developing designer's cognitive models, the existing studies on design cognition suffer from a few problems. First, the investigation of mental stresses is a result of an interdisciplinary study of the brain, but different disciplines (such as philosophy, psychology, artificial intelligence, neuroscience, and linguistics) define the mental stresses in different ways. Analysis of mental stresses has become increasingly important for investigating designer's cognitive procedures. However, a concept of mental stresses accorded with the domain of design has not yet been created. Secondly, 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. Finally, 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.

There are two main models of mental stresses in the literature: 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 [28]. 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 (such as heart rate, blood pressure, and body temperature) that result from exposure to a given stressor [29]. In this case, mental stresses can be associated with an interaction between an individual and his or her working environment.

2.2 BODY LANGUAGE (KINESICS STUDY)

Hart and Staveland defined mental stresses as "the perceived relationship between the amount of mental processing capability or resources and the amount required by the task" [10]. The study of designer's mental stresses can help enhance the designer's effectiveness in the innovative design process [30]. Studies have shown that people actually perform better under appropriate pressure. Little pressure does not give people enough incentives to fully pour their capacity into the task whereas too much pressure will eventually disrupt performance [31]. An understanding of factors that affect designer's mental stresses will help the development of tools supporting design activities. The first step for this understanding is the quantification of mental stresses.

The research about understanding the meaning of nonverbal communications is established in the middle of last century [32] although Darwin started his work around 150 years ago [33]. Serious study requires an interdisciplinary approach and an ability to decode the expressive and communicative aspects of body movements. Therefore, after decades of research, nonverbal communication is widely considered to be composed by the following eight categories: kinesics, occulesics, artifacts, physical appearance, haptics, proxemics, and the chronemics [6, 34]. During the design process, kinesics, namely body movement, represents abundant information of designers' mental activities. Accordingly, we choose to study the design behavior through the kinesics, in addition to our ongoing efforts in protocol analysis and physiological data analysis.

Some researchers insist that body languages describe the involuntary movements of responses while some others consider gestures, facial expressions, and poses are intentionally made by a person [35]. In the present research, we will use kinesics to study design behaviors. Kinesics, as the main subcategory of paralanguage, was defined to describe all physical forms of human communication that are not verbal language, such as the body movements, gestures, postures, gait, facial expressions, eye behaviors, and some small movements that people are not aware of. Each body movement conveys a meaning that depends upon the physical, social and cultural context [36].

Language is a dynamic set of visual, auditory, or tactile symbols of communication, and the elements used to manipulate them. Whereas the paralanguage refers to the non-verbal elements of communication used to modify meaning and convey emotion. Some researches insist the body language describes the involuntary movements of response, however, some others consider that gestures, facial expressions, and poses are intentionally made by a person [35]. Whereas in this chapter, body language, as the main subcategory of paralanguage, was defined to indicate all physical forms of human communication that are not verbal language, such as the body movements, gestures, poses, facial expressions, eye behaviors, and some small movements that people are not aware of. Thus every part of the human body, either in motion or stillness, conveys a meaning which depends upon the physical, social, and cultural context of the action [37].

Kinesics, similar to a verbal language, has many components such as movements and their sequences. Those components correspond to the vocabulary and grammar that build up sentences and paragraphs. In body language study, people express their invisible mind by arranging the movement components. In order to find the "vocabulary" and the "grammar" in a series of body expressions, this study abstract the important factors of the continuous body movements. Meanwhile, a metric system has been used to quantify human mental stresses. Therefore, by using the relation between the movements components and the scaled matrix, we are able to get the relation between the body movements and the designer's mental stresses.

2.3 Heart Rate Variability (HRV)

2.3.1 Introduction

Heart rate variability describes the variation between consecutive heartbeats. The rhythm of the heart is controlled by the sinoatrial node, which is modulated by both the sympathetic and parasympathetic branches of the autonomic nervous system. Sympathetic activity tends to increase heart rate and its response is slow for few seconds [38]. On the other hand, the parasympathetic branch tends to decrease the heart rate and responses faster for 0.2-0.6 seconds [38].

HRV analyzes the modulation of the continuous sympathetic and parasympathetic innervations, which is, the variability of heat rate in our research. Respiratory sinus arrhythmia is the most perceptible periodic component of HRV, which is believed to range from 0.15 to 0.4 Hz in frequency domain [38]. This so called high frequency band (HF), which is physiologically influenced by the breathing, is generally on the behalf of parasympathetic. The other widely studied component of HRV is the low frequency (LF), which is believed to range from 0.04 to 0.15 Hz in frequency analysis [38]. LF band is being thought to on the behalf of both sympathetic and parasympathetic, while some of the researches indicate them to be mainly of sympathetic origin The fluctuation below 0.04 Hz has not been studied as much as the higher frequencies. These frequencies, which have been divided into the very low frequency (VLF, 0.003-0.04 Hz) and ultra low frequency (ULF, 0-0.003 Hz), have been considered to be the characteristic for HRV and have been related to the humoral factors such as the thermoregulatory processes and renin-angiotensin system [38]. Whereas during many research the ULF have been omitted according to the short-term heart rate recording.

2.3.2 History

The physicians realize the potential importance of cardiac rhythms long before the invention of electrocardiograph and the recent emergence of modern constructs of heart rate variability. Before this century, techniques for the patterns of heart rate study were limited, but physicians have already monitored heart sounds and heart rhythms by auscultation and noticed that the beat to beat rhythm shifts according to the aging, illness, and psychological states in the past several hundred years [39]. Chinese medical worker have studied these rhythms for hundreds of years as the major component of Chinese medical diagnostic systems [39]. However, science needs the accurate and reliable quantification of the research result. Therefore, the technology has progressed from the galvanometer, to the kymograph, to the ink-writing polygraph, and finally to digital signal processing system [38].

The early work of Luigi Galvani and Alessandro Volta and the electromagnetic principles deduced by Andre-Marie Ampere and Has Christian Oersted led to the development of the galvanometer in early 19 century [38]. This device allowed the very small electrical currents changes, including bio-potentials generated by heart, to be monitored by machine, by evaluating on magnetic induction to rotate a pointer or a mirror. The smoked kymograph, invented by Ludwing (1847), was able to record the mechanical activities, such as the pressure pulses and the movement of a galvanometer needle, on a smoked drum. MacKenzie (1894) invented an ink-writing polygraph, while Einthoven (1988) integrated the galvanometer with photography to produce accurate and continuous tracings of the electrical activity of heart [38]. With the development of these technologies, monitor the normal and abnormal electrical conduction activity become possible, hence, the beat to beat changes can be recorded for heart rate research.

It is hard to argue the origins of scientific study of heart rate variability predate the development of electrocardiograph. Hales (1733) has observed a respiratory pattern in the blood pressure and pulse of a horse, which is seen as the first documented observation of heart rate variability. Thanks to the kymograph, Ludwig (1847) was able to observe a increase of the rate of inspiration and a decrease of the exhalation rate of a dog. In 1868, Donders focused his work on the relation between respiration, heart rate, and the vagus nerve. The theory that brainstem nucleus controls heart rate which articulated by Traube

(1865), indicated the controlment could be influenced phasically by direct "irradiations" from the medullary respiration centers [38]. As many of these studies directed the connection among respiration sinus rhythm and heart rate, research on heart rate variability moved initially in two directions. First, many researchers work on the understanding of physiological mechanisms related to heart rate rhythm. Second, studies have been performed on medical research of the relation between heart rate variability and clinic status. Later in 1960s, with the availability of polygraphs in academic laboratories, the third trend emerged as psycho-physiologists to investigate the relation between psychological process and heart rate variability [40].

After decades of development, the heart rate variability began to attract attention and to be treated as an interesting and potentially important phenomenon without attributing it to any specific physiological mechanism. Three general perspectives were credited to the previous studies: (a) an individual difference model that manage heart rate variability as a markable variable that inclines toward foreseeable model of behavioral and autonomic response [40-43]; (b) the measurement of heart rate variability as an index of attention, mental effort, or mental load [44-48]; (c) the stimulus control of heart rate variability by operant conditioning or biofeedback techniques [49, 50].

The research questions and the specific problems within these disciplines were often distinguishable. At present, a common reorganization agrees that, the explications and quantification of heart rate variability depend not only on a sufficient comprehension of the physiological mechanism but also on the interaction between these mechanism and behavioral process.

CHAPTER 3

KINESICS ANALYSIS

3.1 INTRODUCTION

This chapter proposes an approach to evaluate the designer's mental stresses during the conceptual design process. The proposed approach, combined with designer's sketches, is based on the kinesics study, which looks into body movements. In this study, participants were assigned a design task in which they need to look for conceptual solutions. Each individual participant's design activities were recorded and analyzed for quantifying the designer's mental stresses during the design process. During the experiment, participants were required to design a litter-disposal system for the passenger compartment. The system should be convenient for the passengers to deposit garbage and meanwhile it is easy for the cleaners to collect the garbage. Three digital cameras and a free sketching tablet were used to record the design activities and participants' body expression. In the interest of finding the general statute of design process, participants were unconstrained in both design method and body movement. The kinesics data is collected through the video recording the designer's behavior in the design process. The sketches are generated on a tablet and recorded by a screen recording system. It is observed from the experiment that designer's mental stresses are closely related to the frequency of the body movements. With a view to evaluate participants' mental stresses, namely, to distinguish the stressful meaning from body language, several cognitive experiments were performed in this study. Experiment method and data analysis will be introduced in the following sections.

The rest of this chapter will be organized as follows: Section 2 introduces the method that we used to collect and analyze designer's cognitive data. Section 3 shows our observations from the experimental data. Section 4 discusses some relevant issues and indicates the future research directions.

3.2 METHOD

Language is a dynamic set of visual, auditory, or tactile symbols of communication, and the elements used to manipulate them. Whereas the paralanguage refers to the non-verbal elements of communication used to modify meaning and convey emotion. Some research insist the body language describe the involuntary movements of response, however some others consider gestures, facial expressions, and poses are intentionally made by a person [35]. Whereas in the present thesis, body language, as the main subcategory of paralanguage, was defined to indicate all physical forms of human communication that are not verbal language, such as the body movements, gestures, poses, facial expressions, eye behaviors, and some small movements that people are not aware of. Thus every part of the human body, either in motion or stillness, conveys a meaning which depends upon the physical, social, and cultural context of the action [37].

Kinesics, similar to a verbal language, has many components such as movements and their sequences. Those components correspond to the vocabulary and grammar that build up sentences and paragraphs. In body language study, people express their invisible mind by arranging the movement components. In order to find the "vocabulary" and the "grammar" in a series of body expressions, this study abstract the important factors of the continuous body movements. Meanwhile, a metric system has been used to quantify human mental stresses. Therefore, by using the relation between the "language components" and the scaled mental stresses, we are able to get the relation between the body movements and the designer's internal mental stresses. Figure 3 shows the relation between the four major components in our study. Body movements, which were used to deduce the mental stresses, were collected by the cognitive design process. A kinesic method was used to investigate the design behaviors, and a metric system was established for studying the mental stresses. Hence, we can get the mental stresses level from the kinesic information.

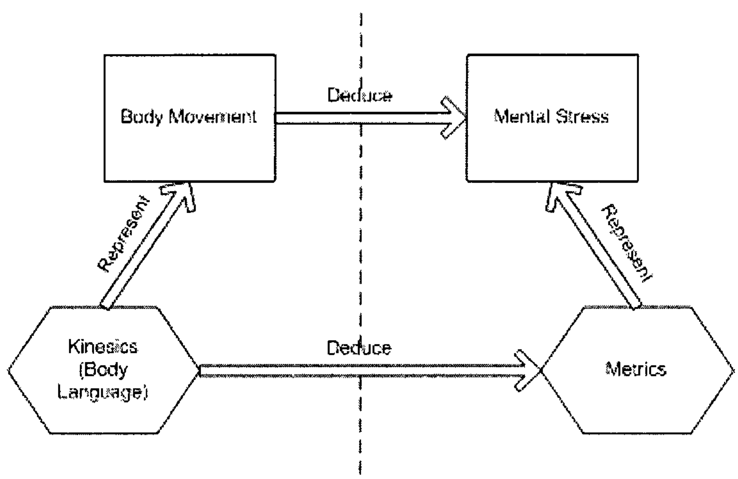


Figure 3. Structure of the mental stress evaluation system

3.2.1 SELECTION OF PARTICIPANTS

In the experiment of body language analysis during cognitive activities, educational background, engineering design experience and language ability were considered during the selection of the participants. Basic knowledge in engineering design and the capability to perform a design task are required for participants. 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 yrs) volunteered as the participants in this study. They are from mechanical engineering, electrical engineering and computer engineering, respectively. Procedures of the experiment were explained by Design Lab, and all the participants have signed a consent form prior to taking part in the study.

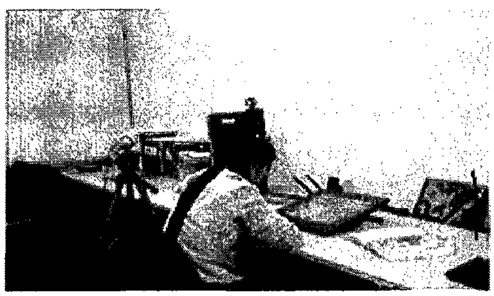


Figure 4. Experiment set-up.1

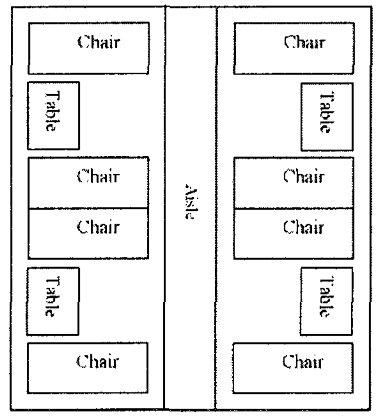


Figure 5. Design problem

3.2.2 MATERIALS

To fulfill the research of body language analysis during cognitive activities, the design problem used by Dorst and Cross [17] was adapted to our research. In response to anticipated participants with diverse backgrounds, the problem is simple to be understood and meanwhile being challenging enough. Participants were presented a pre-prepared description of the design problem as follows:

Design a litter-disposal system for passenger compartments in a train, which is shown in Figure 5. This system should be convenient for the passengers to deposit their garbage and for the cleaners to collect the garbage.

Figure 4 shows the experiment set-up.

3.2.3 COGNITIVE ACTIVITIES DESIGN AND PROCEDURE

Experiment design

We assume that the mental stresses can be indicated by the body movements. By observing the children behavior, we notices that the period when children are hard to focus on one topic generally accompanied by amount of major physical motions, whereas the concentration of one subject significantly reduces their body movements. The curiosity caused by this observation initiates our study on body movements of adult designers.

The objective of this study is to quantify the designer's mental stresses during the design process. Comparisons in different states of design and the comparisons between participants will be performed. In order to reduce the effects of differential external factors, the environmental setups are required to be equal. Meanwhile, the human factors of designers should be monitored. Human factors such as age, gender, health condition, mental state, educational background, and work experiences should be considered.

One requirement of the present research is that the information determining the designer's mental stresses must be recorded truthfully. Various approaches are required to record the information. Another requirement is that the experiment should not interfere with the designer's mental process, thereby the designer's mental stresses are not influenced by the experimental approach.

Within the production of the mental stresses result, disadvantages of the assumption about body language are revealed. The research results could not be verified either by the surveys of participants nor the judgments of researcher. In order to replenish the drawbacks, a wildly accepted method of evaluation of mental stresses and new experiments (CWT) are introduced. By studying the body movements in established stress sections and the rest sections in CWT, the proposed method is proved to be valid.

Alterations of the experiment details are made according to the matters that emerged during the experiments and the data analysis process.

Experiment procedure

To quantify precisely the designer's mental stresses during the design process, activities determining the designer's mental stresses must be recorded faithfully. Thus, various recording approaches are needed. Meanwhile, the experiment procedures must not interfere with the designer's mental process so that the designer's mental stresses are not influenced by the adopted experimental approach.

In our experiment, the researcher presents the pre-prepared problem description to the participant and answers any questions from the participant regarding the procedure of the experiment. The participant will then work alone on the design task in a quiet room. S/he can use references or the internet to find the required information to solve the design problem. The participant is asked to sketch or write anything in a free sketching system installed in a WACOM Tablet; hence, the participant could design as if s/he were designing by using a pencil and a piece of paper. This natural interface does not add any extra mental workload to the designer [30]. A screen recording system by the software MyScreenRecorder was used to record everything that the participant did during the design process, which can be used to analyze the evolving design process. Three webcams have been employed to record the entire process including audio and video information from different angles. Figure 6 shows some sketches generated during the design process.

Figure 6. Design sketches: examples.

3.2.4 SEGMENTATION AND ANALYSIS METHOD

According to the observation of the design process, participants received the design problem and then begin their design process with problem decomposition. Participants divided the problem into parts based on different principles. Some people extract the information by levels, like peeling the onions. They started from the surface information down to the hidden messages whereas the others prefer to proceed by following some methodology, such as the seventh participant. Due to the analysis behaviors that exhibited at the beginning of design process, we define the beginning state of design process as the analysis state (State 1 in Figure 7). Generally, analysis state was represented by reading the original question and generating some ideas in mind. Sketching and writing on the tablet, on the other hand, represent the beginning of a new state, which is state 2 in Figure 7. During the first half of state 2, solution of question 1 was generated and been sketched out, and new question (Problem 2) appeared, which leads the designer to analyze the question 2 (State 2 in Figure 7). At the following state (State 3 in Figure 7), designer produces the response followed by the generation of another question (Problem 3). Consequently, designing proceeds in an evolution structure, as is shown in Figure 7.

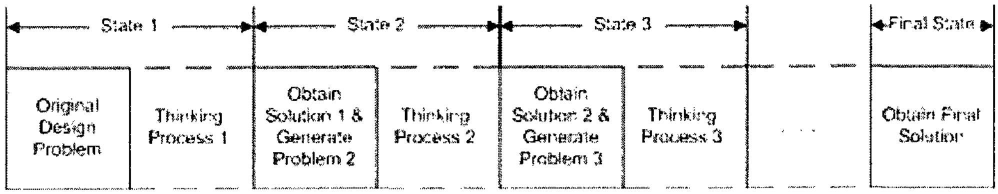


Figure 7. Evolution of the design process

Table 1 illustrates parts of the design states, along with the body movements and sketching activities of the sixth participant. These states were abstracted from the beginning, midway, and the ending of the design process. Segmentation was performed based on the evolution structure of design process shown in Figure 7.

Table 1. Segmentation of design process (Record of body movements & sketching activities)

(By default, the participant is looking at the screen without body movements.)

	Time	Body Movements	Time	Sketch Behavior
State 3			00:07:41-09:03	Read the problem from the screen;
			00:09:03-04	Line on the screen; Selected one sentence on the screen;
	00:09:05-08	Right hand fingers under his nose and look at the screen;		
			00:09:09-10	Cancel the selection;
			00:09:11-00:10:14	Roll the pages down to read the problem from the screen;
			00:10:15-00:10:50	Roll the pages back and forward;
			00:10:50-00:10:54	Roll the pages back;
	00:10:55-11:26	Ask questions; The experimenter explain it to him;		
State 35	01:32:15-21	Right hand fist beside his lips;	01:32:15-21	Look at his product;
	01:32:21-33:12	Move the chair to the dictionary, and check for something;		
	01:33:12-14	Move back to the screen;		
	01:33:14-34:42	Write on the screen;		
			01:34:43-45	Roll down the window;
	01:34:45-35:56	Write on the screen;		
			01:35:56-36:06	Roll down the window;
	01:36:06-16	Write on the screen;		
			01:36:16-27	Roll up and down the window; Look at his product;
	01:36:28-37:13	Write on the screen;		
			01:37:13-18	Erase something on the screen;
	01:37:18-49	Write on the screen;		
			01:37:49-38:03	Erase something on the screen;
	01:38:03-18	Write on the screen;		

			01:38:18-24	Roll down the window;
State 51	02:03:38	Left hand fingers cover his lips;		
	02:03:38-41	look at his product;		
			02:03:41-52	Add something into his product;
	02:03:52-04:02	Look at his product;		
	02:04:02-20	W rite on the screen;		
State 52	02:04:20	Talk to the experimenter;		
			02:04:20-24:00	Look at his product; Give some explanation; Erase some words, and modify them; Highlight some words; Draw the detail of the product; Correct some grammar mistakes;

3.2.5 ANALYSIS METHOD

Compared with the other expression approaches, body movement as an effective approach to express without speech is more connotative, and the stimulation of the movements appears to be more unintentional. When someone feels annoyed, s/he may knit her/his eye brows with or without consciousness of that movement, and s/he may frown in the same way during deep concentration or in the other situation, s/he just does it with no purpose at all. Therefore, Birdwhistell and Fast [37] have pointed out that, the meaning of body movements cannot be defined without the context of the movement maker. A body movement may mean nothing in a context, and yet be extremely significant in another [37]. Accordingly, the learning of kinesics must be performed in terms of the total pattern of movement, thus we must understand the pattern of movement in terms of the "spoken language". The two, while sometimes contradictory, are also inseparable.

In the present thesis, instead of studying the body movements independently, the analyses were performed combined with the context, which were the recorded sketches and the verbal protocol. The body movements were divided to two groups according to the design context: Output-related movements; and Output-stimulated movements.

Output related movements, such as sketching, reading, and writing, are connected to the purpose of accomplishing the design. However, the stimulated movements, such as scratch, rub chin, bite lips and other little physical movements, were aroused under the mental load during the design process. Research shows that, human body is more active during the relaxation, while less movement during concentration [51]. Consequently, the frequency of movements is an important factor for evaluating the mental stresses. The following equation is used to calculate the relative quantity of mental stresses.

$$Mental\ Stress\ Level = \frac{1}{f_r} + \frac{1}{f_s} \tag{3.1}$$

$$f_r = \frac{E_r}{T_r},\ f_s = \frac{E_s}{T_s} \tag{3.2}$$

where, E_r and T_r represent the amount and the duration of the output-related movements respectively, and E_s and T_s represent the amount and the duration of the output-stimulated movements respectively.

While in the color word test, which is the major cognitive test of the present thesis, the experiment process separated in to three sections: Pre-test, test, and post-test. The experiment started with the pre-test section, participants were required to look straight while no subjects have been given in front until the test section began. When all CWT finished, participants have been asked to stare straight again, no subject shows in front as well, this is the post-test section.

Therefore, in the pre-test section and the post-test-section, no output-related movements have been performed. The mental stresses evaluation function changes in this circumstance. The corresponding equation is as follows:

$$Mental\ Stress\ Level_{pre-test\ or\ post-test\ section} = \frac{1}{f_s} \tag{3.3}$$

$$f_s = \frac{E_s}{T_s} \tag{3.4}$$

where, E_s and T_s represent the amount and the duration of the output-stimulated movements respectively. In the test section, the output-related movements are the clicks on the mouse (for choosing the right option of CWT). Frequency of these movements has been set as constants. Details of the CWT parameters will be given in the following chapters.

3.3 RESULT

In present research, differences existed between designers. It's hard to ignore that some students had difficulties on information gathering. Interestingly, the same problems were not difficult for other students, who trended to not gather a lot of information and tended to solve the design problem rather than thought about the potential difficulties.

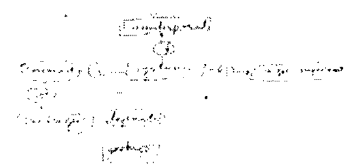
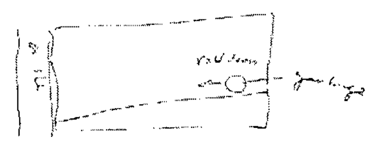
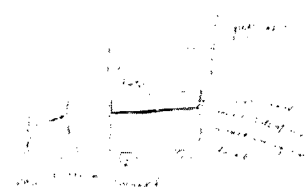
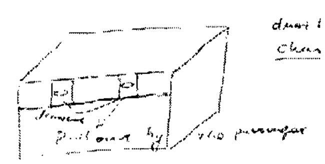
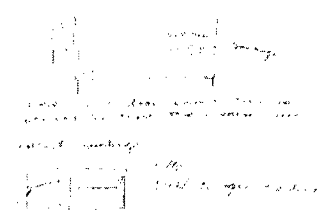
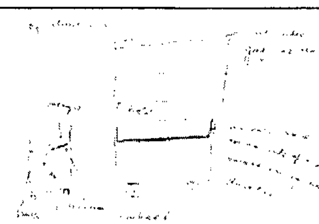
Designers were divided into two groups during the data analysis. The advanced group was marked in terms of their creativities and good comprehension, as well as their quick speed of the designing itself. They quickly indicated priorities. The other group gathered lots of information, but then "gathering data" became a substituted activity of the design work. For example, participant 4, participant 5 and participants 7 have adequately set up the problem for the problem scoping, which included gathering a larger amount and wider range of problem-related information did result in better design. On the other hand, participant 2 and participant 6 stuck in problem-definition and did not progress satisfactorily into further stages of the design process.

Changes in individual behavior were complex and variable. Some participants did not change their behavior models, while the others spent more time on design projects without any behavioral changes. Differences existed between the novice and experienced designers. We have found significant differences between the behaviors of novice of engineering design and experienced students. Participant 1 and participant 2 were junior; participant 3 and participant 6 were intermediate; participant 4, participant 5, and participant 7 were Senior. The novices used "trial and error" techniques of generating and implementing a design modification, evaluating it, and then generating another, and so on through much iteration. Experienced engineers were observed to make a preliminary evaluation of their tentative decisions before implementation, and then making a final evaluation at the end. In contrast to the novices "trial-and-error" approach, the experienced designers employed integrated design strategies.

According to the recorded sketch, the participant had difficulties in performing the design task in the first ten states, then he spent seventeen states to get prepared for the design, after which he started to generate solutions. The most productive section was states 35 to 39 and states 47 to 52, the participant generated most of his final solution. States 40 to 46 were adjustment period when the participant conducted a lot of refinement work.

Mental stresses value of a participant is given in Figure 8. The state 53 was added to illustrate the end of the design process, where the mental stresses level was set to zero. According to Figure 8, the participant had steady mental stresses in the first states. In the middle of his design, the fluctuations of the mental stresses value are revealed. During this section, the participant started to generate some solutions. Later, slight fluctuation merged from the middle to the end of his design. These waves represent the generation process of final results, which are the most productive states.

Table 2. Record of body language and sketching activities

Section	Time	Movement Summary	Sketching Activities
1	00:41:16–01:19:09 (Duration: 00:37:53) States 11-28	In this period, he watched the problem for 9 minutes without any movements or facial expression. Then he changed movements frequently, and asked some questions. At first his voice was a little trembling, later he spoke clearly and confidently.	
2	01:19:50–01:32:10 (Duration: 00:05:20) States 28-35	In this period, the participant touched his lips; touched hair; put his hand against face cheek; drew on the screen; put his hand on the chin; moved his body back and forth; He drew the position of the bin on the train. And according to the desktop records, he modified the pictures in the tablet, got some progress on the design.	 
3	01:33:30–01:42:05 (Duration: 00:09:35) States 35-39	During this period, the participant did eyes blink; drew on the screen; stood up to draw on the screen; watched around; moved his body when moving the chair; touched his lips; touched his face; He got some progress on the design, and then switched the design window to internet.	
4	1:42:05–01:57:32 (Duration: 00:15:27) States 39-47	In this period, the participant frowned; touched his lips; touched his nose; put his hand on his forehead; moved his body back and forth; He rectified his design and met some problems. He checked the original question and his design.	
5	01:57:44–02:23:40 (Duration: 00:25:56) States 47-52	During this period, the participant pursed his mouth firmly; touched his lips; touched nose; put his hand on forehead; scratched head and neck; supported his head by left arm; moved body from side to side; His design was finished. Then he rectified it.	

Participant was under a constant mental workload at the end of the design process. The last wave accompany with the completion of the design task. Data summary of this participant illustrates in Table 2. Summary of body movements, sketch behaviors, and the times are provided in the table.

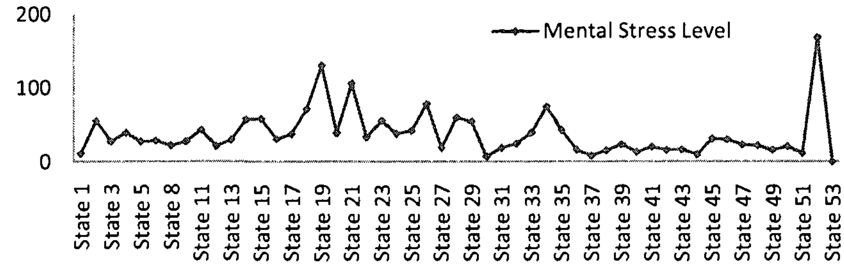


Figure 8. Evaluation result of participant's mental stress

CHAPTER 4

MENTAL STRESS ANALYSIS DURING COGNITIVE ACTIVITIES

Cognitive activities have been analyzed to identify the mental state for the past decades. Most of the researches were performed by clinic populations. As the world bringing more attention into the research of design method and the design activities, a significant approach was similarly used to represent the activities, namely, the performance. Performance was abstracted from the design relevant activities. It can estimate how the activities act on the design result. By quantifying the performance of the design process, researchers elicit the design efficiency, thus obtain the feedback to the design approach.

In this chapter, we will study the effect of human mental stresses on the human design behavior, which will help us to understand the design process. According to the present medical research result, mental stresses are accompanied by dynamic changes in autonomic nervous system (ANS) activity [52], which affects heart rate, digestion, perspiration, respiration rate, salivation, diameter of the pupils, micturition, and so on. The variation in the timing between beats of the cardiac cycle, known as HRV, has been shown to be an indicator of health [39, 52]. HRV analysis is a popular tool for assessing the activities of autonomic nervous system.

In our experiment, participants were asked to seat on a height-fixed chair to perform the standardized Stroop color word test (CWT). The Stroop CWT is a mental stresses test involving sensory rejection and has been used as a model of the defense reaction in humans. The present study was designed to investigate effects of CWT on resting cardiac autonomic nervous system activity evaluated by analyses of HRV. The participants were required to speak aloud the indicated vocabulary, and click on their choices by using the left button on the mouse within the next 3 seconds, and given the instructions that failing to click on the right position as well as mistakes were regarded as errors and that error was recorded to give the level how well they performed. Participants performed twelve sessions of CWT, i.e. mixed difficulty sessions, low difficulty sessions, and high difficulty sessions. The order of these sessions was not randomized because we expected the effect of novelty to be least pronounced in the last session.

The participants were monitored by a video camera, heart rate monitor and the video camera were continuously monitored throughout these periods. Considered the participants should carry the remaining workload to the following test stage, two seconds rest intermission was placed between two response events. Each CWT response event was composed by three steps, flash of the color word (1 second), response interval (2 seconds), and rest interval (2 seconds).

4.1 INTRODUCTION

In the end of last century, the study of HRV was proved to have the significant relationship with the autonomic nervous system [39]. HRV study has been used to study the cardiovascular disease, such as the sudden cardiac death, the arrhythmias, and then encouraged the study of the signs of the autonomic activities.

The heart rate variability was firstly related to clinical way in 1965 when Hon and Lee [53] noted that the alternations of the inter beat interval was preceded during a fatal distress before any other significant changes occurred in the heart rate activities.

Analyzing the time series of beat to beat interval from the ECG or the beat to beat interval from an arterial pressure tracing is usually the main way to calculate the HRV. Many measures of heat rate variability have been proposed, perhaps the simplest to perform are time domain analysis. Time domain measurements include the mean RR interval (NN interval), the mean heart rate, the difference between the longest and shortest RR interval, standard deviation, etc. Power spectral analysis (PSD), which was performed in frequency domain, provided the power distribution as a function of frequency. The application of PSD is a common frequency domain method to estimate the power generated by RR interval.

Both time domain method and frequency domain method are affected by the length of the data size. For example, the standard deviation of the NN interval (SDNN) estimates decreases in the shorter monitoring period. And the very low frequency (VLF) component, which is not firmly defined by the changes of autonomic modulation, has no coherent properties with the alternate epoch. According to the HRV research methods in the past decades, both time domain and frequency domain analysis are occurring in a chosen time window (short term 5-min and long term 24-h ECG recording).

The rest of this chapter will be organized as follows: Section 2 introduces the statistical method that employed to analysis the data. Section 3 shows the frequency domain analysis theory that assisted to abstract the LF and HF components from the experimental data. Section 4 discusses some Nonlinear methods.

4.2 METHOD

4.2.1 TIME DOMAIN ANALYSIS

The fastest way to indicate the changes in HR is to calculate the RR interval, which can be derived from the ECG tracing. The occurrence of the R peak can be identified for each heart beat, and the interval between each R peak is the RR Interval (Figure 9). Furthermore, the NN (normal-to-normal) intervals represent the interval between two successive sinus beats immediately preceding a sinus beat (Figure 10).

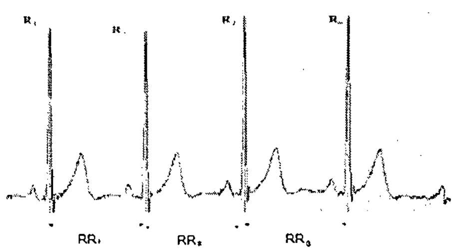


Figure 9. A data slot of RR interval

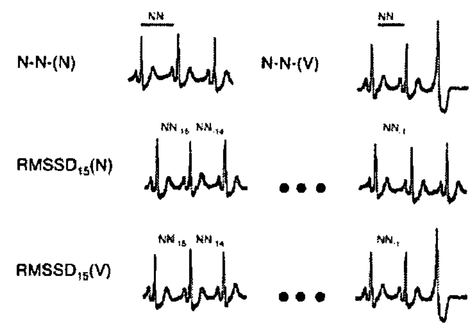


Figure 10. NN interval & RMSSD

Statistical measures

Several statistical measures are calculated. Standard deviation of the NN interval (SDNN) represents the square root of variance. Mathematically, the variance is equal to the total power of spectral analysis, therefore, the SDNN reflects those components that vary with the period of recording. Standard deviation of differences between adjacent NN intervals (SDSD), the standard error (SENN), the square root of mean squared differences of successive NN intervals (RMSSD) (Figure 10), the number of interval differences of successive NN intervals more than 50ms (NN50), and the proportion derived by dividing NN50 by the total number of NN intervals (pNN50) are the most commonly used statistical variables derived from interval differences.

$$SDNN = \sqrt{\frac{1}{N-2}\sum_{n=2}^{N}[\delta(n) - \bar{\delta}]^2} \quad (6.\ 1)$$

$$RMSSD = \sqrt{\frac{1}{N-2}\sum_{n=3}^{N}[\delta(n) - \delta(n-1)]^2} \quad (6.\ 2)$$

$$SDSD = \sqrt{\frac{1}{N-3}\sum_{n=3}^{N}[\delta(n) - \delta(n-1) - \bar{\delta}]^2} \quad (6.\ 3)$$

$$pNN50 = \frac{NN50}{Total\ number\ of\ NN\ intervals} \quad (6.\ 4)$$

Geometric measures

In addition to the above statistical measures, geometric measures have been used to analysis the RR interval histogram. The HRV triangular is obtained as the integral of the histogram, such as the total number of the RR interval, divided by the height of the histogram which depends on the selected bin width. A bin width of 1/128 seconds was used in order to obtain comparable results [39]. The other geometric method, namely, TINN, is the calculated by the baseline width of the RR histogram through triangular interpolation [39].

The major advantage of geometric methods lies in their high correlation with the standard deviation of all RR intervals. On the other hand, the major disadvantage of this method is the requirement of a reasonable number of RR intervals, normally more than 20 minutes recording (but perfectly 24h). Consequently Geometric measures are inappropriate to assess short-term changes in HRV.

4.2.2 FREQUENCY DOMAIN ANALYSIS

Methods of time domain are mathematically straightforward compared with frequency domain methods. In the frequency domain methods, a power spectral density (PSD) analysis has been employed to provide the basic information of power distribution in the form of functions of frequencies. Calculating the fast Fourier transform (FFT) is a common method to get the PSD. Parametric and non-parametric are the general two classes of PSD calculation methods.

The standard PSD calculator assumes equidistant sampling rate, and the RR interval series is converted to equidistantly sample rate by interpolation method prior to the PSD calculation. In our study, an interpolation of 4 Hz has been chosen.

Spectral leakage effects exist due to the windowing process, it leads to masking of weak signal that are present in the data. In order to avoid the problem of leakage and provide better frequency resolution than non-parametric or classical method, the AR method has be used to analysis the data in frequency domain in our research.

In the AR method, data have been modeled as output of a causal, all pole, discrete filter whose input is white noise. AR method of order p is expressed as the following equation:

$$x(n) = -\sum_{k=1}^{p} a(k)x(n-k) + w(n) \qquad (6.5)$$

where *a(k)* are AR coefficients and *w(n)* is white noise or variance equal to σ^2. AR *(p)* model can be characterized by AR parameters $\{a[1], a[2], \ldots, a[p], \sigma^2\}$. According to the work of various accomplished research, such as the paper presented by Akaike [54], in this study, we choose the order of the AR model $p=16$.

4.2.3 NONLINEAR METHODS

Poincare plot is a graphical analysis of each RR interval data as a function of the previous RR interval. Two dimensional vectors, SD1 and SD2, have been elicited to provide summery information as well as the beat to beat information on the behavior of heart. Respectively, SD1 represents the beat to beat variability in HR, and SD2 indicates the standard deviation of long-term RR intervals. Figure 11 shows the Poincare plot of a participant.

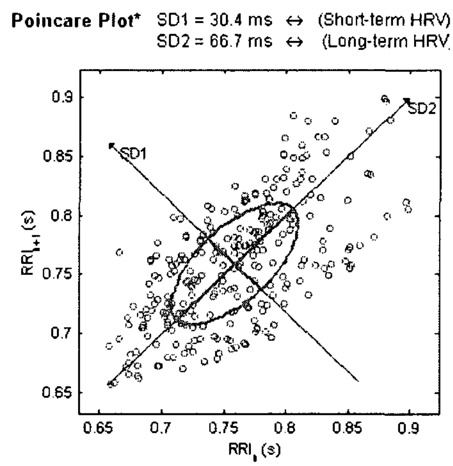


Figure 11. Poincare plot of a normal subject

4.2.4 SELECTION OF PARTICIPANTS

In the experiment of mental stresses analysis during cognitive activities, educational background, design experience and language ability were not considered during the selection of the participants. Five males and two females in good health participated in the study. Participants were having education background in engineering area with various cultural backgrounds volunteered as the participants in this study. They are from mechanical engineering, electrical engineering, computer engineering, information engineering, and chemical engineering, respectively. Three males have engineering design experiences, two males are native Indian speaker and the rest of participants were having native language of Chinese. Their mean age, height, and weight were 28.2 (range from 24-32) yr, 174.8 (160-184) cm, and 68.3 (54.2-72.0) kg. Human research ethics approval for the study has been received from University Human Research Ethics Committee. Procedures of the experiment were explained by Design Lab, and all the participants have signed a consent form prior to taking part in the study.

4.2.5 MATERIALS

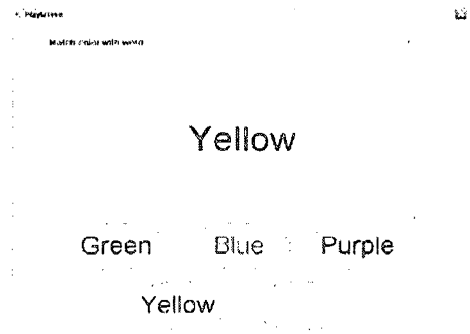
CWT (color word test) was first proposed by John Ridley Stroop in 1935. Current research on the Stroop effect emphasizes the interference that automatic processing of words has on the more mentally "effortful" task of just naming the colors. The task of making an appropriate response -- when two conflicting signals are given -- has tentatively been located in a part of the brain called the anterior cingulate. This is a region that lies between the right and left halves of the frontal portion of the brain. It is involved in a wide range of thought processes and emotional responses.

To fulfill the research of mental stresses analysis during cognitive activities, the Stroop test was adapted to our research. The Stroop CWT is a mental stresses test involving sensory rejection and has been used as a model of the defense reaction in humans. The present study was designed to investigate effects of CWT on resting cardiac autonomic nervous system activity evaluated by analyses of HRV. Participants were presented a pre-prepared description of the design problem as follows:

Please read aloud the displayed vocabulary, and then click on the correct option that indicates the color of the vocabulary.

Figure 12 shows the experiment set-up. The Figure (a) shows the installation and the Figure (b) gives a demo of the screen of a CWT. In this demo, the answer with star mark -- “Purple” is the correct choice, whereas in the real CWT, no star will be displayed.

a) *Installation*



(b) Stroop test demo

Figure 12. Experiment set-up.2

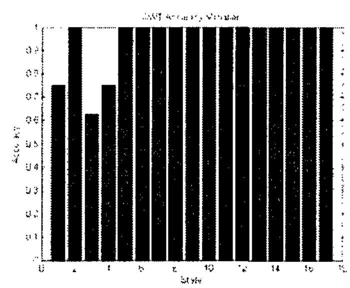
4.2.6 COGNITIVE ACTIVITIES DESIGN AND PROCEDURE

To quantify precisely the designer's mental stresses during the CWT, activities that determining the designer's mental stresses must be recorded faithfully. Thus, various recording approaches are needed. Meanwhile, the experiment procedures must not interfere with the designer's mental process so that the designer's mental stresses are not influenced by the adopted experimental approach.

During the past decades, it was claimed that performance Statistic methods, such as mean value, standard deviation, and the standard error were performed to evaluate the participants' performance. In the present research, the researcher presents a demo of the CWT to the participant and answers any questions from the participant regarding the procedure of the experiment. The participant will then work alone on the CWT in a quiet room. The participant is asked to take 15 minutes pre-test rest as the baseline, then around 15 minutes was consumed on the CWT, and at last 10 minutes post-test rest have proceeded for the data comparing. Three webcams have been employed to record the entire process including audio and video information from different angles. Correctness and elapsed time of the CWT are recorded, as well as the Heart beat to beat interval. Data such as, HF component, LF component, LF/HF (Ratio) are recorded for the mental stresses analysis. Statistical analyses have been performed to study the numerical facts, including the similarity between individuals, and the common character between cognitive stages.

4.3 RESULT

Three principle elements have been considered for performances quantification. They are CWT Accuracy, Difficulty Ratio level (congruent/incongruent level of the test), Elapsed Time (the time duration from the stimulation and the time participant make the choice). Results of participant 1 illustrate in the following figures:



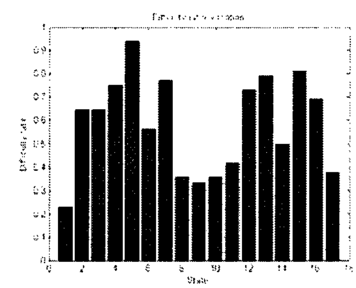


Figure 13. (left) CWT accuracy variation of participant 1
Figure 14. (right) Difficulty ratio variation of participant 1

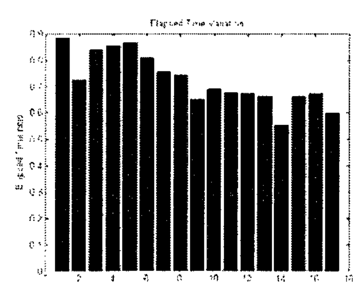


Figure 15. Elapsed time variation of participant 1

CHAPTER 5

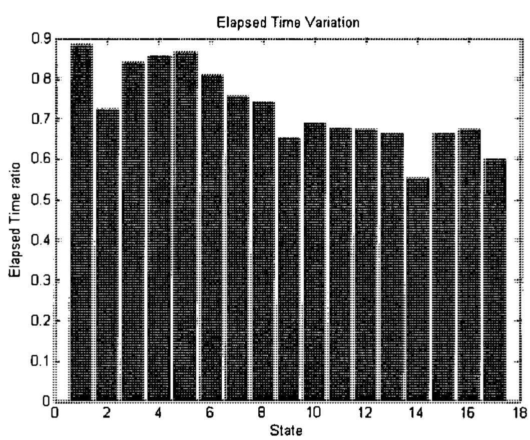
RESULT AND CONCLUSION

5.1 RESULT OF KINESICS ANALYSIS AND HRV ANALYSIS

5.1.1 ACCURACY, DIFFICULTY RATIO AND ELAPSED TIME ANALYSIS

There are three elements included in a CWT test, CWT Accuracy, Difficulty Ratio level (congruent/incongruent level of the test), Elapsed Time (the time duration from the stimulation and the time participant make the choice).

The results of the experiment are shown in the following figures:



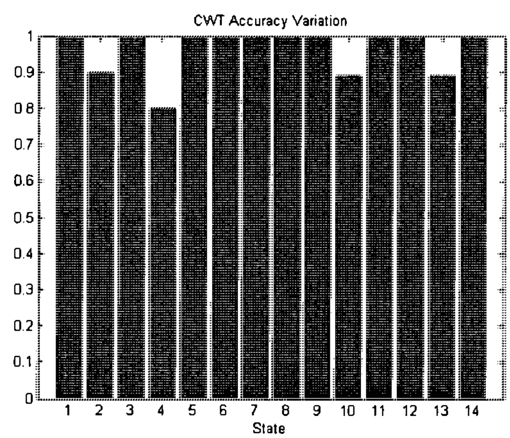
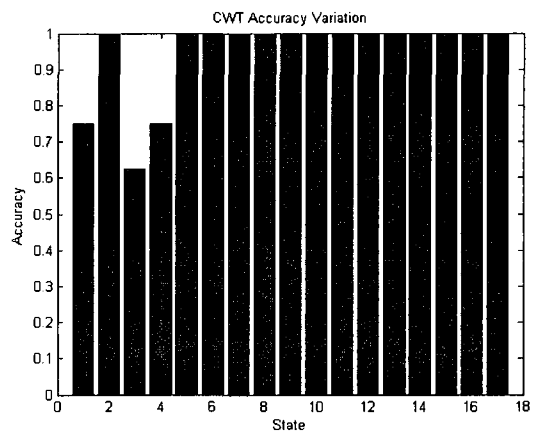


Figure 16. (left) CWT accuracy variation of participant 1
Figure 17. (right) Difficulty ratio variation of participant 1



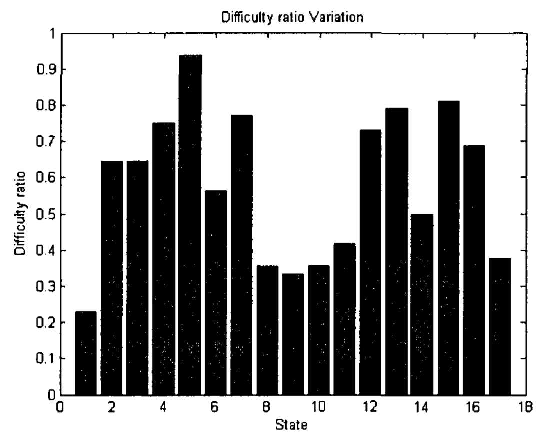
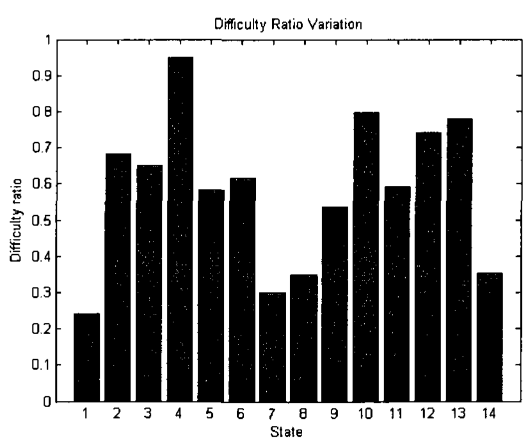


Figure 18. (left) Elapsed time variation of participant 1
Figure 19. (right) CWT accuracy variation of participant 2



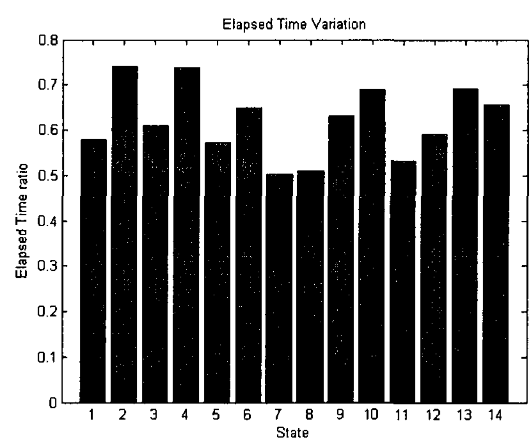
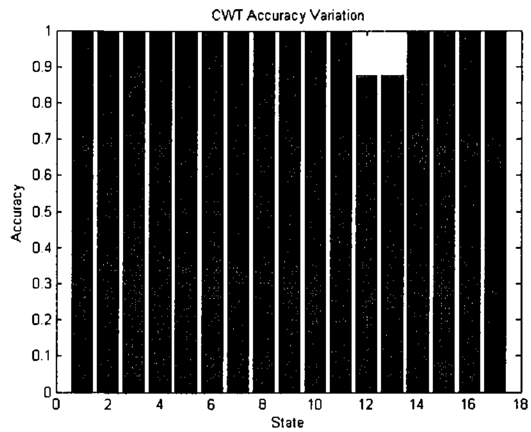


Figure 20. (left) Difficulty ratio variation of participant 2
Figure 21. (right) Elapsed time variation of participant 2



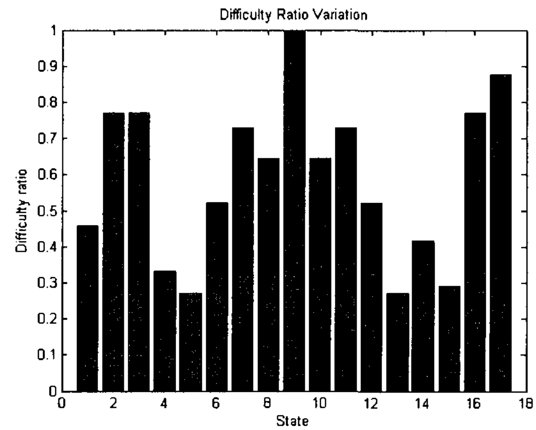
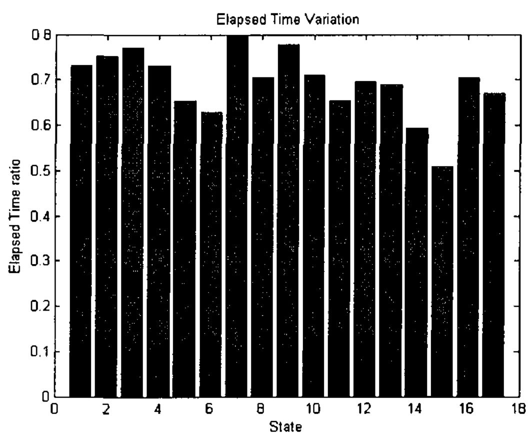


Figure 22. (left) CWT accuracy variation of participant 3
Figure 23. (right) Difficulty ratio variation of participant 3



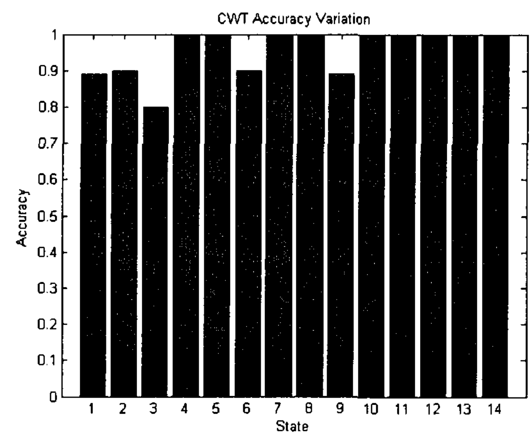
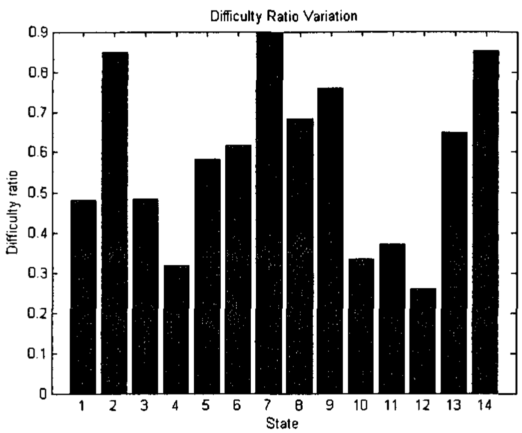


Figure 24. (left) Elapsed time variation of participant 3
Figure 25. (right) CWT accuracy variation of participant 4



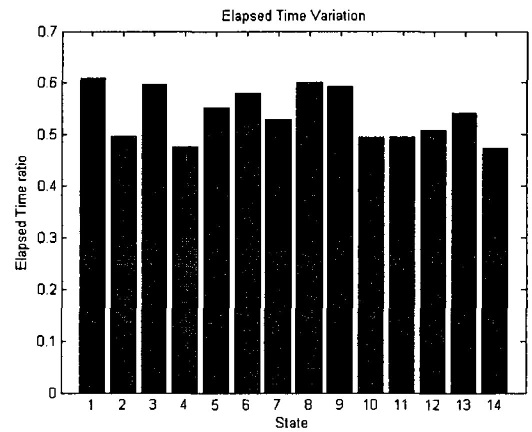
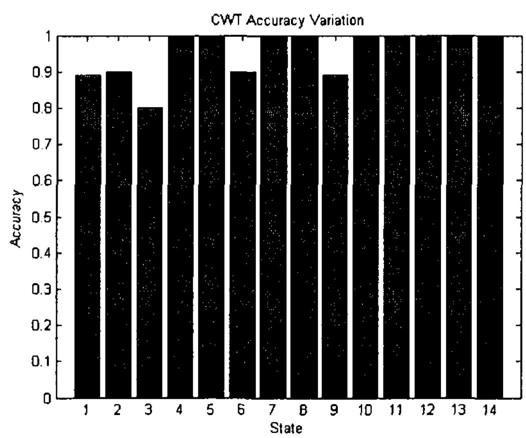


Figure 26. (left) Difficulty ratio variation of participant 4
Figure 27. (right) Elapsed time variation of participant 4



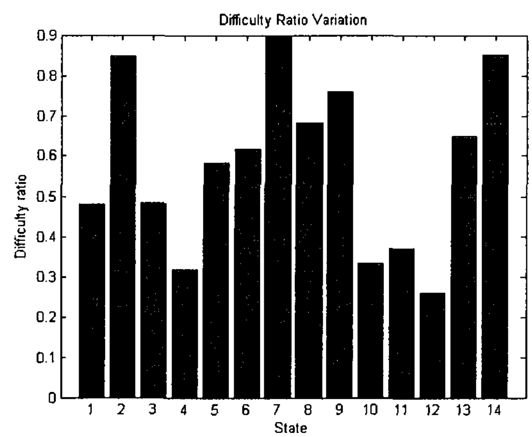


Figure 28. (left) CWT accuracy variation of participant 5
Figure 29. (right) Difficulty ratio variation of participant 5

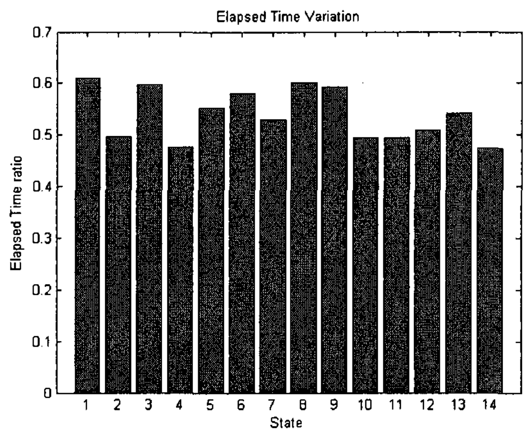
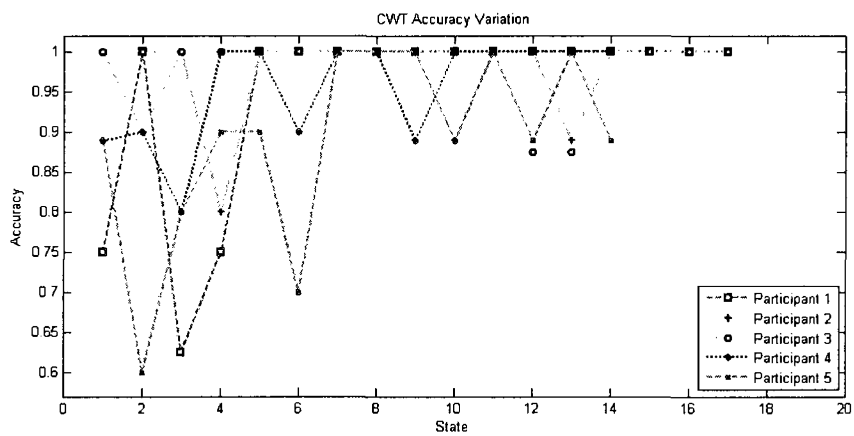
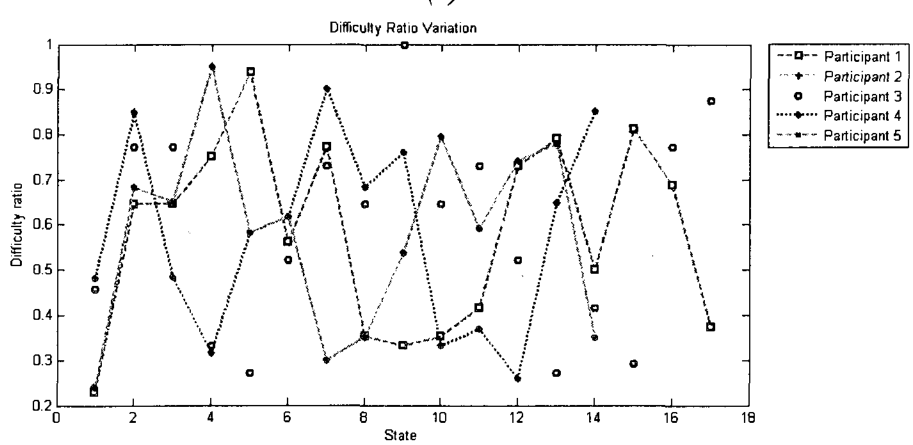


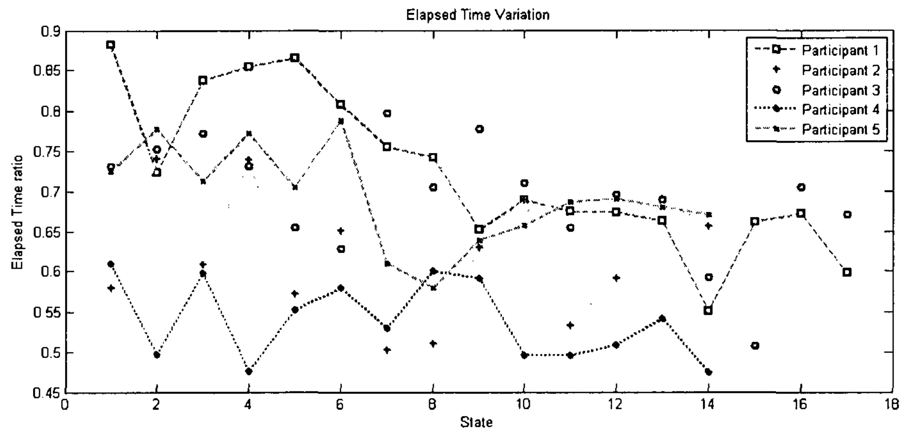
Figure 30. Elapsed time variation of participant 5



(a)



(b)



(c)

Figure 31. (a) CWT accuracy variation; (b) Difficulty ratio variation; (c) Elapsed time variation

Correctness, elapsed time and difficulty ratio of the CWT have been recorded for the performance analysis, as well as the HRV data. Figure 16 to Figure 30 illustrate the histogram of accuracy variation, difficulty ratio variation, and elapsed time variation of each participant. Figure 31 demonstrates the integrated data.

According to the above results, the performance analysis has been carried out, and the results are shown as follows.

Table 3. Performance analysis discussion

Variable & Condition		*Low difficulty test*	*High difficulty test*
Participant 1	*Accuracy*	*0.958333*	*0.9498557*
	Elapsed time (0-1)	*0.706218333*	*0.732866989*
Participant 2	*Accuracy*	*1*	*0.947777778*
	Elapsed time (0-1)	*0.561546375*	*0.64405495*
Participant 3	*Accuracy*	*0.979166667*	*0.988636364*
	Elapsed time (0-1)	*0.650880313*	*0.715111477*
Participant 4	*Accuracy*	*0.948148148*	*0.961111111*
	Elapsed time (0-1)	*0.530181*	*0.54568284*
Participant 5	*Accuracy*	*0.944444444*	*0.867777778*
	Elapsed time (0-1)	*0.646420514*	*0.710478672*

According to the Table 3, participants perform better in the low difficulty levels, comparing with the performance in the high difficulty levels. During the low difficulty tests, the accuracy of the CWT was higher, and elapsed time was shorter. While in the high difficulty tests, the accuracy is lower, and elapsed time was longer. The accuracy and the elapsed time are not necessary related.

An interesting finding

We assume the accuracy is directly related to the performance. Additionally, we consider the elapsed time is the inverse ratio of the efficiency, which is believed to be one of the standards to evaluate performance. We simply calculate the accuracy divided by the elapsed time to observe the results. The results are shown in Table 4. We observe from the table that, generally, people perform better in easy tasks than hard tasks. And participants, who perform the best in the easy tasks, also perform the best in the hard tasks. If we range the participants by their performances in easy tasks, the range in hard tasks will be almost the same. This result may prove a theory that people have different mental capacities, and the high capacity normally defines the better performance, no matter the task is hard or easy. The capacity detection and comparison between each participant will feed back into the future researches.

Table 4. Performance discussion

Variable & Condition	*Low difficulty ratio*	*High difficulty ratio*
Participant 1	*1.356992527*	*1.296081982*
Participant 2	*1.780796822*	*1.47157906*
Participant 3	*1.504372843*	*1.382492654*
Participant 4	*1.788348032*	*1.761299862*
Participant 5	*1.461037241*	*1.221398773*

5.1.2 HRV ANALYSIS

Two groups of analysis have been performed and cross compared to elicit the conclusion. By HRV analysis, we have used the power distribution, time domain analysis, and the nonlinear method to abstract the information from the participant's heart rate variability. Meanwhile, the Stroop test results have been analyzed by using the mean value, variance and the standard deviation to deliver the message of the subject's performance.

Table 5. HRV analysis result; Test represents the color word test (CWT); Pre-test* & Post-test* session represent the rest session.*

Variable & Condition		Pre-test*	Test*	Post-test*
participant 1	LF (ms^2)	379	442	N/A
	HF (ms^2)	236	327	N/A
	LF/HF (Ratio)	1.605	1.35	N/A
participant 2	LF (ms^2)	160	91	161
	HF (ms^2)	375	365	487
	LF/HF (Ratio)	0.426	0.251	0.33
participant 3	LF (ms^2)	1254	879	1207
	HF (ms^2)	561	227	558
	LF/HF (Ratio)	2.235	3.867	2.164
participant 4	LF (ms^2)	397	140	466
	HF (ms^2)	1401	647	551
	LF/HF (Ratio)	0.283	0.216	0.846
participant 5	LF (ms^2)	170	181	266
	HF (ms^2)	162	240	177
	LF/HF (Ratio)	1.052	0.752	1.501

Table 5 and Table 6 show the HRV analysis results of all five participants. According to the majority of the result, the HF component of HRV was significantly reduced during the CWT compared with the other sessions, and the LF/HF ratio was reduced in all data except the participant 3. The LF component and the HF components of

HRV between Pre-test and Post-test session have no identity. However, both the LF and the HF components were significantly higher in the CWT than the rest, and the LF/HF ratio was consistently reduced.

Table 6 gives the LF/HF ratio of each participant. Comparing with the performance analysis result, we can observe that, LF/HF ratio was significantly increased as the accuracy and the Elapsed time were decreased.

Table 6. LF/HF discussion; Test represents the color word test (CWT); Pre-test* & Post-test* session represent the rest session.*

Variable & Condition	*Pre-test** *LF/HF (Ratio)*	Test* *LF/HF (Ratio)*	*Post-test** *LF/HF (Ratio)*
Participant 1	*1.605*	*1.35*	*N/A*
Participant 2	*0.426*	*0.251*	*0.33*
Participant 3	*2.235*	*3.867*	*2.164*
Participant 4	*0.283*	*0.216*	*0.846*
Participant 5	*1.052*	*0.752*	*1.501*

Table 7. Mean and STD of RR and HR of five participants

Variable & Condition		*Pre-test**	*Test**	*Post-test**	*Whole range*
participant 1	*Mean RR(s)*	*0.853*	*0.82*	*N/A*	*0.841*
	STD(s)	*0/054*	*0.045*	*N/A*	*0.051*
	Mean HR(1/min)	*70.98*	*73.59*	*N/A*	*71.95*
	STD(1/min)	*5.68*	*4.7*	*N/A*	*5.4*
participant 2	*Mean RR(s)*	*0.791*	*0.804*	*0.821*	*0.805*
	STD(s)	*0.036*	*0.035*	*0.039*	*0.037*
	Mean HR(1/min)	*76.29*	*75.14*	*73.46*	*74.96*
	STD(1/min)	*4.59*	*4.1*	*4.45*	*4.52*
participant 3	*Mean RR(s)*	*1.039*	*0.987*	*1.041*	*1.024*
	STD(s)	*0.088*	*0.067*	*0.087*	*0.082*
	Mean HR(1/min)	*58.37*	*61.43*	*58.3*	*59.3*
	STD(1/min)	*5.87*	*4.68*	*5,84*	*5.72*
participant 4	*Mean RR(s)*	*0.849*	*0.82*	*0.082*	*0.832*
	STD(s)	*0.077*	*0.051*	*0.054*	*0.064*
	Mean HR(1/min)	*71.67*	*73.69*	*73.74*	*72.86*
	STD(1/min)	*9.35*	*5.51*	*6.35*	*7.8*
participant 5	*Mean RR(s)*	*0.717*	*0.724*	*0.732*	*0.724*
	STD(s)	*0.03*	*0.032*	*0.036*	*0.033*

	Mean HR(1/min)	83.95	83.14	82.38	83.16
	STD(1/min)	3.99	4.01	5.3	4.53

Table 7 shows the mean and standard deviation of RR and HR data of all five participants. Statistical measures have been performed, and the results illustrate in Table 7. We observed from Table 8 that, standard deviations of RR and HR data are lower during the test section, comparing with the pre-test and post-test sessions. This result illustrates that the heart rates, or RR intervals closely distribute in a narrow area during the test section, and loosely distribute in a wide area during the other sections (Figure 32).

Table 8. Statistical analysis of five participants

Variable & Condition		*Pre-test**	*Test**	*Post-test**	*Whole range*
participant 1	*RMSSD(ms)*	*40.3*	*36.8*	*N/A*	*39*
	NN50(count)	*287*	*139*	*N/A*	*426*
	pNN50(%)	*19.4*	*15.9*	*N/A*	*18.1*
participant 2	*RMSSD(ms)*	*39*	*39*	*41.3*	*39.8*
	NN50(count)	*24.1*	*159*	*268*	*666*
	pNN50(%)	*21.1*	*21.5*	*24.5*	*22.4*
participant 3	*RMSSD(ms)*	*90.1*	*70.9*	*88.6*	*84.1*
	NN50(count)	*410*	*319*	*366*	*1099*
	pNN50(%)	*47.2*	*44.1*	*48.8*	*46.9*
participant 4	*RMSSD(ms)*	*109.2*	*73.9*	*64.9*	*88.3*
	NN50(count)	*350*	*185*	*133*	*670*
	pNN50(%)	*33.1*	*25.4*	*18.1*	*26.6*
participant 5	*RMSSD(ms)*	*28.8*	*33.7*	*34.3*	*32.2*
	NN50(count)	*98*	*118*	*135*	*351*
	pNN50(%)	*7.8*	*14.3*	*11*	*10.6*

Figure 32 illustrates the poincare plot of participant 3 during the pre-test and the test sections. The vector SD1 and the SD2 indicates the distribution trend. In the pre-test, SD1 equals to 63.9 ms, SD2 equals to 135.0 ms. During the test, SD1 equals to 50.3 ms, SD2 equals to 127.9 ms. The RMSSD value indicates the square root of mean squared differences of successive NN intervals, the NN50 presents the number of interval differences of successive NN intervals more than 50ms, and the proportion derived by dividing NN50 by the total number of NN intervals is pNN50 value are illustrated in Table 8. These statistical variables derived from interval differences indicate the heart beat to beat features of participants.

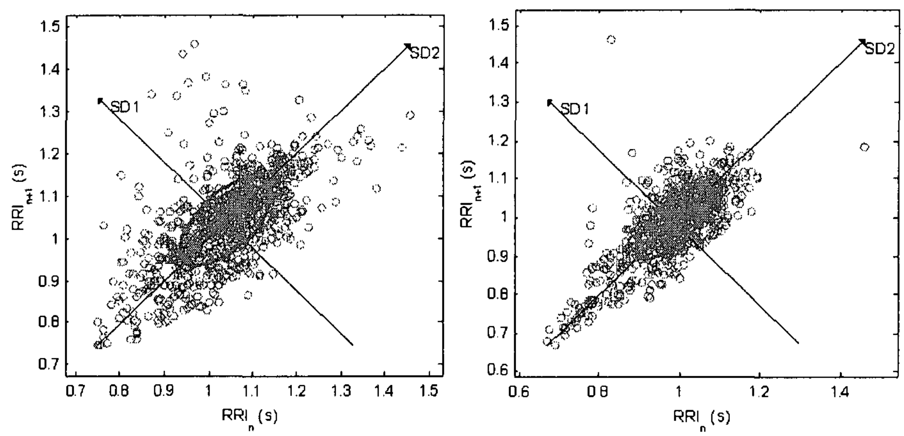


Figure 32. Poincare plot of participant 3 during pre-test (left) and test (right) sections

5.1.3 KINESICS ANALYSIS

Kinesics analysis of design experiment

Segmentations of design behaviors are generated according to the design product. Messages have been taken in three columns from videos, which are "Body Language", "Sketching Activities", and "Analysis". The group estimates two values, "Mental stresses level in design process", and "performance level", in order to compare the differences between the design performances and mental stresses level. Table 9 illustrated the design states and the pertinent design behaviors. With respect to the segments of design states shown in Table 9, we plot the mental stresses to illustrate the trend of real-time stresses level and performance level of each participant. Participants' mental stresses during design activities are shown in Figure 33.

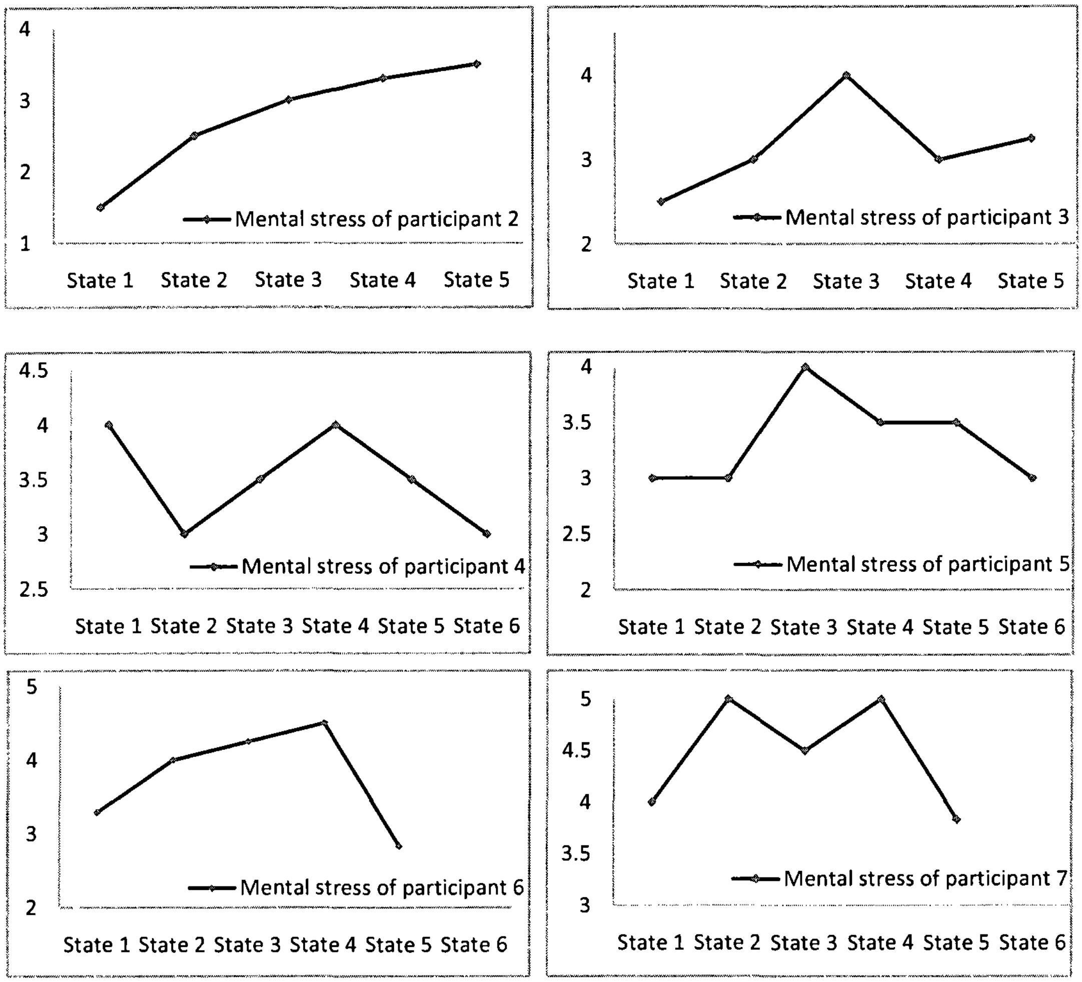


Figure 33. Mental stress variation of participants during design experiment

Since the design experiments were conducted nearly four years ago, the data is not complete for the analysis of mental stresses, which was not one of the objectives of the experiment. Necessary data including health condition surveys and the heart rate records were not recorded. This fact affects the analysis result but it is not fatal. The CWT experiments were performed as a complement to the design experiment.

Table 9. The descriptions of participants' design state

	Design State 1	Design State 2	Design State 3	Design State 4	Design State 5	Design State 6
Participant 2	Thinking the train	The design of garbage bin is easy for passenger and collector	Designing the shape of garbage bin	Considering the garbage bin ' environment	Deciding the size of the garbage bin	Null
Participant 3	Understanding the design problem	Analyzing the requirement by QFD model	Analyzing partial requirements	Designing the whole details of the garbage bin that includes the material, location, fixing way, shape, height etc.	Finalizing the design scheme and design process	Null
Participant 4	Finding out five environments inside the design problem	Creating a rough concept (the shape of garbage bin likes a box)	Analyzing the relationships between passengers and garbage bin	Analyzing the relationships between cleaner and garbage bin	Deciding the material of bin	Designing the cover of garbage bin
Participant5	Reading the problem description	Thinking about the size and convenience for garbage bin.	Figuring out the simple product system and identifying 5 components for environment .	Improving existing garbage bin	Thinking the collector, the cost, and the convenience	Reviewing the design
Participant6	Thinking about the requirements of the design problem	Considering the details structure of the compartment	Focusing on the convenience for passengers	Thinking the cleaners	Adding some supplement and concluding the design	Null
Participant7	Understanding the design problem	Confirming the environment of the garbage bin	Solving the conflicts in the environment	Determining the details of the design	Changing some design and finishing the design process	Null

Kinesics analysis of CWT

During the kinesics analysis of CWT, participants were found blinking very frequently. After investigating, we have found this fact was caused by the high lightness and the high contrast of the screen, other than the mental stresses of participants. For the comfort of the participants, these two factors have been suggested reducing in the future experiments. And during this experiment, the conditions have been seen as a high tolerance environment data, which were used as a high tolerance baseline of normalization. Furthermore, considering the differences between individuals, the normalization of data in processing the CWT kinesics analysis is necessary. Grounded on function (3.1) and (3.3), the normalization function shows as follows:

$$f_{normalized} = \frac{f_s}{\overline{f_s}} \qquad (5.1)$$

$$\overline{f_s} = \frac{1}{n}\sum_{i=1}^{n}(f_s) \qquad (5.2)$$

where, *n* represents the amount of f_s. In the presented CWT experiment, we set *n=1 minute=60 seconds.*

The results of the experiment are shown as follows:

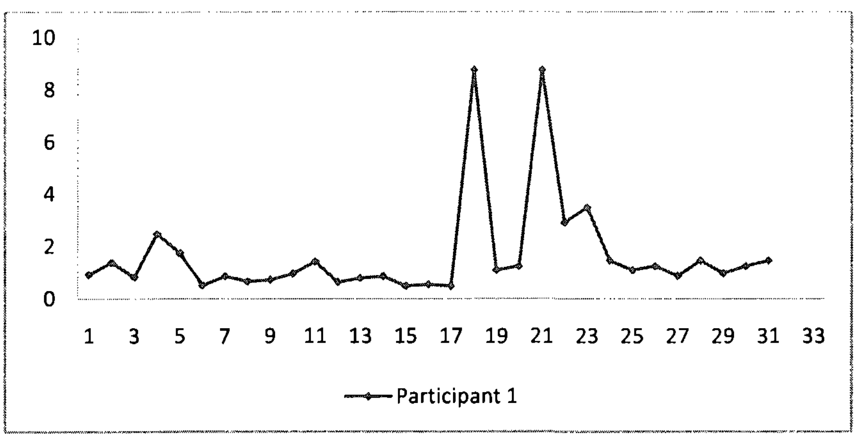


Figure 34. Kinesics analysis of participant 1

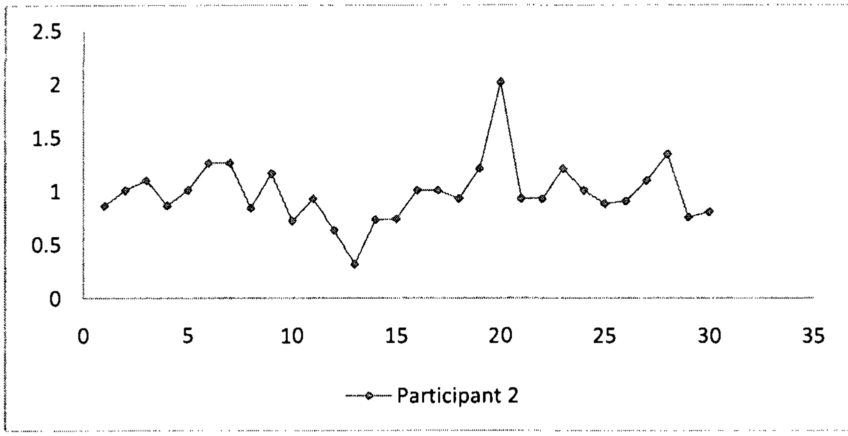


Figure 35. Kinesics analysis of participant 2

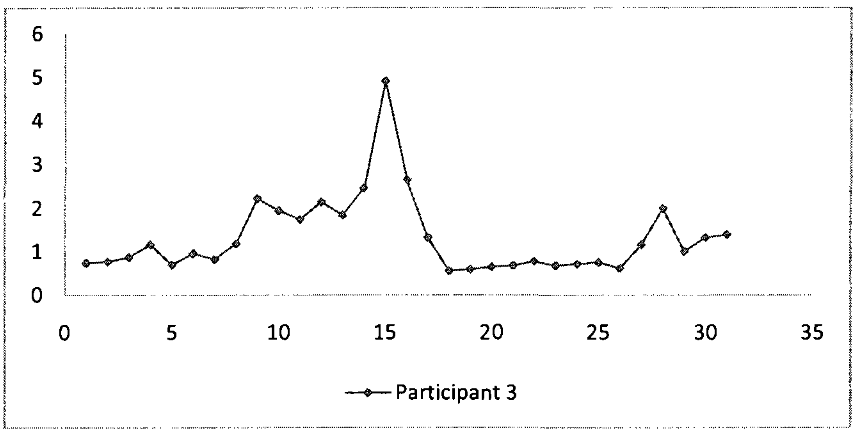


Figure 36. Kinesics analysis of participant 3

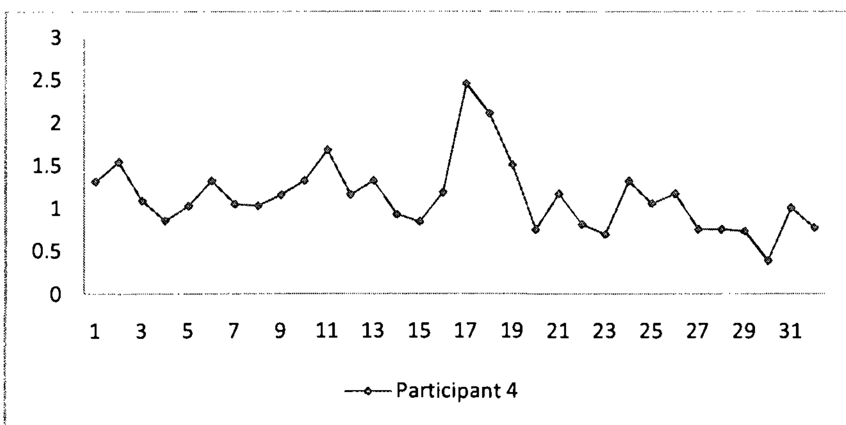


Figure 37. Kinesics analysis of participant 4

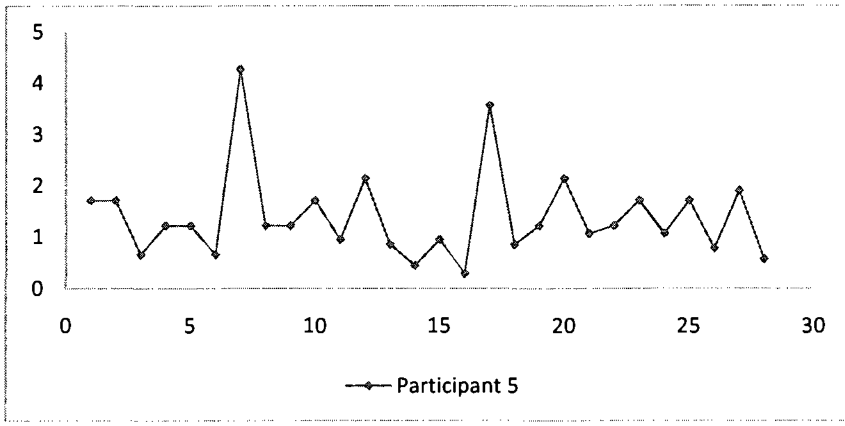


Figure 38. Kinesics analysis of participant 5

Table 10 shows the kinesics analysis results of all five participants. According to the results of participant 1, 2 and 5, the mental stresses levels were significantly increased during test comparing with the other sections. For participant 4, the mental stresses level during test session reduced 0.074% comparing with the pre-test session, but substantially greater than the post-test session. For participant 3, the mental stresses level of test session reduced 9.34% compare with the pre-test session, while the mental stresses level reduced another 13.45% during the post-test session.

Table 10. Kinesics analysis; Test represents the color word test (CWT); Pre-test* & Post-test* session represent the rest session.*

Variable & Condition	Pre-test* Mental stress level	Test* Mental stress level	Post-test* Mental stress level
Participant 1	0.958008	2.575501	N/A
Participant 2	0.904997	1.126112	0.983471
Participant 3	1.342802	1.21738	1.053624
Participant 4	1.17522	1.174346	0.720568
Participant 5	1.325144	1.56464	0.569286

5.2 CONCLUSIONS

Table 6 and Table 10 show the mental stresses ratios of all five participants. Table 11 and Table 12 are deducted from Table 10 and Table 6, respectively. The correlation coefficient of these two matrices is 0.761085. In another word, the evaluation result of mental stresses by using two approaches, which are kinesics analysis and HRV analysis, have a good similarity, the alike degree with the percentage is 76.1085%. As a result, the present research has proved that the kinesics analysis result have a 76.1085% similarity comparing with the result that based on the physiological data analysis.

In virtue to the economic cost of the physiological equipment, the quantification of mental stresses has been performed for decades but mainly restricted in clinic use. The present thesis introduces a new economical approach, kinesics analysis, which can be widely used in psychological study, behaviors study, and the human factor research in engineering. Thanks to the contactless character, the device of kinesics detection can be employed in remote operated environment, such as the study on astronauts in the outer space.

Table 11. Mental stress ratio of kinesics analysis; Test represents the color word test (CWT); Pre-test* & Post-test* session represent the rest session.*

Variable & Condition	Pre-test* Mental stress level	Test* Mental stress level	Post-test* Mental stress level
Participant 1	-0.62803043	1	N/A
Participant 2	-0.196352583	1	-0.12667
Participant 3	0.103026171	1	-0.13452
Participant 4	0.000744244	1	-0.38641
Participant 5	-0.153067798	1	-0.63616

Table 12. Mental stress Ratio of LF/HF discussion; Test represents the color word test (CWT); Pre-test* & Post-test* session represent the rest session.*

Variable & Condition	*Pre-test** *Mental stress level*	*Test** *Mental stress level*	*Post-test** *Mental stress level*
Participant 1	*-0.188888889*	*1*	*N/A*
Participant 2	*-0.697211155*	*1*	*-0.31474*
Participant 3	*0.422032583*	*1*	*0.440393*
Participant 4	*-0.310185185*	*1*	*-2.91667*
Participant 5	*-0.39893617*	*1*	*-0.99601*

5.3 DISCUSSION

5.3.1 CULTURE AND INDIVIDUAL DIFFERENCES

Research in the past decades indicates that, though some gestures are genetic, such as the smiling, most of the gestures are learned, such as nod and thumb-up. Therefore, body movements have different meanings because of the distinct learning system. Head movement "up and down" normally means agreement in many countries; however, it has the opposite meaning in part of Indian culture. Fast [37] believed that culture indoctrination in terms of body language is very difficult to overcome. As a consequence of this fact, we have to define the meaning of body movements in the context of each individual participant.

5.3.2 NUMBER OF PARTICIPANTS

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. 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 [55]. In a design study, usually the response cannot be represented by a crisp value.

Table 13 shows some examples about how many participants are chosen in ergonomic domain. Given the fact of complexity in human factors-related experiments, Kotval determined the number of participants in his study using eye movement parameter by simply surveying about 181 published papers in the area of eye movement study [56]. He found that thirteen participants 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 [57]. Ryan presented concurrent and retrospective verbal protocol methods, which were used to collect thoughts from eighteen participants during a manual handling task involving the repeated transfer of loads between locations at two tables [58]. To explore the interplay between designers' representations and their design activities investigate the engineering students' use of external representations, Cadella selected four students (two seniors and two freshmen) from the original dataset [59]. This method was taken due to the difficulty in determining the sample size for human factors study using those standard principles in statistics [55].

Table 13. Number of participants

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

5.3.3 HEALTH CONDITION OF PARTICIPANTS

Since this is not clinic research, health conditions of participants are not required by our experiments. Self-reports are taken as valid information, as a convention in this kind of research. Surveys of the health condition have been distributed to participants preceding formal experiments. Height, weight, age, gender, as well as present diseases have been recorded for the basic health data. All participants claimed healthy in the experiments. No major health problem has been observed in any of our participants in six months before and after experiments. In the further research, physical parameters, such as blood pressure, heart rate, temperature, lung vital capacity, are expected to be detected to ensure a better baseline.

5.4 SUMMARY OF CONTRIBUTIONS

Studies on mental stresses have been introduced for decades, as well as the utilization of kinesics analysis on study human behaviors. It is not until the latest 30 years, scientists have started to quantify the stresses by using the physiological parameters. But no research was reported to employ the kinesics study quantifying of the mental stresses. The present thesis proposes a new approach for quantifying human mental stresses during the cognitive activities through his/her body language.

The original purpose of the present study was to evaluate the mental stresses during the design process. Therefore, design experiments have been performed. During these experiments, the participants have been asked to design a litter-disposal system for passenger compartments in a train carriage. Kinesics analysis has been employed to quantify the participants' mental stresses. To verify the evaluation result during the design experiment, several independent cognitive experiments are employed in the second session of our experiment. In this session, Stroop CWT has been employed to stimulate the mental stresses. Kinesics analysis has also been employed to quantify the participants' mental stresses. Meanwhile, HRV analysis has been applied to evaluate the mental stresses, in addition to verify the result of kinesics study.

The present research result illustrated that kinesics analysis has 76% accuracy on evaluation of mental stresses comparing with the quantification by using physiological data. Furthermore, according to the economical feature of kinesics detection, the present technique can be widely applied to many domains. Such as psychological research, behaviors study, and the human factor research in engineering area, etc. Due to the contactless character that is advanced to physiological technologies, the kinesics devices can also be applied into remote operated environment, such as the study on astronauts in the outer space.

5.5 FUTURE RESEARCH

The research results presented in the present thesis are preliminary. During the design process, we noticed that participant's creativity varied as the design states, which is preparation, acceptance, creation, confirmation, and solving problem. We can observe the fluctuations of participants' attention and mental stresses through the above data. Meanwhile, we approved the correlation between Yerkes-Dodson principle and our experiment data, the results were satisfying.

During the CWT test, the mental stresses levels are represented in relative values. Since the relative values are conducted from the baseline behaviors of single participant, the comparison of the variations are within, and only within the physical system of separated unit. It can be predict that, in the future, this technique can be applied to evaluate the mental stresses as the unit of measurement, which could be named as "Mental stresses quotient".

Mental stresses are accompanied by many bodily reactions, such as modifications in the heat rate, blood pressure, blood volume, electrical properties of the skin, brain waves, temperature and pupil size. These physiological changes can be measured through some physiological parameters thanks to modern technologies. For example, the HRV that we have introduced within the present thesis is widely accepted that is an indicator of mental stresses. A lot of clinic studies have been done using this technique. The eye gaze tracking system can be used to measure pupil size. It is shown that pupil size increases with the level of mental stresses. The electroencephalogram (EEG) is also used for brain waves. There are two measures of stresses and relaxation which can be observed from the EEG. From the EEG spectrum, activity can be observed in the 8-12 Hz (alpha) frequency band. A more sophisticated measure of stresses and relaxation is the phase coherence which shows the phase synchrony, as a function of frequency, from two Merent spatial locations on the surface of the scalp. It measures the degree to which EEG amplitude increases or decreases are occurring simultaneously in these regions. It has been shown that, during meditation, there is a remarkable increase in coherence, especially in the alpha frequency band.

Newly research result introduces a Doppler radar device to quantify the body movements. The device can convert all body movements into electrical signals, by observing the size and the trajectory of the moving part of the body. The device would help us to improve the manual detection of body movements, and the transformation of movements signal into digital signals.

In our future experiment, all of above approaches/ techniques will be adopted. Three web cameras in the lab can be used to monitor the testing participant. The EEG and Eye-Gaze systems will be the main equipments we are going to explore for this project.

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