Understanding Conceptual Design Activities: Extended Axiomatic Theory of Design Modeling and Physiological Experimentation

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A thesis
In the Department
of
Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Electrical and Computer Engineering) at
Concordia University
Montreal, Quebec, Canada

August 2016

CONCORDIA UNIVERSITY

School of Graduate Studies

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and submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Understanding Conceptual Design Activities: Extended Axiomatic Theory of Design Modeling and Physiological Experimentation

Thanh An Nguyen, Ph.D.
Concordia University, 2016

Conceptual design is an early and critical phase of a design process. Decisions made in this stage can affect seventy five percent of the manufacturing costs. Therefore, one of the important factors to successful production is to have methods and tools that enable designers to work more effectively during the phase of conceptual design. To build such methods and tools, knowledge of design activities such as nature of the design process and factors affecting design activities is indispensable. The present thesis is a continuing effort to build a science of design which aims to discover knowledge of design activities through formal scientific process. The contribution of the current thesis includes the extended Axiomatic Theory of Design Modelling and methodologies to study design cognition physiologically. In particular, two postulates were added to the Axiomatic Theory of Design Modelling to support its explanatory power which was demonstrated through the interpretation of the impact of sketching on design performance and the occurrence of design fixation. An integrated experimental environment was developed to collect and analyze physiological signals during design processes. From this environment, several experiments recording physiological signals were conducted and findings of electroencephalography, heart rate variability, and skin conductance were reported.

ACKNOWLEDGEMENTS

There was a time…

I asked my supervisor:

“Why do you want to do this research? We do not have the expertise.

Why do you want to do this way? No one has ever succeeded.

Why do you want to choose this path? It is full of uncertainties…”

He replied: “We are seekers, seeking for the truth.”

We choose this research and do it this way because we think it can help us move closer to the truth. The seekers have to accept uncertainty as part of their lives.

This is about **TRUTH**

He asked us to respect….

….ourselves: do not plagiarize, be confident, cultivate the mind and heart, do one’s best and do the right things.

…others, others’ works and others’ ideas: always remember that “if I have seen further, it is by standing on shoulders of giants” (Isaac Newton).

…society and nature: give back, treat others fairly and do not harm.

…science: contribute to the progress of science.

We made mistakes and we probably will make many more mistakes, major or minor, but what’s more important is that we learn from those mistakes and we are always trying to do the right things.

This is about **ETHICS**

His guidance helps me realize the beauty of the universe...The universe is ruled by laws. The laws are predictable enough so that we know the sun rises in the east and sets in the west, day follows night, birth follows death….but, at the same time the laws are so random that we do not know exactly what will happen to us in the next few years, few months, few weeks, or even few days,…It is the beauty of the universe, ordered yet chaotic, rigid yet flexible, simple yet complex….

This is about **BEAUTY**

TRUTH, ETHICS and **BEAUTY,** the three cannot be separated. In searching for the truth, one aims at beauty, the path to beauty can only be discovered by an ethical heart.

I would like to express my gratitude to Dr. Yong Zeng for his supervision during my graduate studies. His guidance has not only focused on technical materials and research but also on different aspects of life. I believe that if it were not him who was my supervisor, I would not be able to complete my PhD thesis. His teaching, encouragement, understanding, patience, and generosity has pushed me through my graduate years. What I have learnt the most from him is his optimistic attitude towards everything in life.

I would like to thank my family for their support and love. My parents have been always supportive and patient. I thank my grandmother for her unconditional love, my brother and my aunt for their company, and Uncle Anh Ngoc Nguyen for his financial support during my first few years in Canada.

I thank all members in Design Lab. I feel very fortunate to know each one of them.

I thank all the students who participated in my experiments. I thank Concordia University and Concordia staffs for providing a very friendly and professional environment that facilitates studies and researches.

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Chapter 1. Introduction

1.1. Conceptual design and the importance of understanding design activities

Conceptual design is the first phase of an engineering design process. "Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems[1], such that this technical system meets the requirements of mankind." (Hubka & Ernst Eder, 1987). An engineering design process is mainly divided into three phases: conceptual design, embodiment design (also known as preliminary design, configuration design, analytical design or layout design) and detail design (Birkhofer, 2011; Hales & Gooch, 2004; Mayer, 2012). In conceptual design, designers identify problems, elicit requirements, generate and evaluate possible design concepts (Pahl et al., 2007). Conceptual design is a very important phase in design process as it has tremendous influence on the manufacturing cost (Ullman, 2010). Although the cost incurred during the design phase constitutes only a fraction of the manufacturing cost (5% in car industry), approximately 50% to 75% of the manufacturing cost is committed[2] at the end of conceptual design phase (Ullman, 2010). The idea is presented in Figure 1.

A recent online survey of 212 CAD users from 31 different countries reveals some negative effects of current computer-aided design (CAD) system on creativity when being used in the early design phase (Robertson & Radcliffe, 2009). Every day, the United States Department of Defense wastes $200 million due to poor design methods, tools and processes (Collopy, 2013). These surveys reinforce the importance of understanding design activities. Understanding design gives

[1] A set of orderly interacting elements with properties not reducible to the properties of the individual elements, and designed to perform some useful functions (Salamatov, 1996).

[2] Committed cost is cost that will incur in the future based on current decisions and is difficult to change (Drury, 2008)

us a foundation to improve the current design practice as well as to develop design tools and design methods to help designers create quality design solution effectively and efficiently.

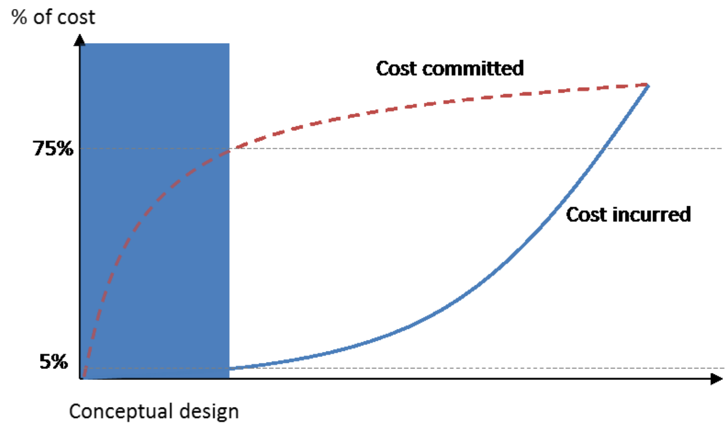


Figure 1. High percentage of cost committed at the end of the conceptual design phase.

1.2. Research objectives

This work is a continuing effort to establish a science of design (Zeng, 2002; Zeng, 2004b). Cross defined science of design as “body of work which attempts to improve our understanding of design through ‘scientific’ (i.e., systematic, reliable) methods of investigation.” In short, science of design is the study of design, a scientific discipline where the main goal is to understand design.

Shneider proposed that a scientific discipline is developed through four main stages (Shneider, 2009). At stage one, objects of study are identified and new language is introduced. Mistakes, imprecision and uncertainty are the characteristics of this stage. At stage two, methods and techniques for investigation of the subjects are introduced. This is the stage where the language of the subject is refined. At stage three, most of important and useful knowledge constituting the discipline is generated in this stage. Finally, the last stage is to carry on the knowledge and focus on application. The four evolutionary stages are depicted in Figure 2.

Ironically, despite a large amount of knowledge and number of articles have been published since 1980s after design was regarded as a discipline of study (Cross, 2007), research in design seems to barely sufficiently pass its first stage. Design researchers use different terms to describe the same concept and develop different models that indeed share common properties (McMahon, 2011). This lack of agreements is due to the absence of an accepted fundamental theoretical foundation.

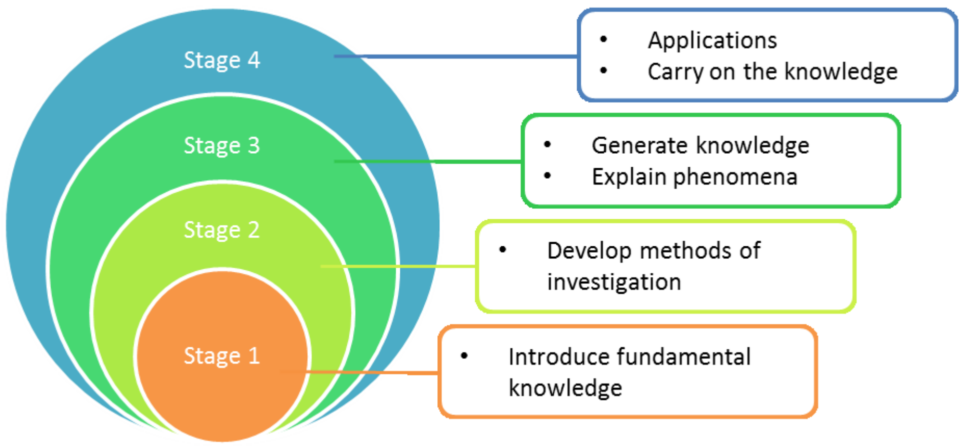


Figure 2. Shneider's four stage development of a scientific discipline.

In an effort to establish a solid foundation for design discipline, Zeng introduced objects of study (Yan & Zeng, 2009; Zeng, 2004b), logic of design (Zeng & Cheng, 1991) and axiomatic theory of design modeling (ATDM) (Zeng, 2002) as reasoning and representation tools (Zeng, 2004a). The present work continues this effort by extending ATDM, showing the application of the theory in understanding design phenomena, and introducing a physiological experimental approach to studying design. The focus is illustrated in Figure 3.

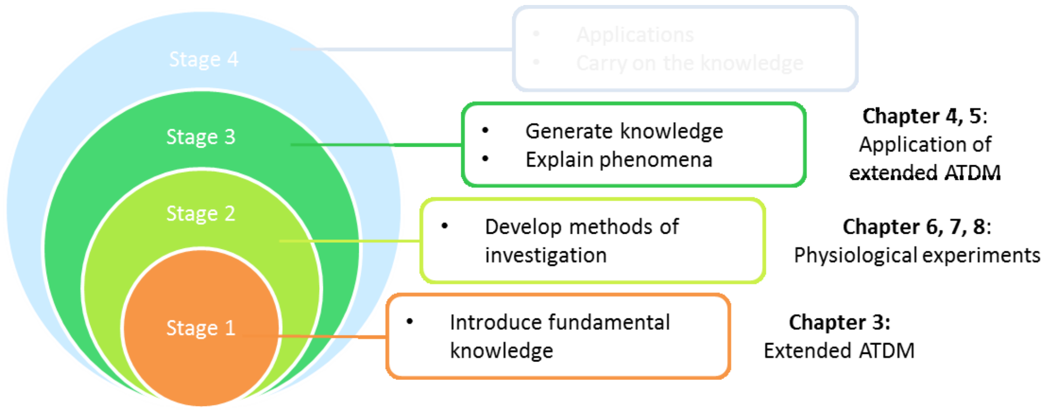


Figure 3. Focus of the present thesis.

1.3. Thesis organization

Chapter 2 introduces the existing works in design theories and existing methods in conducting design research.

Chapters 3, 4, and 5 focus on the introduction to extended ATDM and its application.

Chapter 6 presents a brief introduction to physiological measurement of mental effort and mental stress, focusing on electroencephalography (EEG), skin conductance, and heart rate variability. Chapter 7 shows an initial attempt to use physiological signals to study design cognition.

Chapters 8 and 9 report findings from physiological experiments on design cognition.

Chapters 10 and 11 presents some ongoing studies. Finally, chapter 12 concludes the thesis.

Chapter 2. Literature Review

2.1. Theories of design

2.1.1. General Design Theory (GDT)

GDT based on set theory was proposed by Yoshikawa (Yoshikawa, 1981). Important concept in GDT is the concept of entity from which abstract concept, concept of attributes, concept of morphology and concept of functions are defined. The concept of entity is a notion one has about an entity by actual experience. The abstract concept is a concept of common attributes or functions of a class of entities (topology of the entity concept). The abstract concept includes concept of attribute and concept of function. Design knowledge includes entity concept and abstract concept. In GDT, design specification is represented by the intersection of set of abstract concepts. Design solution is represented by the intersection of sets of attribute concepts. Design specification is usually described in terms of functions. Hence, the designing process is a mapping from a point in the function space to a point in the attribute space.

2.1.2. Function-Behaviour-Structure (FBS)

The FBS framework proposed by Gero (Gero, 1990) represents a model of design process as a group of design activities linking together. FBS models design activities in terms of interactions between function, behaviour and structure. Design knowledge is expressed by the concept of design prototype. A design prototype is a conceptual schema, i.e. a generalized concept derived from experience or similar design cases. A design prototype includes function (F), behaviour (B), structure (S), and (operation) knowledge. A design prototype is the starting point of a design process. Initial design prototype may contain more of function and behaviour; final design prototype has more details on structure. Design process is mainly the process of retrieval and transformation of design prototypes. To address the dynamic context of design (i.e. design is different under different perspectives), the author extends FBS to situated FBS (Gero & Kannengiesser, 2002; Gero & Kannengiesser, 2004). In the situated FBS, aside from the existing elements in FBS, the authors propose three types of environments: external world, interpreted world and expected world, where the interactions between F, B and S occur. In other words, situated FBS accommodates knowledge of environment to the model.

2.1.3. Axiomatic Theory Of Design Modelling (ATDM)

ATDM proposed by Zeng Zeng (2002) introduces mathematical representations of design objects and their relationships. The ATDM enables researchers to use mathematical operation on design objects to derive formal representations of design activities. In particular, a formal representation of design process, named design governing equation, was derived using ATDM and the recursive logic of design. This design governing equation implies a nonlinear chaotic dynamics which has similar characteristics with a creative process.

2.1.4. Concept-Knowledge (CK)

C-K theory proposed by Hatchuel and Weil (Hatchuel & Weil, 2003) describes designing as a process of expanding concept (C) and/or knowledge (K) spaces. The K space is a set of statements that are either true or false and the C space is a set containing statements that are neither true nor false. In short, the K space contains knowledge of known objects or known relations between objects and the C space contains unknown objects. Under this definition, design solution belongs to K space and design requirement belongs to C space. Even though the C-K theory appears to be able to describe any design activity, the description requires substantial inputs of one's own interpretation and assumption.

2.1.5. Limitations

All of the above theories are mainly descriptive and lack explanatory power. For C-K theory, although it claims to be able to interpret design phenomena, the interpretation is highly abstract that it does not give much insights into the design process.

2.2. Empirical methods for studying design

2.2.1. Protocol analysis

Protocol analysis is the most popularly used empirical method in design cognition (Cross, 2006). "Protocol analysis is a set of methods for obtaining reliable information about what people are thinking while they work on a task." (Austin & Delaney, 1998). Although the word "protocol" means recording of subject's output or behaviors such as documents, drawings, verbal data, body movement etc. (Akin, 1979), the primary focus of protocol analysis is verbal data. It seems to be the most reliable way to know what a person is thinking by asking him/her to verbalize his/her thoughts. There are two methods of collecting verbal protocol: concurrent protocol and retrospective protocol. In concurrent reporting, subjects are instructed to think-aloud (i.e. to verbalize his thought) while working on a task. In retrospective reporting, after completing the design subjects are asked to recall their thought during the process. Some research work combines the two approaches (Chandrasekera *et al.*, 2013). The conventional protocol analysis, which focuses on the study of individual, has been extended to study design team under assumption that communication between team members reflects their thinking (Cross *et al.*, 1997).

According to (Cross*, et al.*, 1997), Eastman (Eastman, 1968) is the first who uses protocol analysis to study design activities. Since then, the use of protocol analysis in design research has been increasing rapidly particularly after the Delft Protocol Workshop (Cross*, et al.*, 1997; Jiang

& Yen, 2009). A review of protocol analysis in design research can be found in (Jiang & Yen, 2009).

Limitation of protocol analysis is if we only rely on verbal data, we lack data of nonverbal thinking, which is inherent in engineering design (Ferguson, 1977; Schön & Wiggins, 1992). Examples of nonverbal thinking can be perception or simply an image of an object in mind. Although one can argue that we can always describe an object in our mind, in practice the image can be very vivid and details and a lot of thinking has been done but these thoughts are not verbalized completely. The following protocol is excerpted from (Schön & Wiggins, 1992):

"She begins sketching in section, saying, "Maybe it's arched, and it's open, and it gets light in at the end. Or it's a very tall truss (sketches truss) that somehow moves up into the space, so that it becomes a focus for all of these parts. Maybe that truss could even move out (sketches a five foot displacement of the truss), just for a portion. And then take a flat roof off of it (sketches roof). We'll get some stories into it""

From the subject's verbal protocol, we do not know exactly what designer perceives in his/her mind. Is the verbal thinking or nonverbal thinking dominant? What we get is a very limited information of the object. In order words, verbal protocol data is an expression of what is going on in the mind. In the case of nonverbal thinking, the expression may not be as close to the thinking as in the case of verbal thinking. Therefore, verbal protocol is usually complementary by other protocols such as writings, sketches. A method of capturing the image knowledge which cannot be appropriately verbalized is given in (Yan & Cheng, 1992).

Another limitation of protocol analysis is in the data processing and data analysis. It is labour-intensive and time-consuming. Transcription alone, not to mention segmentation and coding, can take 6 to10 hours for an hour of video (Allen, 1989; Chi, 1997). Various software has been developed to assist researchers (Sarkar & Amaresh, 2007) and the time taken has been reduced to half (Sarkar & Amaresh, 2007).

Despite all the limitations, research on protocol analysis technique continues to thrive. Protocol analysis tool and coding schemes have been developed (Gero *et al.*, 2011; Pourmohamadi & Gero, 2011) and segmentation procedure is proposed to ensure the reliability of the data (Perry & Krippendorff, 2013).

2.2.2. Physiological experiment

In recent years, there is a growing interest in using physiological signals to study designer's thinking in design research community even though experimental studies of neurological basis of design activities has dated back to 1997. Goel and Grafman studied patients who had frontal lobe lesion and showed that impaired prefrontal cortex compromised the skills for ill-structured representations and computations (Goel & Grafman, 2000; Goel *et al.*, 1997). The first reported experiment using electroencephalography (EEG) to investigate design thinking was run by Göker (Göker, 1997). Göker studied the differences in regional brain activation between expert and novice designers in an object assembly task. The subjects were divided into 2 groups: 5 experts and 6 novices. The experts were subjects who knew already all the objects, the objects' functions and configurations before the test began. The study showed that the activity of visual area (right parietal region) lasted longer in the experts whereas the verbal-abstract area (left parietal region) lasted longer in the novices. The author concluded that for this particular test, experts seemed to rely on visual experience whereas novices solved the problem through reasoning.

In 2009, Alexiou *et al.* (2009) published a preliminary fMRI study of design cognition, exploring the possibility of using brain imaging in design research. One year later after the first report, they showed that the right dorsolateral prefrontal cortex was significantly more active during designing than during problem solving (Gilbert *et al.*, 2010). This implies the important role of this prefrontal cortex in design cognition, which can be related to problem structuring (Goel & Grafman, 2000). In the same year, we presented a pilot study of EEG in a design conference (Nguyen & Zeng, 2010).

From 2011, there has been a growing interest in adopting biological mechanism to study design activities. Researchers called for the use of physiological measurement in the science of design (Balters & Steinert, 2015; Steinert & Jablokow, 2013). Besides, some preliminary results have been reported such as how mental stress — measured by heart rate variability — is distributed throughout a design process (Nguyen *et al.*, 2013), how eye tracker helps study engineers' behaviors during analysis of technical systems (Matthiesen *et al.*, 2013). The most recent achievement is the automated segmentation of design process based on EEG transient microstates (Nguyen *et al.*, 2015a; Nguyen *et al.*, 2015b).

Chapter 3. Extended ATDM

3.1. The original ATDM and its limitation

3.1.1. A reasoning and representation tool

The axiomatic theory of design modeling (ATDM) developed by (Zeng, 2002) is a design theory to model design activities. The theory includes two groups of axioms: axioms of objects and axioms of human thought. The axioms of objects lay a foundation for the development of mathematical reasoning and representation of design activities whereas the axioms of human thought constitute the principles of the theory and addresses the nature of human thought process

Mathematical operators in ATDM are equality (=), union ($\cup$), intersection ($\cap$), relation ($\otimes$), and structure ($\oplus$). The structure ($\oplus$) is an important operation and is defined as the union ($\cup$) of an object and the relation ($\otimes$) of the object with itself:

$$\oplus O = O \cup (O \otimes O), \tag{1}$$

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

The structure operator provides a means to represent the structure of an artefact being designed during the design process without prior knowledge of its actual structure. It puts the known and the unknown into the same representation framework.

Due to the capacity of human cognition and scope of applications, a group of primitive objects can always be defined as (Zeng, 2002; Zeng, 2008):

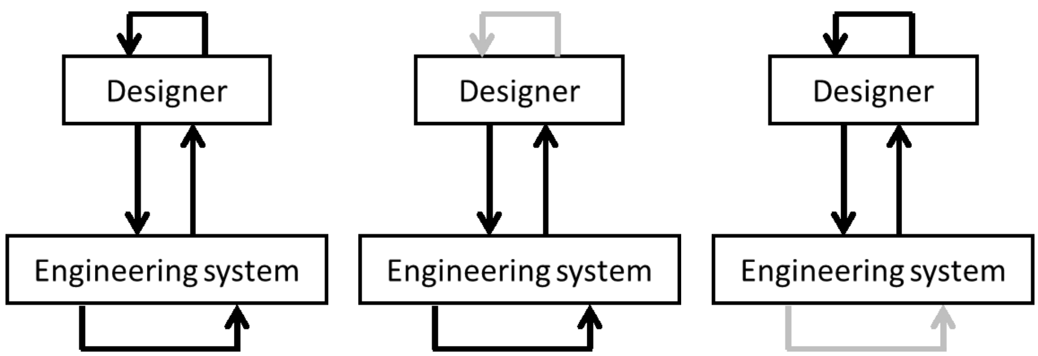
$$\oplus O_i^a = O_i^a, \exists n, i = 1, \dots, n, \tag{2}$$

where $\mathrm{O_i^a}$ is a primitive object that cannot or need not be further decomposed and n is the number of primitive objects.

Mathematically, ATDM is different from set theory in that there is no generalization hierarchy; hence, membership operation ($\in$) does not exist anymore. The benefit of eliminating the membership operation is the capability to represent the unknown design information. This is critical for creative design in that structure of design solutions are often new and thus cannot be represented in a previously defined structure.

3.1.2. Objects of study

From ATDM, the objects of study in design research are identified (Zeng, 2002). They are designers, engineering system which consists of product and environment, and their interactions, as shown in Figure 4(a).



(a) (b) (c)

Figure 4. Objects of study.

3.1.3. Limitation

ATDM was showed to successfully formulate design knowledge, requirements and design process for deductive reasoning as well as for software use (Zeng, 2001). Nevertheless, it is unclear how ATDM explains various phenomena in design and its explanatory power seems to be limited to the evolution of design states (Figure 4b). The role of designers' cognition in the design process, as shown in Figure 4(c), is not directly addressed in the original ATDM.

3.2. Extended ATDM

To clarify the thinking process and design activities in ATDM, the following two postulates are introduced:

Postulate of nonlinear design dynamics: Design reasoning follows a nonlinear dynamics which may become chaotic.

Postulate of designer's stress-creativity relation: Design creativity is related to designer's mental stress through an inverse U shaped curve.

3.2.1. The postulate of nonlinear design dynamics

The following design governing equation was introduced in (Zeng, 2004a; Zeng & Gu, 1999; Zeng & Jin, 1993; Zeng *et al.*, 2004b):

$$\oplus E_{i+1} = K_i^s\left(K_i^e(\oplus E_i)\right) \tag{3}$$

where E_i is the design state i, K_i^e is the evaluation operator and K_i^s is synthesis operator or solution generation. Eq.(3) models the recursive logic of design. The equation describes design as a recursive process in which the current design state E_{i+1} is determined by its previous design state E_i through synthesis K_i^s and evaluation K_i^e operators. Figure 5 shows a graphical presentation of Eq.(3).

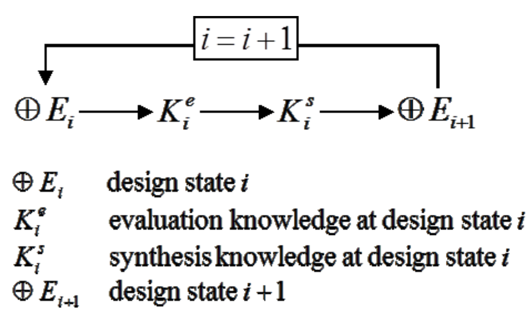


Figure 5. Recursive interdependence between design problem, design solutions and design knowledge (Nguyen & Zeng, 2012).

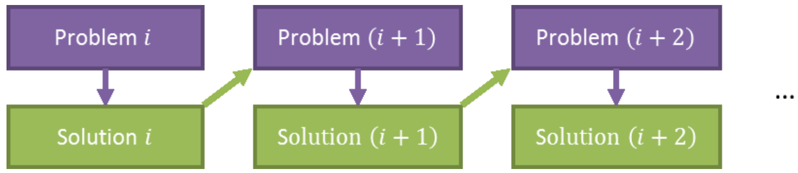


Figure 6. A co-evolutionary process of design problem and design solution.

Eq.(3) can be further formulated as

$$\oplus E_{i+1} = K_i^s\left(K_i^e(\oplus E_i)\right) = D^i(\oplus E_i). \tag{4}$$

In Eq.(3), the synthesis operator K^s and the evaluation operator K^e are interdependent: the synthesis operator K_i^s is defined in terms of the outcome generated from the evaluation operator K_i^e which is in turn determined by the solution formed by the synthesis operator K_{i-1}^s of the previous design state. The function D^i is nonlinear. Furthermore, the synthesis process K_i^s, responsible for proposing a set of candidate solutions based on the design problem, acts like the stretching operator in chaotic dynamics to expand the state space of design. The evaluation process K_i^e, screening candidate solutions against design requirements, acts like a folding operator in chaotic dynamics to shrink and adjust the state space of design.

Therefore, the design process has an underlying nonlinear dynamics with stretching and folding operators, which are major necessary conditions for a dynamical system to have chaotic motions. This leads to the postulate of nonlinear design dynamics which is stated as follows

Postulate of nonlinear design dynamics: Design reasoning follows a nonlinear dynamics which may become chaotic.

3.2.2. The postulate of designer's stress-creativity relation

Postulate of designer's stress-creativity relation: Design creativity is related to designer's mental stress through an inverse U shaped curve.

The second postulate is proposed based on the inverted U model (also called Yerkes-Dodson law) of the relationship between arousal and performance (Yerkes & Dodson, 1908). It implies that designer's creative ability is at best when his/her mental stress is at medium level as depicted in Figure 7.

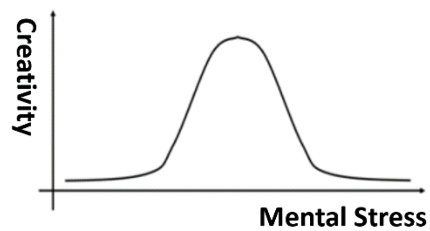


Figure 7. Inverted U model between creativity and mental stress.

We assume that the designer's mental stress is associated positively with external workload and inversely with designer's mental capability. The relationship can be described as:

$$Mental\ stress = \frac{Workload}{Mental\ capability}. \tag{5}$$

Workload can be defined as an external load assigned to a person whereas mental capability is the person's ability to handle the external load at that time. The same workload may trigger different mental stresses in different individuals and trigger different mental stresses for the same individual under different circumstances.

Mental capability includes knowledge, skills and affect[3]. Knowledge is "data and/or information that have been organized and processed to convey understanding, experience, accumulated learning, and expertise as they apply to a current problem or activity" (Rainer & Cegielski, 2010). Although there are other definitions of knowledge (Rowley, 2007), the definition of knowledge proposed in (Rainer & Cegielski, 2010) is chosen because it fits in the current

[3] Some of these proposed factors have also been discussed by other researchers such as Chakrabarti (Chakrabarti, 2006), McKim 1980 (McKim, 1980), Perkins (Perkins, 1988), and Torrance (Torrance, 1965). They consider motivation, knowledge and flexibility in thinking as the most influential factors in creativity.

context. Skills refer to the thinking styles, thinking strategy or reasoning methods. With skills, knowledge can be expanded and the right knowledge can be identified to solve problems. Affect refers to emotions and any mental states associated with feeling (Salovey & Sluyter, 1997). Affect is determined by personality, attitude, belief, motive and stress. Affect has impact on how much of one's knowledge and skills can be effectively used in solving problems.

The lack of skills and knowledge for the current design problem may increase mental stress and the emotional state of designer may either impede or facilitate the retrieval of knowledge and skill essential for problem solving.

Knowledge and skills that can be retrieved and used at a specific moment depending on the available cognitive resources and affect. Figure 8 shows the relationship between mental capability, workload and mental stress. Depending on the mental capability, the mental workload which is the workload perceived by an individual can be higher or smaller than the actual workload. The mental workload will then determine the mental stress. The level of mental stress, in turn, affects designer's creativity performance.

Based on the discussions above, it can be inferred that:

(1) Mental capability cannot be viewed in separation of workload. Facing different design problem, a designer could exhibit different mental capability. This is because designer can be very knowledgeable in one design problem but may lack knowledge of another one.

(2) Affect determines how well knowledge and skills can be used in the design process.

(3) When a designer recognizes the complexity and the uncertainty of the problem which is beyond the designer's mental capability, the designer's mental stress will be high. In contrast, when the complexity and/or the uncertainty in the problem perceived by a designer are well below the designer's capability, the designer's mental stress will be low.

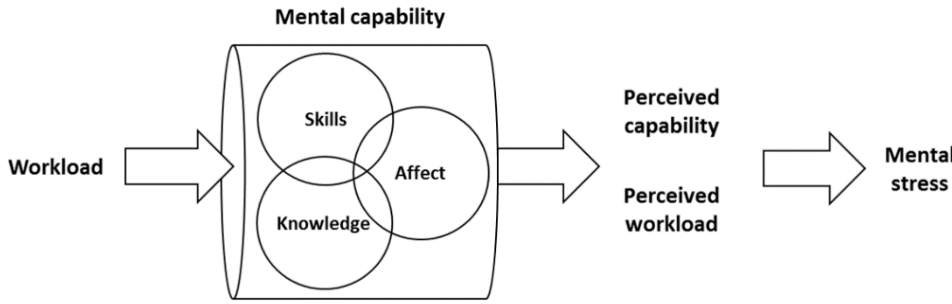


Figure 8. Relation between mental capability, workload and mental stress.

This postulate emphasizes the importance of designer's mental state during the design process (i.e the relation from the engineering system to designer and the relation from designer to itself as shown in Figure 4(c)).

3.3. Interpretation of design phenomena

In the next two chapters, phenomena found in design will be interpreted following four steps:

Step 1 – Introduction to the phenomenon,

Step 2 – Derivation of a theoretical model to answer the research question,

Step 3 – Interpretation of existing research findings using the model.

Chapter 4. Sketching in Design

4.1. Introduction to the phenomenon

Sketching is an important activity in early conceptual design phase. It is a means of communication between designers, serves as a memory aid to free up designer's cognitive load and archives ideas for later refinement. The flexibility of sketching enables designers to quickly capture ideas arising in mind (Goldschmidt, 1991) and sits casualty puts designers in a relaxed state to explore all ideas without imposing judgments (Schenk, 1991). The ambiguity in sketches help designers see different possibilities (Tovey, 1989) whereas drawing helps them restructure and integrate knowledge to arrive at a solution (Römer *et al.*, 2000; Schenk, 1991). In order to take advantage of the benefits of sketching, researchers have developed computerized freehand sketching system to make the process more productive (Company *et al.*, 2009; Soufi & Edmonds, 1996).

In summary, research indicates that sketches play the following main roles in a design process:

(1) Sketches serve as memory aids to relieve cognitive load (Suwa *et al.*, 1998; Ullman *et al.*, 1990; Zeng *et al.*, 2004a).

(2) Sketches serve as stimuli to trigger knowledge required by the design process (Ellen Yi-luen & Mark, 1996; Goel, 1995; Goldschmidt, 1994; Schön, 1983; Yang, 2009).

(3) Sketches serve as a medium to facilitate communication between designers.

Given the importance of sketching in design, the question is raised as follows: how do sketches and sketching influence design performance, including design creativity? In the next section, a model will be proposed to explain the role of sketches and sketching in design.

4.2. Theoretical model

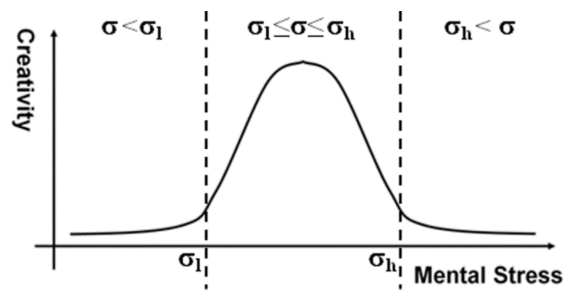


Figure 9. Level of mental stress.

It can be assumed that the mental stress, denoted by σ, can be divided into three levels: low, medium and high as shown in Figure 9:

$$\sigma < \sigma_l,\ \sigma_l \leq \sigma \leq \sigma_h,\ \sigma > \sigma_h. \tag{6}$$

Suppose that the mental stress before and after sketching are σ_o and σ_u, respectively. Three possibilities exist: after sketching mental stress increases ($\sigma_u > \sigma_o$), decreases ($\sigma_u < \sigma_o$), or unchanged ($\sigma_u = \sigma_o$).

Assume that information being processed is stored in the working memory. Let $g(C_o)$ and $g(C_u)$ be the workload of a problem before and after sketching.

In design, sketch serves as a memory aid (let mental stress in this case be denoted by σ_u^m) or a stimulus to provoke synthesis knowledge (mental stress is denoted by σ_u^s). Sketch can also provoke evaluation knowledge (mental stress is denoted by σ_u^e). The following rules are proposed:

When sketch serves as a memory aid, cognitive load reduces and mental stress decreases:

$$\sigma_u^m < \sigma_o, \forall \sigma_o. \tag{7}$$

When sketch activates synthesis knowledge that is necessary for generating solution, mental stress decreases:

$$\sigma_u^s \leq \sigma_o, \forall \sigma_o < \sigma_h. \tag{8}$$

When sketch activates evaluation knowledge that makes the workload of the problem increase substantially, mental stress increases:

$$\frac{g(C_u)}{g(C_o)} > \delta \rightarrow \sigma_u^e > \sigma_o, \forall \sigma_o < \sigma_h, \tag{9}$$

where parameter δ is a cognitive threshold value, which decides whether σ_u^e is lower or higher than σ_o.

On the other hand, if the evaluation knowledge reduces the workload of the problem, mental stress decreases:

$$\frac{g(C_u)}{g(C_o)} \leq \delta \rightarrow \sigma_u^e \leq \sigma_o, \forall \sigma_o < \sigma_h. \tag{10}$$

When mental stress is high, we believe that the only purpose of sketching is to help release cognitive load. Because all cognitive resources are heavily overloaded, not enough working memory is left for other functions of sketch. Therefore, except Eq.(7), other equations (i.e. Eq.(8), Eq.(9) and Eq.(10)) requires stress input to be low or medium (i.e. $\sigma_o < \sigma_h$).

Furthermore, since sketch can assume different functions simultaneously, the output mental stress σ_u can be treated as an aggregation of σ_u^m, σ_u^s and σ_u^e. For the sake of simplicity, σ_u is taken as the sum of σ_u^m, σ_u^s and σ_u^e, as shown in Eq.(11).

$$\sigma_u = \sigma_u^m + \sigma_u^s + \sigma_u^e. \tag{11}$$

It should be noted that designer's performance is determined by the mental stress σ_o. For instance, if mental stress σ_o is high and decreases, a reduction in mental stress may help increase performance because mental stress moves towards the optimal level, as illustrated in Figure 10. Figure 10, Figure 11 and Figure 12 show possible scenarios in which sketch and sketching may cause mental stress to increase or decrease.

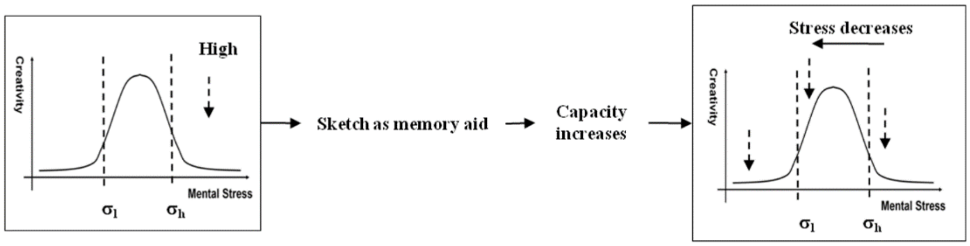


Figure 10. The effect of sketching when mental stress is high.

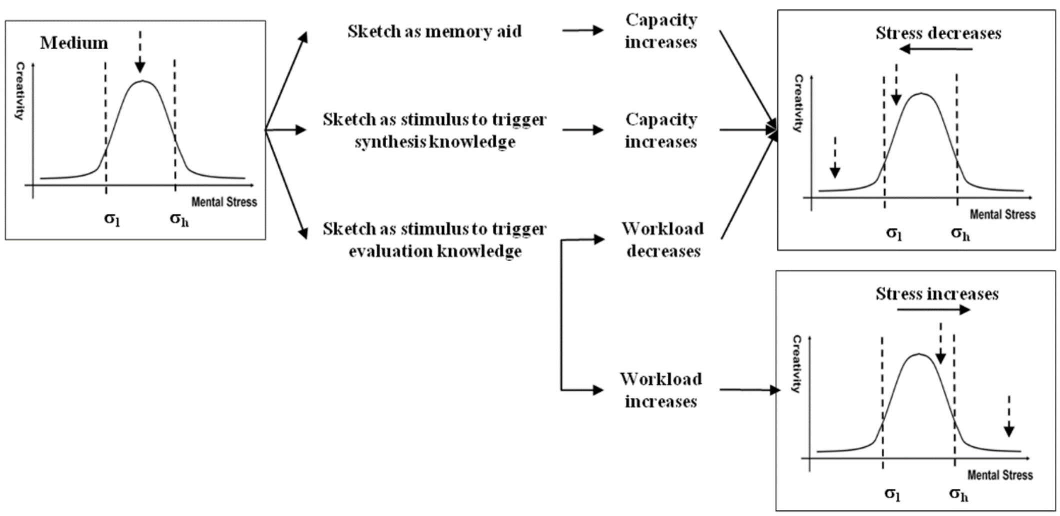


Figure 11. The effect of sketching when mental stress is medium.

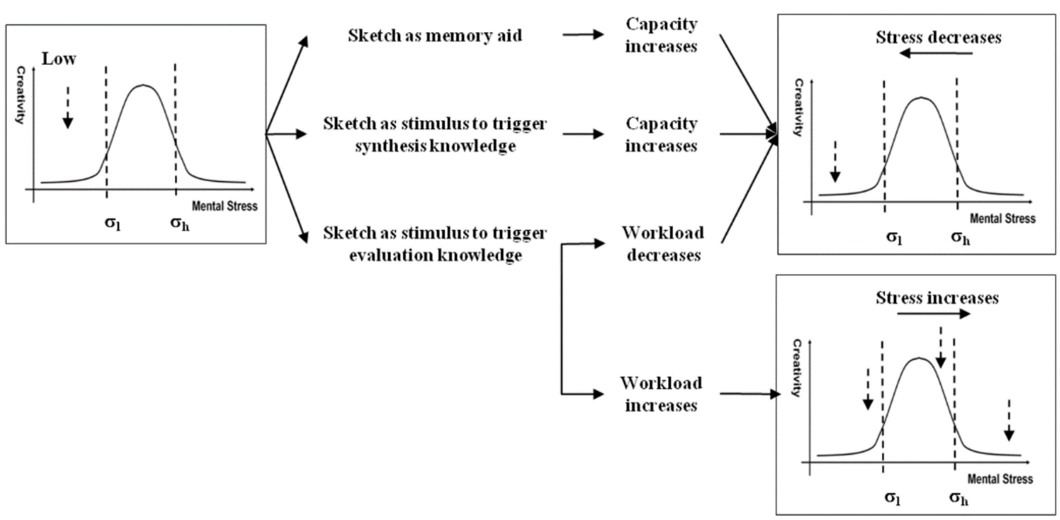


Figure 12. The effect of sketching when mental stress is low.

4.3. Interpretation of phenomena

4.3.1. The impact of ambiguity in sketches on design

Experiment: twenty one expert designers and twenty one novice designers were asked to create design concepts from sketches of different levels of ambiguity (Tseng & Ball, 2011).

Finding 1: experts generates more concepts than novices.

Interpretation: let an ambiguous sketch be denoted by S_0. For S_0 is ambiguous, it can be assumed that it has m substances: $S_{0k}, k = 1,2, \dots, m$. According to the ATDM,

$$S_0 = \oplus \left(\cup_{k=1}^{m} S_{0k}\right) = \left(\cup_{k=1}^{m}(\oplus S_{0k})\right) \cup \left(\cup_{k=1}^{m} \cup_{\substack{l=1 \\ l \neq k}}^{m}(S_{0k} \otimes S_{0l})\right). \tag{12}$$

According to EBD, sketch is part of evolving environment structure $\oplus E$ during the design process. Let $\oplus E_i$ be the environment system before a sketch is generated, then the updated environment system $\oplus E_{i+1}$ after the sketch is generated can be represented as:

$$\oplus E_{i+1} = \oplus (E_i \cup S_0) = (\oplus E_i) \cup (\oplus S_0) \cup (E_i \otimes S_0) \cup (S_0 \otimes E_i). \tag{13}$$

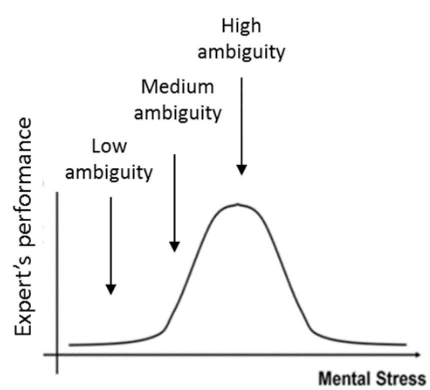
Eq.(13) determines what is going to happen in the next step of the design and the m components included in S_0 in Eq.(12), implies many possibilities for the next move. Needless to say, the more substances the ambiguous sketch can stimulate (i.e., large m), the more possible different moves there will be. Therefore, different design ideas can be resulted from the ambiguity of sketches.

Let m_e and m_n be the number of substances that can be realized by the experts and novices from the m substances ($m_e < m,\ m_n < m$), respectively. Since experts' capability is higher than the novices' capability, experts can realize more substances than novices can: $m_n < m_e$.

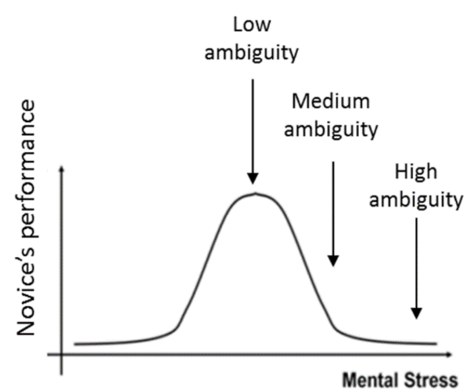
Thus, according to Eq.(12) and Eq.(13), there are more possible moves for experts than for novices, which may result in more number of design solutions.

Finding 2: the number of ideas generated by experts increased with the increasing levels of ambiguity in sketch whereas the number of ideas generated by novices decreased as the level of ambiguity increased.

Interpretation: as the ambiguity of sketch increases, the possible number of environment system $\oplus E_{i+1}$ increases, which means the workload increases. Recall that stress and performance is inverse U related and $stress = \frac{workload}{capability}$. As workload rises, stress rises. Because experts' capability is high, their stress level may initially locate on the left side of the inverse U curve as depicted in Figure 13(a). Hence, when ambiguity of sketch increases, stress increases and performance gets better. On the contrary, novices' capability is low, their stress level may initially locate on the right side of the inverse U curve as illustrated in Figure 13(b).



(a)



(b)

Figure 13. Expert's vs Novice's performance at different levels of ambiguity due to difference in capability.

4.3.2. The impact of sketching and non-sketching on design

Experiment: six award-winning expert architects participated in the control and blindfolded design sessions (Bilda & Gero, 2006). Design task in the control session is to design a house for two artists, in the blindfolded session is to design a house for a couple with five children. Each design session lasts 45 minutes and is one month apart. Half of the participants were assigned to the control session first and half were assigned to the blindfolded session first. In the blindfolded session, the participants were given 5 minutes at the end of the session to sketch the solution on paper.

Finding: no difference in quality of design solutions and distribution of cognitive activities between expert architects who are allowed to sketch and those who are not allowed to sketch (Bilda & Gero, 2006).

Interpretation: assume that expert architect 1 (EA1) is allowed to sketch whereas expert architect 2 (EA2) is not allowed to sketch. Let σ_{o_sk} and σ_{o_nsk} be initial mental stress of EA1 and EA2, σ_{u_sk} and σ_{u_nsk} be average mental stress of EA1 and EA2 caused by sketching.

Assume that both architects have similar mental capabilities and the workload induced by the problems in both sessions is similar. That is to say,

$$\sigma_{o\_sk} \approx \sigma_{o\_nsk} \approx \sigma_o \tag{14}$$

According to Eq. (7), sketching can decrease mental stress by reducing cognitive load:

$$\sigma_{u\_sk}^{m} < \sigma_o \tag{15}$$

So, without sketching, mental stress may increase due to high cognitive load

$$\sigma_{u\_nsk}^{m} \geq \sigma_o \tag{16}$$

Hence,

$$\sigma_{u\_nsk}^{m} \geq \sigma_{u\_sk}^{m} \tag{17}$$

Let $\sigma_{u\_nsk}^{m} - \sigma_{u\_sk}^{m} = \varepsilon$, we have $\varepsilon \geq 0$.

Let the average mental stress triggered by the effects of sketch (in the case when the designer is allowed to sketch) on synthesis and evaluation be denoted by $\sigma_{u\_sk}^{s}$ and $\sigma_{u\_sk}^{e}$, respectively. Then

$$\sigma_{u\_sk} = \sigma_{u\_sk}^{m} + \sigma_{u\_sk}^{s} + \sigma_{u\_sk}^{e} \tag{18}$$

Let the average mental stress triggered by the effects of mental image (in the case when the designer is not allowed to sketch) on synthesis and evaluation be denoted by $\sigma_{u\_nsk}^{s}$ and $\sigma_{u\_nsk}^{e}$. Then

$$\sigma_{u\_nsk} = \sigma_{u\_nsk}^{m} + \sigma_{u\_nsk}^{s} + \sigma_{u\_nsk}^{e} \tag{19}$$

Because design performance was similar, average mental stress can either be the same (Eq.(21)) or very high in one session and very low in the other session (Eq.(20)). According to the analysis, some participants in the non-sketching session were frustrated because they found it difficult not to sketch.

$$\sigma_{u\_sk} < \sigma_{l} < \sigma_{h} < \sigma_{u\_nsk} \tag{20}$$

$$\sigma_{u\_sk} \approx \sigma_{u\_nsk} \tag{21}$$

If $\sigma_{u\_sk} < \sigma_{l} < \sigma_{h} < \sigma_{u\_nsk}$, we have

$$\sigma_{u\_sk}^{m} + \sigma_{u\_sk}^{s} + \sigma_{u\_sk}^{e} \ll \sigma_{u\_nsk}^{m} + \sigma_{u\_nsk}^{s} + \sigma_{u\_nsk}^{e} \tag{22}$$

which means that without sketching, the designers experienced high cognitive load, had difficulty generating solutions and evaluating solutions.

If $\sigma_{u\_nsk} \approx \sigma_{u\_sk}$, we have

$$(\sigma_{u\_nsk}^{m} - \sigma_{u\_sk}^{m}) + (\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) + (\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) = 0 \tag{23}$$

Hence,

$$\varepsilon + (\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) + (\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) = 0 \tag{24}$$

There are four possibilities for Eq.(24) to hold true:

Possibility 1: $\varepsilon \approx 0$, $\sigma_{u\_nsk}^{s} \approx \sigma_{u\_sk}^{s}$ and $\sigma_{u\_nsk}^{e} \approx \sigma_{\mathrm{u\_sk}}^{e}$.

- $\varepsilon \approx 0$: Stress caused by non-sketching activity was very small.

- $\sigma^{s}_{u\_nsk} \approx \sigma^{s}_{u\_sk}$, $\sigma^{e}_{u\_nsk} \approx \sigma^{e}_{u\_sk}$: Sketch and mental image triggered similar synthesis and evaluation knowledge.

This is the case where the problem is relatively easy for the architects.

Possibility 2: $\varepsilon \approx 0$ and $(\sigma^{s}_{\text{u\_nsk}} - \sigma^{s}_{\text{u\_sk}}) + (\sigma^{e}_{\text{u\_nsk}} - \sigma^{e}_{\text{u\_sk}}) \approx 0$, $\sigma^{s}_{\text{u\_nsk}} \neq \sigma^{s}_{\text{u\_sk}}$, $\sigma^{e}_{\text{u\_nsk}} \neq \sigma^{e}_{\text{u\_sk}}$

- $\varepsilon \approx 0$: Stress caused by non-sketching activity was very small, which means the problem was not difficult for the architects.
- $\sigma^{s}_{u\_nsk} + \sigma^{e}_{u\_nsk} \approx \sigma^{s}_{u\_sk} + \sigma^{e}_{u\_sk}$

  $$\Rightarrow \begin{cases} \sigma^{s}_{u\_nsk} > \sigma^{s}_{u\_sk} \\ \sigma^{e}_{u\_nsk} < \sigma^{e}_{u\_sk} \end{cases} \text{(Case 1) or } \begin{cases} \sigma^{s}_{u\_nsk} < \sigma^{s}_{u\_sk} \\ \sigma^{e}_{u\_nsk} > \sigma^{e}_{u\_sk} \end{cases} \text{(Case 2)}$$

Case 1:

- $\sigma^{s}_{u\_nsk} > \sigma^{s}_{u\_sk}$: Sketch was more effective in activating synthesis knowledge than mental image or sketch triggered more relevant knowledge to solve the problem (i.e. mental capability increased).
- $\sigma^{e}_{u\_nsk} < \sigma^{e}_{u\_sk}$: Sketch activated evaluation knowledge that caused the workload to increase.

Case 2:

- $\sigma^{s}_{u\_nsk} < \sigma^{s}_{u\_sk}$: Mental image activated synthesis knowledge more easily than sketch did.
- $\sigma^{e}_{u\_nsk} > \sigma^{e}_{u\_sk}$: Workload of evaluation in non-sketching task was greater than that in sketching task.

Possibility 3: $\varepsilon + (\sigma^{s}_{u\_nsk} - \sigma^{s}_{u\_sk}) \approx 0$ and $(\sigma^{e}_{u\_nsk} - \sigma^{e}_{u\_sk}) \approx 0$

- $\varepsilon + \left(\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}\right) \approx 0 \Rightarrow \begin{cases} \sigma_{u\_nsk}^{s} < \sigma_{u\_sk}^{s} \\ \varepsilon = \sigma_{u\_sk}^{s} - \sigma_{u\_nsk}^{s} \end{cases}$

  Mental image activated more synthesis knowledge. The difference between $\sigma_{u\_nsk}^{s}$ and $\sigma_{u\_sk}^{s}$ was equal to ε.

- $(\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) \approx 0$: Workload of evaluation in sketching and non-sketching tasks were similar.

Possibility 4: $\varepsilon + (\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) \approx 0$ and $(\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) \approx 0$

- $\varepsilon + \left(\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}\right) \approx 0 \Rightarrow \begin{cases} \sigma_{u\_nsk}^{e} < \sigma_{u\_sk}^{e} \\ \varepsilon = \sigma_{u\_sk}^{e} - \sigma_{u\_nsk}^{e} \end{cases}$

  Workload of evaluation was higher in sketching than in non-sketching session. The difference between $\sigma_{u\_nsk}^{e}$ and $\sigma_{u\_sk}^{e}$ was equal to ε.

- $(\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) \approx 0$: Sketch and mental image triggered similar synthesis knowledge.

From the analysis of the experiment, Bilda and Gero (2006) noticed that one significant difference between sketching and non-sketching sessions was participants in the blindfolded session recalled more knowledge than in the control session. Therefore, it is more likely case 2 possibility 2 or possibility 3 is the reason for similar design performance in sketching and non-sketching sessions.

In summary, design performance was similar between experts in sketching and non-sketching tasks because:

- Average mental stress was very high in non-sketching task and very low in sketching task. This could make design performance similarly low in both cases according to the inverse U curve.

- The design problem was simple. Therefore, whether designers were allowed to sketch or not to sketch did not affect the cognitive load. In addition, it could be easier to generate solutions in non-sketching case but more difficult to evaluate solutions. Thus, average mental stress remained similar to the sketching case.
- Without sketching, cognitive load could be higher in non-sketching session but at the same time it could be easier to generate solutions. Therefore, average mental stress could stay equal to the sketching case.

4.4. Summary

The section showed that the nonlinear design dynamics model and mental stress-creativity relation model could be used to interpret the effect of sketches and sketching on design. In particular, postulate 1 was applied to explain why the ambiguity in sketch can help designers generate different design solutions and postulate 2 was used to explain why the number of ideas generated by experts/novices was positively/negatively related with the levels of ambiguity in sketch and why it was possible that there were no differences in quality of design solutions when sketching was allowed and when sketching was not allowed.

Chapter 5. Design Fixation

5.1. Introduction to the phenomenon

In psychology, fixation is the state in which an individual is attached to a specific idea, setting, or concept (Alexander *et al.*, 2010). In the context of design, fixation is "a blind …adherence to a limited set of ideas" (Jansson & Smith, 1991). It is "an inability to overcome a bias in the interpretation of a situation by transferring knowledge from prior experiences in an inappropriate manner" (Hertz, 1992). The inadequate transferring of knowledge from previous design situation to a current design situation without transformation (Goldschmidt, 2011) is regarded as a failure in updating the meta-representation (Dong & Sarkar, 2011). A meta-representation is a representation of the relation between the represented and the representative. It is the mind's ability to generate different concepts for the same stimuli. Failure to realize a new meta-representation is to not realize new semantics of the represented in a new situation.

Design fixation is found in almost all design fields and design expertise (Jansson & Smith, 1991; Linsey *et al.*, 2010; McLellan & Nicholl, 2011). The problem with design fixation is that it obstructs creative thinking. Designers who fixate on an existing idea tend to generate solutions similar to that idea. In order to overcome the negative impact of design fixation, researchers have attempted to understand its causes and mechanisms and have proposed approaches to de-fixating designer's mind.

5.1.1. Causes and mechanisms of design fixation

The tendency of a newly generated product to contain properties similar to existing ones is attributed to structured imagination (Ward, 1994). When people create a novel entity, they refer to existing relevant categories and use imagination to go beyond commonality (Ward, 1994). The structure of the imagination, which is shaped by previously acquired knowledge, is a main factor influencing the performance of idea generation in design (Perttula & Liikkanen, 2006b; Purcell *et al.*, 1993). When one bases the imagination on general information of the category rather than specific information, creativity is more likely to happen (Ward, 1994). This explains why examples that are specific and closely related to the problem cause fixation and hinder creativity whereas distant information results in solutions that are more creative (Bonnardel, 2000; Dahl & Moreau, 2002). The phenomenon is also interpreted as constraints on solution search space, caused by the effect of concrete examples on mental problem representation (Perttula & Liikkanen, 2006a).

From the cognitive load theory point of view, design fixation arises from the substantial occupation of previously known design knowledge and such occupation reduced the designer's mental capability of processing information (Hertz, 1992). Consequently, designers do not have sufficient mental resources to attend to available information. Fixation is also considered as a lack of cognitive iterations between configuration space and concept space (Jansson *et al.*, 1993). The configuration space contains representation of specific entities and the concept space contains knowledge to produce entities in the configuration space. Using similar ideas, C-K describes fixation as a result of spontaneous activation of the knowledge space which triggers a traversal of small branches of the concept space while leaving other branches unexplored (Agogue & Cassotti, 2013).

The study of fixation has been closely linked to the study of memory. The search of associative memory theory describes information stored in memory as cue-dependent, meaning what is retrieved at a time depends on its strength with the cues used to probe the memory (Raaijmakers & Shiffrin, 1980; Tulving, 1974). Thus, fixation is assumed to be caused by the blocking of appropriate knowledge from memory because the associative strength between the target knowledge and the cue is weaker than the association between the inappropriate knowledge and the cue (Smith, 1995b). The blocking is explained by construction of inappropriate memory search plan or by following an improper memory searching path (Sio *et al.*, 2015; Smith, 1995a). Even though the theories of memory address some cognitive aspects of design fixation, they miss some other important cognitive entities such as emotion.

5.1.2. Approaches to overcoming fixation

Researchers propose that fixation can be overcome by exposing designers to a wide range of remote analogies (also known as between-domain stimuli) because the between-domain stimuli is more likely to enable the transfer and mapping of relations rather than properties from the stimuli to the solution (Goldschmidt, 2011; Smith & Linsey, 2011).

Fixation might be avoided if incubation takes place, allowing fixated features to be free from designer's memory (Smith, 1995b) or to be forgotten. In fact, research has suggested that forgetting caused by the act of problem solving and memory retrieval has implications for overcoming fixation (Storm & Angello, 2010; Storm *et al.*, 2011). The forgetting is assumed to be the result of inhibiting irrelevant information during problem solving or memory recall (Storm, *et al.*, 2011). Therefore, a break during a design process or a context change may weaken memory of inappropriate knowledge and give rooms for appropriate knowledge to emerge (Smith, 1995b). Other approaches to minimizing fixation are reformulating problems (Smith & Linsey, 2011; Zahner *et al.*, 2010), training designers, and using de-fixation tools (Goldschmidt, 2011; Howard *et al.*, 2013; McCaffrey, 2012; Youmans & Arciszewski, 2014).

Though a great deal of research has been conducted, no formal model exists yet to interpret phenomena associated with fixation in design. A formal model — a set of presumptions and axioms presented in symbolic terms that are solved analytically or numerically to derive predictions

(Morton, 1999) — of design fixation would provide a mechanism underlying fixation so that interpretations and predictions of fixation can be logically derived. In this paper, we will introduce a theoretical model of design fixation based on the design creativity theory that was proposed in (Nguyen & Zeng, 2012).

5.2. Theoretical model of design fixation

5.2.1. Formal definition of design fixation

As mentioned in the Introduction, design fixation refers to the condition wherein designers use an inappropriate existing design idea to solve a design problem due to their strong attachment to the idea. It can be seen that two concepts are central in design fixation. The first is potential solutions to a design problem whereas the second is the designer's preference for a known solution over other possible solutions.

Assume that for each design problem (or subproblem) a designer encounters, denoted by d, there is a solution space S which includes all possible potential solutions:

$$S = \{s_i | i = 1, 2, \dots, n\}, \tag{25}$$

where s_i is the potential design solution i and n is the number of possible solutions. Theoretically, n can be infinite.

Obviously, for each solution s_i, there is an expected (or real) fitness value r_i to the design problem d such that

$$r_i = g(s_i, d), r_i > 0, \forall s_i \in S. \tag{26}$$

The expected fitness r_i is independent of designer's knowledge. Meanwhile, the designer may have a preference value for each solution. This preference value can be defined by a selection probability p_i, which defines the probability of choosing s_i as a solution to the design problem d.

$$p_i = h(s_i, d), p_i \in [0,1], \forall s_i \in S. \tag{27}$$

Needless to say, the selection probability p_i is determined by the designer's preferences, skills, and knowledge.

Design fixation can be defined as:

$$\exists s_i \in S: p_i > p_j, r_i < r_j, \forall s_i \in S, s_i \neq s_j. \tag{28}$$

Eq.(28) describes a situation where a designer picks a known solution s_i that is less suitable for her/his current design even though s/he is capable of finding a better solution s_j.

The study conducted by Jansson and Smith (1991) can illustrate this concept. In the study, thirty-five mechanical engineering students were randomly divided into two groups and were instructed to design a spill-proof coffee cup. One group was shown an example design that had some design flaws and was instructed not to include these flaws in the solution. Another group (control group) was not shown any example. The result was that the group who viewed the example created more solutions containing similar design flaws than the group who did not view the example. Obviously, the group who viewed the example must have been as capable of avoiding these design flaws as their peers in the control group were. It was the example that had been known to them influenced their solutions. Instead of creating new solution s_j, they ended up creating solution s_i similar to the example even though it is not suitable for the design.

5.2.2. Mechanism leading to design fixation

We have now introduced selection probability p_i and expected fitness r_i. After all, how can we determine the selection probability p_i and the expected fitness r_i?

The expected fitness r_i of a solution s_i can be measured by assessing s_i against complete requirements. Methods on how to find complete requirements have been discussed in (Chen & Zeng, 2006; Wang & Zeng, 2009). It is more challenging to compute the selection probability p_i

because the number of candidate solutions is unknown and the probability of choosing a solution cannot be computed. Therefore, to determine selection probability, the concept of perceived fitness is introduced.

According to the principle of least effort, animal and human naturally choose a path of least resistance or least effort to complete a task (Zipf, 1949). Thus, in order to understand the mechanism leading to design fixation, we need to look into the needed effort associated with each candidate design solution.

It was assumed that mental stress and workload are related as follows (Nguyen & Zeng, 2012; Nguyen & Zeng, 2016):

$$\sigma = \frac{d}{(K+M)\times\alpha}, \tag{29}$$

where σ represents designer's mental stress, d represents workload, K denotes designer's knowledge and experience pertaining to d, M is designer's design related skills; the affect α represents the designer's emotional state or mood. Positive emotions will result in a greater α than negative emotions. The affect α determines how much a designer can retrieve his/her knowledge and skills. Empirical research has demonstrated that positive affect improves working memory (Carpenter *et al.*, 2013), enhance decision making process (Carpenter*, et al.*, 2013; Isen & Means, 1983), facilitate creative problem solving (Hirt *et al.*, 1996) and broaden attention (Rowe *et al.*, 2007). In contrast, negative affect was found to be associated with decreased working memory capacity (Brose *et al.*, 2012) and attention (Brose*, et al.*, 2012). A review of the influence of positive and negative affect on behaviour can be found in (Hayton & Cholakova, 2012; Lyubomirsky *et al.*, 2005).

Recalling the definition of fixation in psychology as an obsession of an idea, concept or context, the designer's attachment to a set of knowledge or to a candidate solution is a kind of affect. This affect would lead the designer to use a specific candidate solution without essential transformation, which is often in the form of fast and effortless intuitive thinking (Kahneman, 2011; Zeng, 1989).

In the meantime, since design is an evolving process in which design problem, design solutions, and design knowledge recursively change each other (Zeng, 1989; Zeng & Cheng, 1991; Zeng & Gu, 1999), different designers would see the same design problem differently. This resulted in a perceived problem d^e related to a design problem d as follows:

$$d^e = \rho(d, K, M, \alpha). \tag{30}$$

As a result, for each solution candidate s_i, there is a perceived fitness value r_i^e to the design problem d:

$$r_i^e = g(s_i, d^e), r_i^e > 0, \forall s_i \in S. \tag{31}$$

It should be noted that the perceived fitness r_i^e is different from the fitness r_i. The perceived fitness r_i^e depends on designer's knowledge and experience as the selection probability p_i does. Hence, the selection probability p_i can be positively correlated with the perceived fitness r_i^e.

Each solution s_i can be associated with a value f_i that measures the discrepancy between the expected fitness and perceived fitness as follows:

$$f_i = \frac{r_i^e - r_i}{r_i^e + r_i} \tag{32}$$

When the perceived fitness r_i^e equals to the expected fitness r_i (i.e. when designers perceive correctly the fitness of the solution s_i), $f_i = 0$. When a solution s_i is perceived as more suitable for the problem than it actually is, $f_i > 0$ and when s_i is an appropriate solution but is not perceived as such, $f_i < 0$.

5.2.3. Paths to design fixation

By substituting Eq.(30) into Eq.(31), we get:

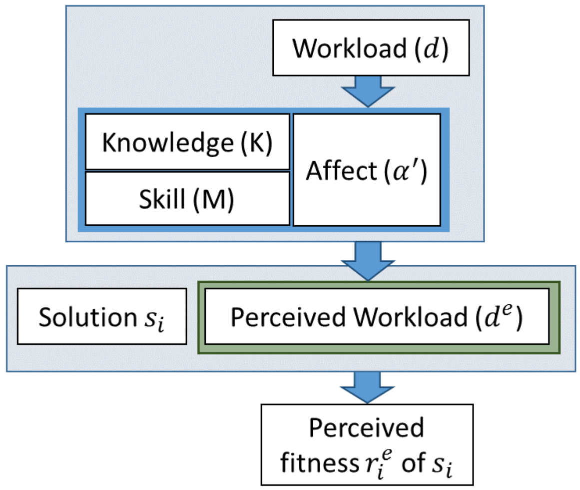
$$r_i^e = g(s_i, d^e) = g(s_i, \rho(d, K, M, \alpha)), r_i^e > 0, \qquad \forall s_i \in S. \tag{33}$$

It can be seen from Eq.(33) that there are three main paths which will lead to high perceived fitness for a design solution:

- First, designers are so attached to a solution s_i that they are unable to abandon s_i or to make major changes to s_i. Viswanathan and Linsey (2011) proposed that one of the causes of this attachment is due to the Sunk Cost Effect, which states that designers are reluctant to change their current solution because of fear of losing resources already being invested.
- Second, designers do not have the right perception of the current requirement $d^e = \rho(d, K, M, \alpha)$.
- Third, designers do not properly execute g, i.e. misjudge the fitness of s_i for the requirement d^e.

5.2.4. Summary

The proposed model is summarized in Figure 14. The perceived fitness is influenced by perceived workload, knowledge, skills, and affect. Affect controls the knowledge and skills that can be retrieved and applied at a time. It should be noted that the stress-workload equation and the perceived fitness equation are intended to describe qualitatively the relationships among variables rather than for the purpose of quantification. For this reason, the actual quantitative formulas may be very different.



$$\sigma = \frac{d}{(K+M)\times\alpha}\ ,\quad r_i^e = g(s_i, d^e) = g\big(s_i, \rho(d, K, M, \alpha)\big)\ ,\quad f_i = \frac{r_i^e - r_i}{r_i^e + r_i}$$

Figure 14. Proposed model of fixation

5.3. Interpretation of phenomena in design fixation

In this section, the proposed model will be used to interpret some research findings in the literature and to derive related hypotheses.

5.3.1. The impact of prototyping and team work on design fixation

Experiment: The experiment conducted by (Youmans, 2011a; Youmans, 2011b) aimed to study how prototyping or teamwork would affect design fixation. One hundred and twenty students participated in the experiment. They were asked to design two tools: one was designed on paper and with prototype (referred to as full environment) while the other tool was designed on paper only (referred to as partial environment). Ninety minutes were given for each task. Sixty out of the 120 participants worked alone whereas the rest formed a team of three. Before the experiment, all participants duplicated the two pre-existing tools, which deliberately contained ten fixation features. Five out of the ten features were design flaws.

Findings: It was found that (a) fixation was lower in prototyping condition. Switching back and forth between physical and mental representations of a potential design reduced the tendency of being fixated on an idea; (b) team created better solution than individual.

Interpretation: As stated in previous section, there are three paths leading to design fixation: attachment to the example, wrong perception of design requirements and ineffective evaluation of solution-requirements. Based on these three paths, Table 1 and Table 2 list scenarios under which a fixation is and is not likely to occur.

Interpretation of finding (a): Through testing the physical model, the fitness of fixated features was identified. Therefore, the perceived fitness moved closer to the real fitness.

Table 1. Prototyping condition

Paths leading to design fixation	**Prototyping: scenarios/reasons for which**	
	fixation is likely to occur	**fixation is not likely to occur**
Attachment to the solution example	Fixated features are easy to prototype Perceived workload of choosing another solution is high. The designer is not willing to give up bad design ideas..	Fixated features are not easy to prototype Perceived workload of choosing another solution is not high. The designer is willing to give up bad design ideas.
Inaccurate perception of the design requirements	N/A	N/A
Poor evaluation of solution-requirements	Prototypes cannot be tested or is not tested properly.	Ideas can be tested properly through prototyping,

Conditions under which fixation may be overcome:

- Prototype can be tested to check if the idea meets requirements.
- Fixated features are not easy to be prototyped.
- Designers should be willing to give up bad ideas.
- The workload of removing the fixated ideas is not too high. For example, if the designers think they do not have enough time or resources to make changes, they will try to stick to the fixated ideas.

Interpretation of finding (b): Team members might all fixate on the same features of the example but team communication helped reveal bad ideas. Alternatively, team member fixated on different features of the example but through team discussion they realized the real fitness of fixated features.

Table 2. Scenarios under which fixation may and may not occur in teamwork

Paths leading to design fixation	Teamwork: scenarios/reasons for which fixation is likely to occur	Teamwork: scenarios/reasons for which fixation is not likely to occur
Attachment to the solution example	Perceived workload of adopting another solution is high.	Attachment to fixated ideas can be lessened due to group pressure if its real fitness is realized. If the workload can be shared among group members, perceived workload of choosing another solution can be low
Inaccurate perception of the design requirements	Team members have false perception of the problem and communication does not change the wrongly perceived problem d^e.	Through effective communication, collective knowledge and skills, perceived problem d^e can approach real problem d.
Poor evaluation of solution-requirements	Communication is ineffective. Team members are intimidated to challenge each other so evaluation is not performed effectively.	If workload is divided among group members, each member may have sufficient cognitive resources, skills and knowledge to do evaluation properly. Through effective communication, evaluation can be done properly.

Conditions under which fixation may be overcome:

- Effective team communication.
- Social loafing (spending less effort when working with group than when working alone) and evaluation apprehension (fear of being criticized) are minimized.
- Workload can be shared among group members.

5.3.2. The impact of periodic interruption on design fixation

Experiment: The experiment by Youmans (2011a) aimed to investigate how interruption in the early stage of conceptual design might affect fixation. Seventy-two students were asked to design a poster in 15 minutes. Before the experiment started, they were shown an example of a poster. In the first 3 minutes of the design process, participants in the interruption condition had to solve math equations every 30 seconds.

Finding: The result showed that participants in the interruption condition had fewer fixations than participants in the control condition.

Interpretation: possible scenarios that may develop under this experimental condition are shown in Table 3. We can assume that when being exposed to examples that were closely related to the design problem, the designer was more likely to use ideas from the examples to solve the task according to the principle of least effort. Being interrupted to perform another mental task forced the designer to temporarily "forget" or "detach from" the examples. After the interruption, the designer retrieved again the design knowledge including the knowledge of the examples to continue the design. There are three possibilities that minimize the fixation effect: 1) the designer could not completely recall the example, 2) the solution example was not used to frame the problem so perception of the design problem became more accurate, and 3) the temporary detachment provided the designer with enough cognitive resources to evaluate the fitness of his solutions.

Conditions under which fixations may be reduced:

- During interruption, designers perform tasks that require them to temporarily "forget" the current design knowledge.
- Interruption is introduced at the early stage of the design process where the workload of changing solutions are perceived low and knowledge of the example have not yet been incorporated into the design.
- Designers are willing to drop inappropriate ideas.

- Knowledge of the examples are not easily recalled.

Table 3. Scenarios under which fixation may and may not occur in periodic interruption condition

Paths	Periodic interruption: scenarios/reasons for which	
	fixation is likely to occur	**fixation is not likely to occur**
Attachment to the solution example	Attachment may not change after interruption if knowledge of the example is easily recalled. Perceived workload of adopting another solution is high. The designer is not willing to give up bad design ideas.	Attachment may be lessened after interruption if knowledge of the example is not easily recalled. Perceived workload of adopting another solution is not high. The designer is willing to give up bad design ideas.
Inaccurate perception of the design requirements	After interruption, perception of design problem does not change.	After interruption, perception of design problem changes and becomes more accurate because the example is not used to frame the problem.
Poor evaluation of solution-requirements	After interruption, the designer tries to recall and reviews all the design knowledge without evaluating.	After interruption, the designer retrieves and evaluates the design knowledge. Without being occupied by the solution example , there is enough cognitive resources to do evaluation properly.

5.3.3. Effect of delay between viewing examples and solving a design task

Experiment: Experiment 1 conducted by Smith *et al.* (1993): 91 participants were asked to generate as many solutions as possible for two design problems. The participants were divided into two groups: example and control. At the beginning of the experiment, the example group viewed two sets of solution examples of the two problems in 180 seconds. Participants had 23 minutes to solve each of the design problems, which means that there was no delay between viewing the example and solving the first design task and there was a 23-minute delay between viewing the example and solving the second design task for the example. Meanwhile, the control group viewed each set of the solution examples immediately before each task. Thus, in the control group, there was no delay between viewing the examples and solving the design problems

Experiment 2 conducted by Marsh *et al.* (1996): two groups of participants viewed the same sets of stimuli. One group (control group) was instructed to solve the problem right after viewing the example and the other group was asked to return the next day.

Findings: In the experiment 1, Smith*, et al.* (1993) reported that fixation tended to decease after a 23-minute delay. In contrast, Marsh*, et al.* (1996) in the experiment 2 found that the 1-day delay group showed more fixation than the control group.

Table 4. Scenarios under which fixation may and may not occur in delay condition

Paths	**Delay: scenarios/reasons for which**	
	fixation is likely to occur	**fixation is not likely to occur**
Perception of design problem	N/A	N/A
Solution-problem evaluation	N/A	N/A
Solution example	Attachment does not change after a delay when knowledge of the example is easily recalled.	Attachment is lessened after a delay when knowledge of the example is not easily recalled.

Interpretation: Table 4 presents scenarios under which fixation is likely and not likely to occur. As in other situations, closely related examples occupied designer's mind and the designer use the example's ideas for the current design task without carefully considering their fitness. The delay helped relieve this occupation so that when the designer returned to the design task, s/he could use less the example's ideas or s/he could gain a better view of the fitness of the example.

One explanation for the decreasing fixation in the 23-minute delay group (compared to control group) is that after the 23-minute task, the designers might feel tired and stressed, which further impeded their performance in memory retrieval. Another explanation is that according to studies on memory, new information needs to undergo through stages of stabilization before being successfully stored in the long term memory (McGaugh, 2000; Müller & Pilzecker, 1900). In particular, the preservation-consolidation hypothesis states that memory of newly acquired information is susceptible to disruption and only becomes hardened over time (Müller & Pilzecker, 1900). Therefore, it is possible that in experiment 1, the 23 minute was too short for memory of the examples to be formed completely. Additionally, during the 23 minutes, the participants had to solve another design problem, which might disrupt the newly formed memory. As a result, participants were not able to remember the examples so they did not show as much fixation as the control group did.

A similar line of explanation can be applied to the experiment 2. The 1-day delay participants showed more fixation than the control group because they were able to start fresh, so they experienced less tiredness and stress. In addition, their memory of the example might have been hardened over a 1-day period, which helped them easily recall the example.

Conditions under which a delay may decrease fixations:

- During the delay, participants perform tasks that cause them to forget the example.
- The examples are not easily recalled.

5.3.4. Hypotheses

We have used the model to derive causes of fixation and give conditions under which fixation may be overcome. From these conditions, we can further derive the research hypotheses listed in Table 5. Hypotheses in the delay condition are similar to some of those in the periodic interruption because delay can be viewed as a special case of periodic interruption where the interruption occurs only once in the beginning of the design task.

Table 5. Hypotheses derived for prototyping, teamwork, periodic interruption and delay conditions

	Hypotheses
Prototyping	On the one hand, prototyping can help reduce fixation compared to traditional pen and paper method because it provides designer a means to evaluate a solution idea. On the other hand, prototypes may contain even more fixated features than sketches because the perceived workload of making change to prototypes may be higher than making changes to sketches. Therefore, *Hypothesis 1:* If prototype cannot be tested, prototyping does not help reduce fixation.
Teamwork	As seen in Table 2, communication and individual's knowledge play important roles in reducing fixations. Therefore, *Hypothesis 1:* effective team communication reduces fixation. *Hypothesis 2:* given that other things are equal, teams consisting of members from diverse backgrounds with different knowledge and skills have less fixation than teams with members from the same background.
Periodic interruption	Interruption temporarily detaches designers from the task and the solution example and may change perception of the design task: *Hypothesis 1:* given that other things are equal, if a designer is more likely to recall the example, she/he is more likely to be fixated. As proposed in the model, retrieval of knowledge is dependent on affect. Thus, *Hypothesis 2*: if a designer is in a negative affective state, she/he is less likely to recall the knowledge of the example. Fixation can be low. *Hypothesis 3:* fixation is higher when the initial interruption is introduced at the later stage of the process because the workload of making changes to fixated ideas can be perceived as too high.
Delay	Fixation still occurs after a delay if a designer is able to recall the example. Hence, *Hypothesis 1*: given that other things are equal, if a designer is more likely to recall the example, she/he is more likely to be fixated. Moreover, affective state impacts knowledge recall. Thus, *Hypothesis 2*: if a designer in a negative affective state, she/he is less likely to recall the knowledge of the example. Fixation can be low.

5.4. Fixation assessment

To further evaluate the model, it is necessary to collect empirical data and compare fixation levels across experimental conditions to refute or confirm hypotheses derived from the model.

Ideally, existing methods of computing fixation are used to avoid reinventing the wheel. However, because the proposed model is developed on the ground of perceived fitness, perceived workload, and mental capability, use of existing methods may not reflect this principle of the model. Therefore, Eq.(32) is proposed to assess the level of fixation in a solution. Eq.(32) can also be used to study the effects of design inspirational sources on design outcome.

5.4.1. Procedure

Step 1: the objective is to identify features of solutions that are similar to a given solution example. The word *features* refers to both functions and structures of the design. Only solutions that have similar features with the solution example are subject to fixation calculation. Step 1 can be further divided into:

- Step 1.1: generate questions by using the environment roadmap (Chen & Zeng, 2006) and ROM-based question asking technique (Wang & Zeng, 2009) which are one of the EBD steps (Zeng, 2011). Then, identify *design features in the solution example* that answer the questions generated.
- Step 1.2: identify *design features in the designer's solution* that address the questions in step 1.1. Compare if these features are similar to the features identified in step 1.1.

Step 2: evaluate the design features found in step 1.2 against the complete design requirements to get the expected fitness. Step 2 includes two sub-steps:

- Step 2.1: find complete design requirements.
- Step 2.2: rate the features in step 1 against the complete requirements.

Step 3: calculate expected fitness. Calculate discrepancy value f using Eq.(32).

5.4.2. Example: a device to shell peanut

The example is taken from Linsey, et al. (2010). The design problem is to build a device that shells peanuts (Linsey, et al., 2010):

Problem description:

"In places like Haiti and certain West African countries, peanuts are a significiant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50kg (110 lbs) per hour.

Customer needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

The example given to participants and solutions generated by participants are shown in Figure 15 and Figure 16.

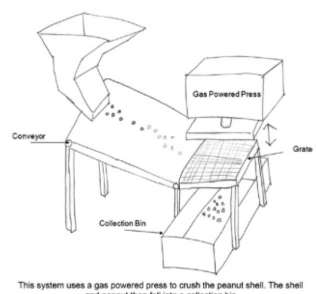
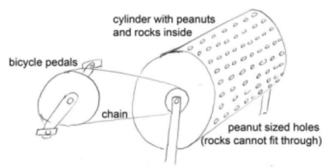
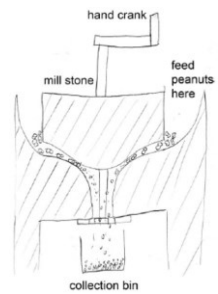


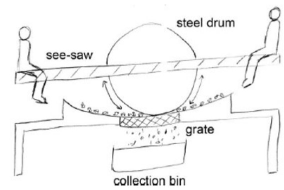
Figure 15. Solution example provided to the participants (Linsey, *et al.*, 2010).



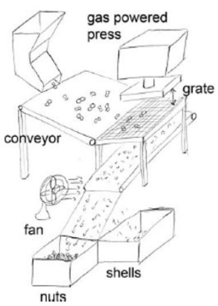
Solution 1



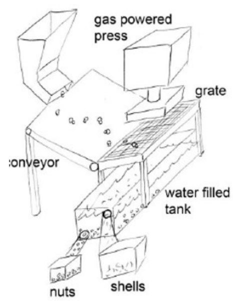
Solution 2



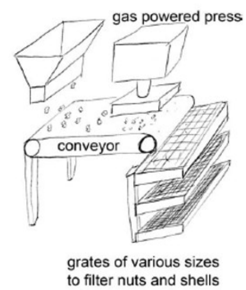
Solution 3



Solution 4



Solution 5



Solution 6

Figure 16. Solutions from the participants (Linsey, *et al.*, 2010).

Step 1.1: generate questions using the environment roadmap and ROM-based question asking technique which are one of the steps in EBD (Zeng, 2011). The environment roadmap is a category of environment components as shown in Figure 17. ROM, abbreviation of Recursive Object Modelling, is a graphical tool for semantic analysis. ROM components and the question asking rules are displayed in Figure 18.

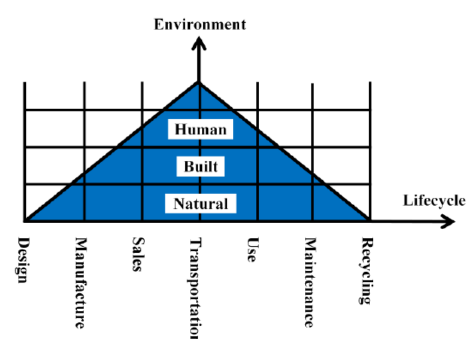
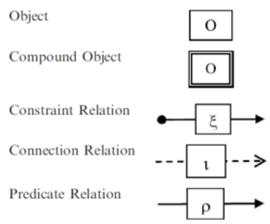


Figure 17. Roadmap (Zeng, 2011).



(a) Components of ROM diagram

Rule 1	Before an object can be further defined, the objects constraining them should be refined.
Rule 2	An object with the most undefined constraints should be considered first.

(b) Rules for object analysis

	Conditions	Question
T1	For a concrete, proper, or abstract noun N	What is N?
T2	For a noun naming a quantity Q of an object N, such as height, width, length, capacity, and level	How many / much / long / big / … is the Q of N?
T3	For a verb V	How to V? Or Why V?
T4	For a modifier M of a verb V	Why V M?
T5	For an adjective or an adverb A	What do you mean by A?
T6	For a relation R that misses related objects	What (who) R (the given object)? Or (the given object) R what (whom)?

(c) Question template for object analysis

Figure 18. ROM: components and question generating rules (Wang & Zeng, 2009).

First, ROM is generated for each of the sentences in the requirement text and questions are generated using the question template. To illustrate, ROM diagrams and questions for some sentences from the design brief are presented in Table 6, Table 7, Table 8, and Table 9.

Not all the questions need to be answered because some questions such as "how to remove peanut shells?" can only be answered after the solution is generated. The quality of the answers is determined by respondent's knowledge and assumption and there can be more than one answer to each question. The ROM-question-answer process can be iteratively performed to obtain the desired details or to further clarify the answers.

Second, using the environment roadmap, lifecycle of peanut shelling process is constructed. The lifecycle of a peanut shelling process is described in Table 10. ROM is generated for each sentence (not shown) and questions are asked; some questions may be repeated from previous steps. Again, not all questions need to be answered.

A complete list of questions can be obtained by applying the above process to all the sentences in requirement text and to the lifecycles of product and process. However, for the current analysis, it is not necessary to find the complete list of questions.

Third, questions that can be answered by the solution example are extracted from the question list, as presented in Table 11. These questions and answers were collected from 15 students participating in an Engineering design course.

Table 6. Questions generated for the sentence "(The goal of this project is to design and build) a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers"

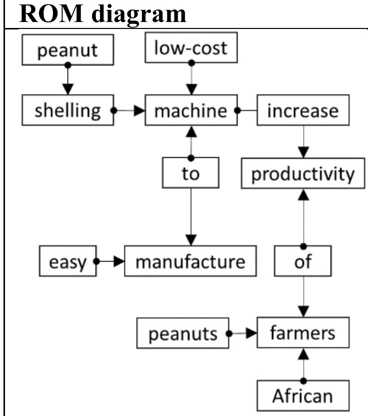
ROM diagram	Questions	Answers
	What does it mean by *low-cost*?	Low cost in production Affordable by African farmers (purchase, use, and/or repair)
	What is to *manufacture*?	To make, to produce
	How/When is *the machine manufactured*?	
	Where is *the machine manufactured*?	It is manufactured in African countries to save cost
	Why is *the machine manufactured*?	To improve productivity of African peanut famers
	Who/What *manufactures the machine*?	Local people
	What does it mean by *easy to manufacture*?	Easily made by local people
	What is *peanut*?	-
	What is *shelling*?	-
	What is *peanut* shelling?	To take peanut shells away from peanut kernels
	What are *farmers*?	-
	Who are *African peanut farmers*?	Male and female adults live in Haiti or West African countries with low income, does not speak English and have little sophisticated technical skills
	What is *productivity*?	To shell 50kg peanuts per hour
	What is to *increase (productivity)*?	
	How/When/Why/Where is *productivity increased*?	-

Table 7. Questions for the sentence “(Machine) must remove shell with minimal damage to the peanuts”

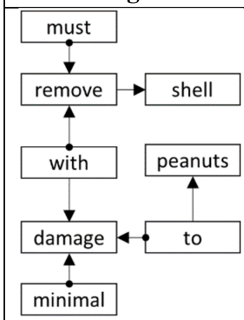
ROM diagram	Questions	Answers
	What are *peanuts*?	Peanut kernels
	What is *damage*?	Peanut kernels are split, broken.
	What does it mean by *minimal damage*?	The number of damaged peanut kernels is low.
	What is *shell*?	Peanut shells
	What is to *remove shell*?	To take peanut shells away from peanut kernels
	Why is *shell removed*?	To get peanut kernels
	Who/What *removes shell*?	-
	How are *shell removed*?	-
	When is *shell removed*?	During the daytime
	Where is *shell removed*?	In Haiti and West African countries, indoor/outdoor

Table 8. Questions for the sentence “Electrical outlets are not available as a power source”

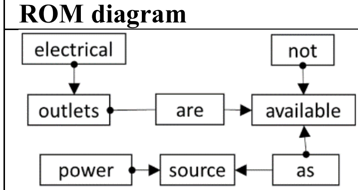
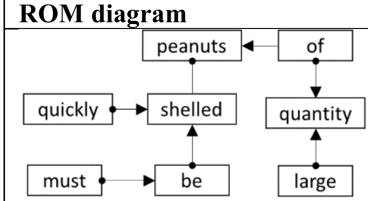
ROM diagram	Questions	Answers
	What is *power*?	
	What is *source*?	
	What is *power source*?	A source to supply power
	What are *electrical outlets*?	
	What does it mean *by not available*?	Does not have

Table 9. Questions for the sentence “A large quantity of peanuts must be quickly shelled”

ROM diagram	Questions	Answers
	What is to *shell*?	
	What does it mean by *quickly shelled*?	50kg/hour
	How/When/Where/Why are *peanuts quickly shelled*?	
	What does it mean by *large quantity of peanuts*?	50kg

Step 1.2: identify solutions similar to the example by answering the questions in Table 12.

Step 2.1: find complete requirements. The complete requirement can be found using EBD. However, in this analysis, because all of the solutions address only the explicit requirements stated in the design task, only elicited requirements in Table 13 that are most related to the given requirements are chosen. The chosen elicited requirements are displayed in Table 14.

Table 10. Questions based on lifecycle

Lifecyle of peanut shelling process	Questions	Answers
Peanuts are fed into the machine	What are *peanuts*?	-
	What is to *feed into the machine*?	
	Who/What *feeds peanuts into the machine*?	-
	How/When/Why/Where are *peanuts fed into the machine*?	-
Peanut shells are removed	What are *peanut shells*?	-
	What is to *remove peanut shells*?	
	What/Who *removes peanut shells*?	-
	How/When/Where/Why are *peanut shells removed*?	-
Peanut shells and kernels are seperated	What are *peanut shells*?	-
	What are *peanut kernels*?	-
	What is to *separate*?	-
	How/When/Where/Why are *peanut shells and kernels separate*?	-
	Who/What *separate peanut shells and kernels*?	-
Peanut kernels are passed to next stage	What are *peanut kernels*?	-
	What is the *next stage (after shells are removed)*?	Inspection, grading, or packaging
	What is to *pass*?	
	When/Why/How/Where are *peanut kernels passed to the next stage*?	
	What/Who *passes peanut to the next stage*?	-

Table 11. Questions addressed by the solution example

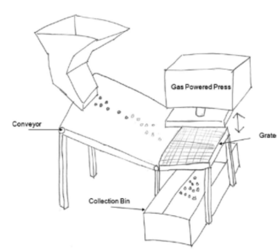
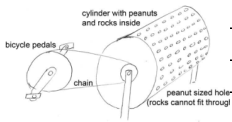
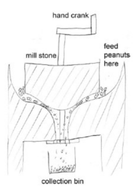
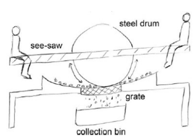
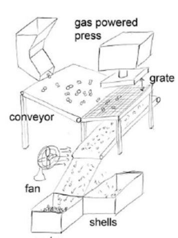
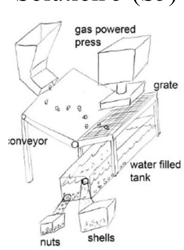
No.	Questions	Answer from the solution example	The example
Q1	Where are *peanuts fed into the machine*?	Through a hopper onto an incline conveyor belt	 This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin.
Q2	How are *peanut shell removed*?	By pressing. The gas powered press presses the peanuts through the grate.	
Q3	What *removes peanut shells*?	The gas powered press	
Q4	What is *power source*?	Gas power, Probably electricity (conveyor may use electricity to run)	
Q5	Where are *shells removed*?	At the grate	
Q6	When are *shells remove*d?	When the press presses presses the peanuts through the grate	
Q7	Why are *peanuts shelled quickly*?	Many peanuts can be shelled at one time.	
Q8	What is *the next stage*?	Collect peanuts in bin	

Table 12. Answers based on participants' solutions

	Question No.	Answers	Similar with example?
Solution 1 (S1)	Q1	-	-
	Q2	By abrading The rocks abrade the peanuts	-
	Q3	The cylinder and the rocks	-
	Q4	Human power	-
	Q5	Inside the cylinder	-
	Q6	When the peanuts pass through the cyclinder holes	-
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	-	
Solution 2 (S2)	Q1	Directly to the bed stone	-
	Q2	By crushing The millstone crushes the peanuts.	**-**
	Q3	Millstone and bed stone	-
	Q4	Human power	-
	Q5	In the millstone	-
	Q6	When the peanuts pass through the narrow gap between the millstone and bedstone	-
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	Collect peanuts in bin	**Yes**
Solution 3 (S3)	Q1	-	-
	Q2	By pressing The steel drum presses the peanuts through the grate.	**Yes**
	Q3	The steel drum, the grate	-
	Q4	Human power	**-**
	Q5	At the grate	**Yes**
	Q6	The steel drum presses the peanuts through the grate.	**Yes**
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	Collect peanuts in bin	**Yes**
Solution 4 (S4)	Q1	Through a hopper onto a conveyor belt	**Yes**
	Q2	By pressing. The gas powered press presses the peanuts through the grate.	**Yes**
	Q3	The gas powered press and the grate	**Yes**
	Q4	Gas power and probably electricity	**Yes**
	Q5	At the grate	**Yes**
	Q6	When the gas powered press presses the peanuts through the grate.	**Yes**
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	Seperate peanut shells from peanut kernels	-
Solution 5 (S5)	Q1	Through a hopper onto a conveyor belt	**Yes**
	Q2	By pressing. The gas powered press presses the peanuts through the grate.	**Yes**
	Q3	The gas powered press and the grate	**Yes**
	Q4	Gas power and probably electricity	**Yes**
	Q5	At the grate	**Yes**
	Q6	When the gas powered press presses the peanuts through the grate.	**Yes**

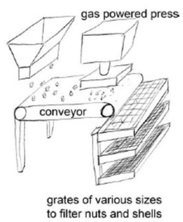
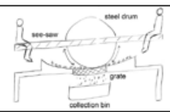
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	Seperate peanut shells from peanut kernels	-
Solution 6 (S6)	Q1	Through a hopper onto a conveyor belt	**Yes**
	Q2	By pressing. The gas powered press presses the peanuts against the conveyor belt.	**Yes**
	Q3	The gas powered press and the conveyor belt	**Yes**
	Q4	Gas power and probably electricity	**Yes**
	Q5	On the conveyor	**-**
	Q6	When the peanuts fall into the first grate	**-**
	Q7	Many peanuts can be shelled at one time	**Yes**
	Q8	Sorting peanuts by size	-

Table 13. Requirements elicited from given requirements

Given requirements	**Questions**	**Answers**	**Elicited requirements**
Must remove the shell with minimal damage to the peanuts.	When is *shell removed*?	During daytime	(The machine) must be available to for use during the daytime.
	Where is *shell removed*?	indoor in Haiti and West African countries.	Must be resistant to the climate in Haiti and West African.
	What is *damage*?	Peanut kernels are split, broken.	The number of split and broken peanut kernels are low.
	What does it mean by *minimal damage*?	The number of damaged peanut kernels is low.	
Electrical outlets are not available as a power source.	What is *power source*?	A source to supply power	Use another power source rather than electricity.
	What does it mean *by not available*?	Does not have electrical outlets	Do not use electrical outlet
A large quantity of peanuts must be quickly shelled.	What does it mean by *quickly shelled*?	50 kg/ hour	Shell 50kg peanuts per hour
	What does it mean by *large quantity of peanuts*?	50 kg	
Low cost.	What does it mean by *low-cost*?	Low cost in production Affordable for African farmers (purchase, use, and/or maintenance)	Affordable for African farmers to purchase, use, and repair.
Easy to manufacture.	What is to manufacture?	To make, to produce	Easily made by local people in African countries.
	Who/What manufactures the machine?	Local African people	
	What does it mean by *easy to manufacture*?	Easily made by local local African people	
	Why is the machine manufactured?	To improve productivity of African peanut famers	Easy to be used by African peanut farmers regardless of their gender and educational level.
	Where is the machine manufactured?	In African countries to save cost	Materials must be easily found locally

Table 14. Elicited requirements

No.	Given requirements	Requirements elicited
R1	Remove the shell with minimal damage to the peanuts	The number of split and broken peanut kernels are low.
R2	Electrical outlets are not available as a power source	Do not use electrical outlets
R3	A large quantity of peanuts must be quickly shelled	Shell 50kg peanuts per hour
R4	Low cost	Affordable for African farmers to purchase, use, and repair.
R5	Easy to manufacture	Easily made by local people in African countries.



	Q2: The steel drum presses the peanuts through the grate to remove shells.	Q5: (Peanuts are shelled) at the grate	...
R1: The number of split and broken peanut kernels are low.	☐ 0 not meet ☑ 1 unlikely ☐ 2 likely ☐ 3 meet ☐ X unrelated	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	
R2: Do not use electrical outlets	☐ 0 not meet ☐ 1 unlikely ☐ 2 likely ☑ 3 meet ☐ X unrelated	☐ 0 not meet ☐ 1 unlikely ☐ 2 likely ☐ 3 meet ☑ X unrelated	
R3: Shell 50kg peanuts per hour	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	
R4: Affordable for African farmers to purchase, use, and repair.	☐ 0 not meet ☑ 1 unlikely ☐ 2 likely ☐ 3 meet ☐ X unrelated	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	
R5: Easily made by local people in African countries.	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	☐ 0 not meet ☐ 1 unlikely ☑ 2 likely ☐ 3 meet ☐ X unrelated	

Figure 19. Evaluating features that are similar to the example.

Table 15. Evaluation result

Solution	No.	R1	R2	R3	R4	R5
S1	Q7	X	X	3	X	X
S2	Q7	X	X	3	X	X
	Q8	X	3	X	3	3
S3	Q2	1	3	2	1	2
	Q5	2	3	X	2	2
	Q6	1	3	2	1	2
	Q7	X	X	3	X	X
	Q8	X	3	X	3	3
S4	Q1	X	1	2	0	0
	Q2	2	3	3	1	1
	Q3	X	3	3	1	1
	Q4	X	1	3	0	0
	Q5	2	3	X	2	2
	Q6	2	3	3	1	1
	Q7	X	X	3	X	X

Solution	No.	R1	R2	R3	R4	R5
S5	Q1	X	1	2	0	0
	Q2	2	3	3	1	1
	Q3	X	3	3	1	1
	Q4	X	1	3	0	0
	Q5	2	3	X	2	2
	Q6	2	3	3	1	1
	Q7	X	X	3	X	X
S6	Q1	X	1	2	0	0
	Q2	2	1	3	1	1
	Q3	X	1	3	1	1
	Q4	X	1	3	0	0
	Q7	X	X	3	X	X

Step 2.2: choose features that are similar to the example and evaluate them against the requirements. The rating starts at 0 (does not meet requirements), 1 (unlikely to meet

requirements), 2 (likely to meet requirements), 3 (meet requirements) and X (unrelated). For instance, solution S3 has 5 features that are similar to the example, identified by the example: Q2, Q5, Q6, Q7 and Q8. These features were then assessed by two raters against the requirement as illustrated in Figure 19. The rating results were compared between the two raters. The final results were obtained after the raters discussed with the moderator to reach a consensus. Table 15 shows the assessment result for all the solutions.

Step 3: Compute expected fitness = total assessment points /(highest score in the rating scale × total number of entries being assessed). In our case, the highest score in the rating scale is 3. So, expected fitness = total assessment points /(3 × total number of features being assessed). For example, the total assessment value for S2 is (Q7R3 + Q8R2 + Q8R4 + Q8R5)/ (3 × 4) = 12/(3 x 4) = 1.

Computing f requires perceived fitness. In this example, all the perceived fitness equals to 1 — the maximum value — because we assume that the participants only chose solutions that they perceived as the most suited for the problem. Table 16 shows the discrepancy f computed for each solution.

Table 16. Fixation assessment

Solution	Expected fitness r_i	Perceived fitness r_i^e	Value $f_i = \frac{r_i^e - r_i}{r_i^e + r_i}$
S1	1	1	0
S2	1	1	0
S3	0.72	1	0.16
S4	0.58	1	0.27
S5	0.58	1	0.27
S6	0.44	1	0.38

As seen from Table 16, S1 and S2 do not carry fixated features ($f = 0$), S3 to S6 have some fixations and S6 has the highest fixation ($f = 0.38$).

Solution S3 has the second lowest f because the only feature similar to the example is the method of shelling: pressing peanuts through a grate. However, this solution is unlikely to satisfy requirement R1 "minimal damage to the peanuts" because the weight of the two people and the steel drum probably damages more peanuts than the weight of gas-powered press does.

Solutions S4, S5 and S6 adopt many ideas from the solution example such as shelling peanuts by pressing them through a grate, using a conveyor belt, using a hopper, using gas-powered press, etc. However, S6 has higher f than S4 and S5 because the pressing plate in S6 presses peanuts on the conveyor belt to remove shells instead of pressing on the grate as in S4 and S5. This causes more damages to the peanuts, which severely violates the requirement R1 "minimal damage to the peanuts".

5.5. Summary

A theoretical model of design fixation was proposed with the concept of perceived fitness and expected fitness. From the model, three paths leading to a design fixation were derived. The first is when a designer is heavily attached to a solution. The second is when a designer does not have the right perception of the current design problem because he/she would apply his pre-occupied design solution to frame the problem. The third is when a designer poorly evaluates the fitness of the solution example. Existing research findings on design fixation were used to demonstrate how the proposed model can be applied to interpret phenomena related to design fixations and to derive hypotheses. Finally, assessment of fixation based on the concepts of perceived fitness and expected fitness was presented.

Chapter 6.
Physiological Experiments: Background

6.1. Electroencephalography (EEG)

EEG is a method to record neurons' postsynaptic potentials by computing the potential difference between two electrodes placing on the scalp. EEG was first measured on animal in 1875 by Caton (Collura, 1993). The first EEG recording on human was conducted in 1924 and was published in 1929 by Hans Berger (Collura, 1993). At that time, Berger worked with at most two channels. Today, a dense array EEG system can record up to 256 electrodes.

The human scalp can be divided into four main regions known as lobes: frontal lobe, parietal lobe, temporal lobe, and occipital lobe as shown in Figure 21. The position of the electrodes on the scalp follows international standard 10-20, 10-10 or 10-5 systems and is denoted by a first letter of the lobe and a numeric value. The 10-20 system can record a maximum of 19 electrodes, the 10-10 system records a maximum of 81 electrodes and the 10-5 system can record more than 300 electrodes.

Shown in Figure 20 is a 10-20 system. F stands for frontal lobe, T for temporal lobe, P for parietal lobe, O for occipital lobe, C for central area (the motor cortex in the frontal lobe), Fp for prefrontal cortex (in the frontal lobe). The odd numbers 3, 5, 7 indicate left hemisphere and even numbers 2, 4, 8 indicate right hemisphere.

EEG signals are divided into four bands: delta (from 1Hz up to 4Hz), theta (from 4Hz up to 8Hz), alpha (from 8Hz up to 13Hz), beta (from 13Hz up to 30Hz) and gamma (over 30Hz).

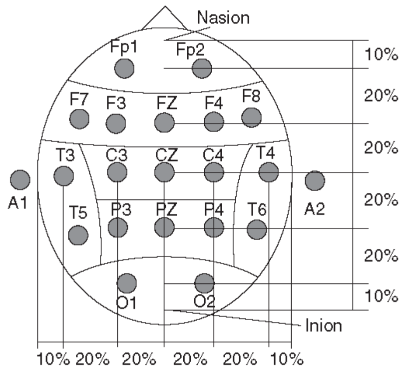


Figure 20. 10-20 system.

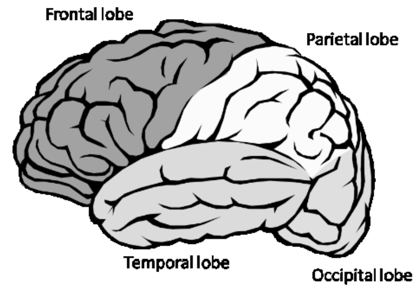


Figure 21. Brain areas.

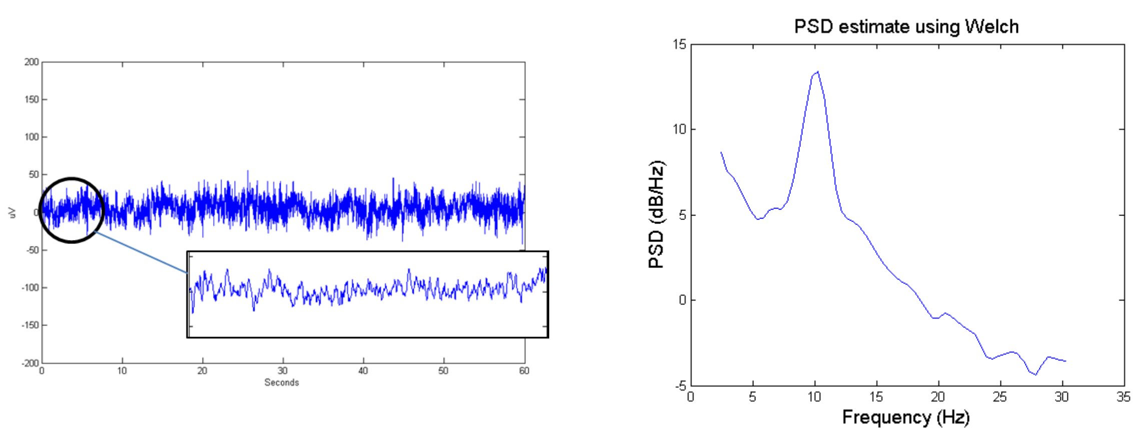
Some researchers believe that mental effort links to the activity of the anterior cingulate cortex (ACC) (Mulert *et al.*, 2008) which situates in the frontal lobe. The activity of ACC can be measured by some EEG features. For instance, Mulert *et al.* (2007) (2008) found that the gamma-activity in ACC increased with increased auditory task difficulty and the N1 component potential in high effort auditory task was larger than the N1 component in low effort auditory task. Howells *et al.* (2010) reported a positive correlation between perceived mental effort and left parietal beta power during attentional tasks whereas Chang and Huang (2012) demonstrated an association between elevated theta and high-attention tasks. Fink *et al.* (2005) presented a link between decreased alpha and increased mental effort which was similar to the finding of a negative correlation between EEG relative alpha power and blood flow velocity during cognitive effort by Szirmai *et al.* (2005).

6.2. Methods of EEG analysis

The section introduces methods that will be used in the current thesis.

6.2.1. Power spectral analysis

The objective of power spectral analysis, also known as power spectral density (PSD) estimation, is to determine the distribution of the power (amplitudes squared) of a signal over frequencies. The PSD has the unit power per Hz (uV^2/Hz) but often the power is expressed as decibel, which equals to $10x\log_{10}(uV^2)$. The analysis helps reveal information that is not visible in time domain. For example, Figure 22 shows an EEG signal in time domain at Oz channel during rest with eyes closed of a subject and the corresponding PSD. The PSD (Figure 22(b)) reveals the dominance of 10Hz frequency during this period, which cannot be observed in time domain (Figure 22(b)).



(a) (b)

Figure 22. (a) EEG signal at Oz channel during rest with eyes closed, (b) PSD of the signal shows a peak at 10Hz.

There two main techniques to computing PSD: parametric and non-parametric estimation. In parametric estimation, PSD of a signal is estimated based on the parametric model describing the generator of the signal. Thus, computing PSD involves three steps: (1) choose an appropriate parametric model, (2) estimate the parameters of the model, and (3) compute the PSD of the model (Djuric *et al.*, 1999). The three basic models are autoregressive (AR), the moving average (MA) and the autoregressive moving average (ARMA). In practice, the AR model was found the most suitable for EEG signal (Akin & Kiymik, 2000; Tseng *et al.*, 1995). The AR model can be described as:

$$x[n] = -\sum_{k=1}^{p} a_k x[n-k] + \varepsilon[n] \tag{34}$$

where p is the order of the system, a_k is the coefficient, $\varepsilon[n]$ is a zero mean white noise process with variance σ^2. The PSD is then given by:

$$S(f) = \frac{\sigma^2}{\left|1 + \sum_{k=1}^{p} a_k\, e^{-j2\pi fk}\right|^2} \tag{35}$$

Hence, to find the PSD of a signal we need to choose appropriate order p and estimate σ and a_k. Order p can be found using model order selection criteria such as Akaike Information Criterion (AIC), Minimum Description Length (MDL), Bayesian Information Criterion (BIC), Reflection Coefficient criterion, Final Prediction Error, and many others (Stoica & Selen, 2004). The most popular method to estimate σ and a_k for EEG is Burg (de Hoon *et al.*, 1996; Jansen *et al.*, 1981; Saidatul *et al.*, 2011).

For non-parametric method, PSD is estimated directly from the observed signal. The PSD can be estimated by taking the Fourier transform (FT) of the signal or by taking the FT of the autocorrelation of the signal. To improve the performance of the estimator, the data is usually windowed and averaged. The PSD is, thus, estimated by dividing the entire signal into segments and computing the average PSD of all the segments. The idea is given in Eq.(36) and Eq.(37).

$$S(f) = \frac{1}{K}\sum_{i=0}^{K-1} S_i(f) \tag{36}$$

$$S_i(f) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x[n]w[n]e^{-j2\pi fn}\right|^2 \quad (37)$$

where K is the number of segments, $S_i(f)$ is the PSD estimate of segment i of length N, and $w[n]$ is a window function. However, window functions are usually zero near boundaries; thus, multiplying a signal with a window function will eliminate the signal information near the boundaries. To solve this problem, the segments are overlapped as shown in Figure 23.

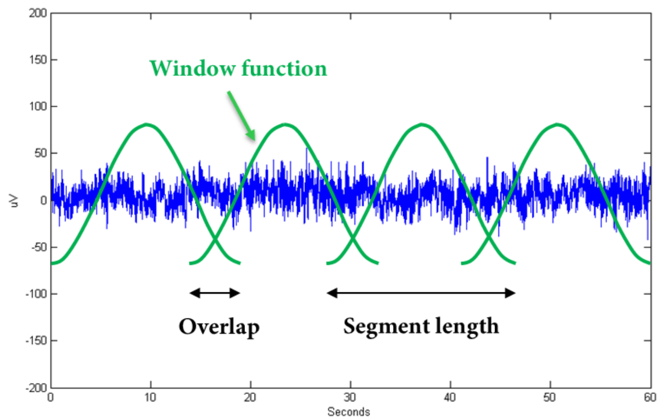


Figure 23. Overlapping segments.

The non-parametric method is not suitable for short data length but it is simple to compute. The parametric method can be used for short data length and provides higher resolution than non-parametric methods but computational complexity of estimating parameters is $O(n^2)$ and if the model and its parameters are not chosen properly, false peaks may occur (Poisel, 2004).

6.2.2. Time frequency analysis

The time frequency (TF) analysis enables researchers to see the how the power is distributed across frequency with respect to time. In this section, we introduced the short-time Fourier Transform (STFT) to estimate TF. The basic idea of STFT is to divide the entire data into small consecutive segments and apply FT to each of these segments. In practice, a window function is slided along the signal and FT is performed to the data within the window. The window can be overlapping or non-overlapping.

The problem with STFT is that there is a trade-off between temporal (time) and spectral (frequency) resolution. If a window is wide, the frequency resolution is high, the time resolution is low and vice versa. The relationship between frequency resolution and window length is shown in Eq.(38)

$$\Delta f = \frac{f_s}{N} \tag{38}$$

where Δf is the frequency resolution (i.e. the minimum distance in Hz that the two frequencies can be distinguished; thus, the smaller the value, the higher the frequency resolution), f_s is the frequency sampling, and N is the window length.

Figure 24 shows the time-frequency representation of EEG signal at Oz channel during one minute rest with eyes closed. Overall, the power is strong at 10Hz for the entire period.

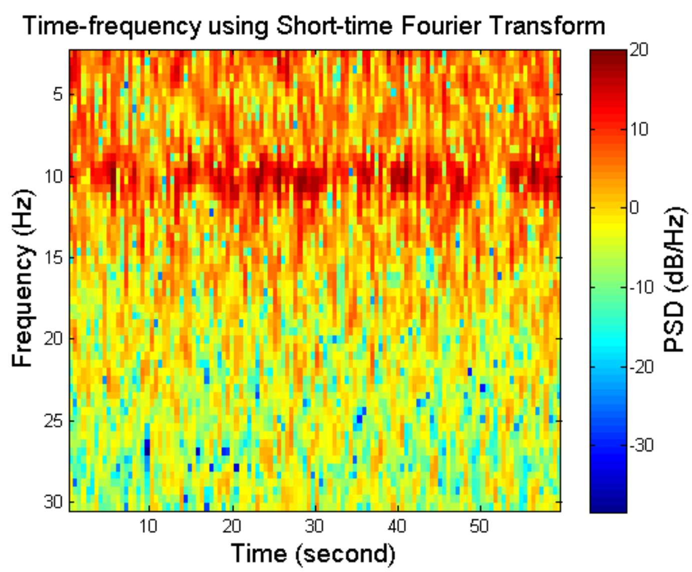


Figure 24. Time-frequency information of EEG signal at Oz channel during rest using STFT.

6.2.3. Microstate analysis

In 1980s, Lehmann *et al.* (1987), after studying a series of continuous spatial distribution of EEG potential (also known as EEG landscape, EEG topography, EEG map, scalp map, or scalp field potential distribution map), found that the spatial configuration of EEG potential changed gradually instead of jumping unexpectedly from one configuration to another configuration. The authors suggested that these periods of partially stable scalp field map reflects a unit of information processing or mental state at micro level. Thus, the word EEG microstate was created to refer to the "quasi-stable spatial distribution" of EEG potential (Koenig *et al.*, 1999; Lehmann*, et al.*, 1987; Lehmann *et al.*, 1998). Figure 25 shows gradual changes of EEG scalp maps.

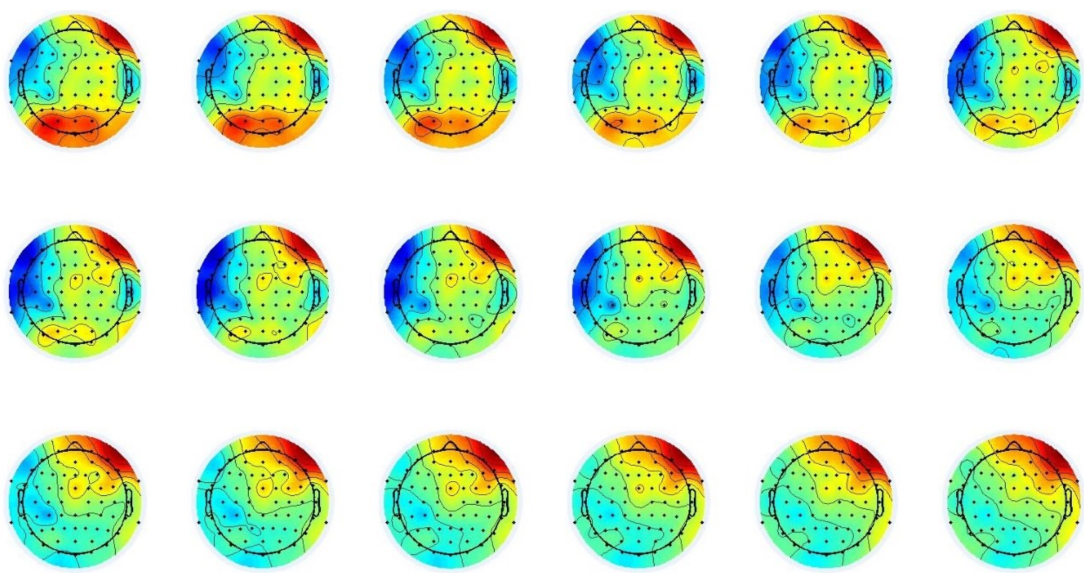


Figure 25. EEG topography changes gradually from one configuration to another configuration.

An important concept in microstate analysis is Global Field Power (GFP). Global Field Power (GFP) at a given time is a single value, measures the potential strength of the scalp, and is computed as (Murray *et al.*, 2008):

$$GFP = \sqrt{\frac{1}{n_e}\sum_{i=1}^{n_e} {u_i}^2} \tag{39}$$

where n_e is the number of electrodes, u_i is the average potential of the ith electrode at the given time point. Local maximum GFPs are usually extracted to represent the period of quasi stable of EEG scalp maps and are then clustered. The centroids of clusters are microstate classes — also known as template maps. Detailed calculation of microstate classes can be found in (Murray*, et al.*, 2008).

Microstate analysis aims to find microstate classes that represent activities of interest because different microstate maps are assumed to link to different brain functions. Features of the microstate classes such as duration of occurrence (Koenig*, et al.*, 1999; Yoshimura *et al.*, 2007), sequence of occurrence (Murray*, et al.*, 2008) and topography (Koenig*, et al.*, 1999) are also compared between activities.

6.3. Mental effort and EEG

Mental effort can be defined as the total use of cognitive resources (Heemstra, 1986), the energy expenditure of the brain (Fairclough & Mulder, 2012) or cognitive capacity that is actually used to cope with task demands (Paas & Van Merriënboer, 1993). The mental effort is reflected by the changes in blood flow measured by functional magnetic resonance imaging (fMRI) and the firing of neurons measured by electroencephalography (EEG). Use of fMRI for studying design activities is less preferable to EEG because fMRI is very noisy and severely restricts movement of subjects. We believe that this environment is extremely unnatural and will result in considerable laboratory effects. In contrast to fMRI, EEG recording makes absolutely no noise and movements are more tolerant. Therefore, we use electroencephalography (EEG) to measure brain activities.

Some researchers believe that mental effort links to the activity of the anterior cingulate cortex (ACC) (Mulert*, et al.*, 2008) which situates in the frontal lobe. The activity of ACC can be measured by some EEG features. For instance, Mulert*, et al.* (2007) (2008) found that the gamma-activity in ACC increased with increased auditory task difficulty and the N1 component potential in high effort auditory task was larger than the N1 component in low effort auditory task. Howells*, et al.* (2010) reported a positive correlation between perceived mental effort and left parietal beta power during attentional tasks whereas Chang and Huang (2012) demonstrated an association between elevated theta and high-attention tasks. Fink*, et al.* (2005) presented a link between decreased alpha and increased mental effort which was similar to the finding of a negative correlation between EEG relative alpha power and blood flow velocity during cognitive effort by Szirmai*, et al.* (2005).

6.4. Mental stress and its measurement

The concept of stress is defined from different perspectives. From physiological perspective, Selye (1974) defined stress as "nonspecific response of the body to any demand made upon it."; from psychological perspective, stress is a "a perceptual phenomenon arising from a comparison between the demand and coping ability" (Cox, 1978). From stressor point of view, stress is "anything that induces increased secretion of glucocorticoids" (Levine, 2000).

The response of stress involves the activation of two systems: autonomic nervous system (ANS) and the endocrine system (Seaward, 2011):

- The ANS includes two main subsystems: sympathetic (SNS) and parasympathetic (PNS) nervous systems. The SNS prepares the body for the "fight-or-flight" response by accelerating heartbeat, dilating pupils, and increasing blood glucose. The PNS does the opposite.

- The endocrine system includes a number of glands that secrete hormones. Glands that are most involved during stress response are pituitary gland and adrenal gland.

The mechanism of stress response is as follows:

(1) Under stress, the anterior hypothalamus releases corticotropin-releasing factor (CRF). The posterior hypothalamus activates the adrenal medulla and the sympathetic nervous system (SNS) to secrete epinephrine (adrenaline) and norepinephrine (noradrenaline) (Jacobson & Marcus, 2008). These substances causes a raise in heart rate, increase in respiration rate, contraction of muscle, dilation of pupils, elevation in blood glucose level, and breakdown of lipids.

(2) The CRF activates the pituitary gland to release adrenocorticotropic hormone (ACTH). The ACTH in turn activates the adrenal cortex. The adrenal cortex, then, releases glucocorticoids (esp. cortisol) and mineralocorticoids (esp. aldosterone).

Stress is present even at rest or during sleeping. Selye (1974) used the term “distress” for excessive, unpleasant, damaging stress. He also stated that lack of stress (boredom) or too much stress will make a person distress. The right amount of stress makes a person feel happy, which he called “the optimal stress level” (Selye, 1974).

Measurement of stress can be psychological or physiological. Psychological measurement are self-report measurement (such as Perceived Stress Scale (PSS) (Cohen *et al.*, 1983), Subjective Stress Scale (SSS) (Kerle & Bialek, 1958), Hassles Scales (Kanner *et al.*, 1981), Hassles and Uplifts Scale (DeLongis *et al.*, 1988)), questionnaires, and interviews. Physiologically, stress can be assessed by heart rate (HR), heart rate variability (HRV), salivary cortisol, blood pressure, galvanic skin response, respiration, and skin temperature.

6.4.1. Heart rate variability

Among heart rate (HR), heart rate variability (HRV), salivary cortisol, blood pressure, galvanic skin response, respiration, and skin temperature, HR and HRV analysis are the popular metrics for assessing mental stress (Ranganathan *et al.*, 2012). HR is the number of heart beat per minute. HRV is the variation in time intervals between R-R waves of two consecutive normal heartbeats; a heartbeat consists of five waves: P, Q, R, S and T as shown in Figure 26.

To test which HR and HRV features is the most sensitive to stress, a member in our group conducted a Stroop test experiment and quantified mental stress in terms of HR and HRV parameters (Petkar, 2011). The result shows that LF/HF of HRV (LF: low frequency, HF: high frequency) is the most sensitive measure for mental stress. Based on this study, we use LF/HF of HRV to quantify mental stress in our work.

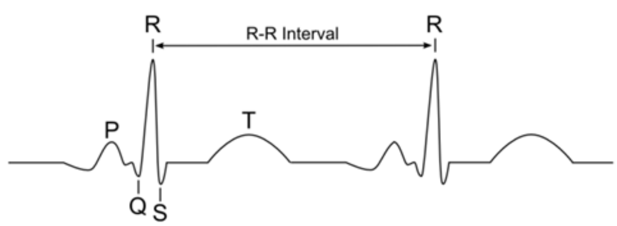


Figure 26. R-R interval
(http://eleceng.dit.ie/tburke/biomed/assignment1.html).

6.4.2. Skin conductance

Skin conductance (SC) refers to the electrical conductance of the skin and its unit of measure is microsiemens (μS). SC includes tonic (basal) and phasic (event-related) activities (Stern *et al.*, 2001). The tonic activity, known as skin conductance level (SCL), is the background activity. The phasic activity, known as skin conductance response (SCR) or galvanic skin response (GSR), is a fast transient event which lasts for several seconds. The SC varies with the moisture of the skin. The moisture results from the production of sweat glands which are regulated by the sympathetic nervous system (SNS). Measurement of SC is one of the indirect ways to measure the activity of stress system (Southwick *et al.*, 2009).

SC has been used to measure psychological arousal in various tasks. London *et al.* (1972) showed that performers had higher average SC when doing boring tasks than when doing interesting tasks. Healey and Picard (2005) used SC to detect driver stress and reported that it was well correlated with stress levels. Unlike heart rate, and heart rate variability, SC is a stable indicator of mental stress and is not affected by cardiac medications (Jacobs *et al.*, 1994). Due to its non-invasive measurement, simplicity of measurement and reliability, SC was considered as an acceptable method to record soldier stress in the battlefield (Perala & Sterling, 2007). SC was also used as an objective measure of user experience such as enjoyment, frustration, and boredom (Mandryk *et al.*, 2006) and it showed the highest correlation with user emotional preference when compared with heart rate, blood volume pulse and respiration (Tognetti *et al.*, 2010).

Chapter 7. Preliminary Study

In the early days of our research, we wanted to use physiological signals to measure creativity and mental stress in design. However, we were uncertain of how to adapt the technology to design research. This section introduces our very first attempt in tackling the issue.

7.1. Experiment

7.1.1. Recording devices and laboratory setting

Devices: we acquired an 8 channel EEG system from Grasslab. The system came with disc electrodes. Usually, the electrode paste was sufficient to keep the electrodes adhesive to the scalp but we also used medical tape to secure the electrodes.

Other devices are USB webcams and screen recording software.

(a) (b) (c)

Figure 27. (a) EEG recorder (Grass technologies), (b) A disc electrode (Grass technologies), and (c) Logitech webcam (Logitech).

Experiment room: the experimenter stayed in the same room with the participants. The experiment sat behind the participant as depicted in Figure 28. The disadvantage of this setting is that the participants felt distracted and uncomfortable and the experimenter could barely observe the design process.

Data storage: experiment data were manually copied to a portable hard drive.

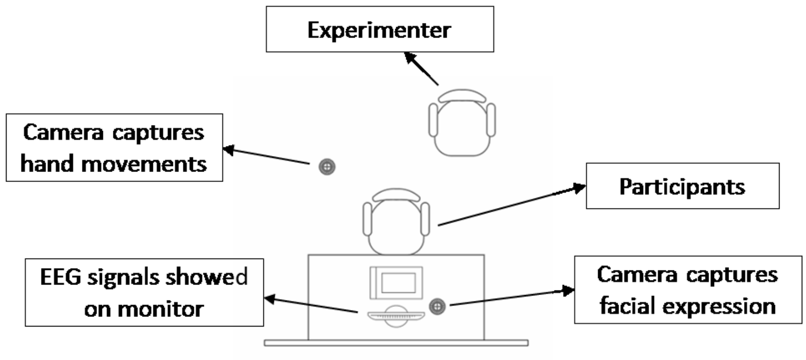


Figure 28. The experiment room (preliminary study).

"A family has just purchased a vacation cottage located on a mountain XYZ. Considering the limited rooms of the cottage, they have to put their seven young children into one big bedroom. The following table lists the children's information

Name	Gender	Age	Height (m)	Weight (kg)	Special Needs
Kaya	Female	12	1.55	40	Reading area
Jeason	Male	10	1.37	38	Play space for all of them for playing games.
Mark	Male	6	1.15	25	
Lily	Female	8	1.32	34	
Jonne	Female	4	1.05	18	
Amanda	Female	8	1.32	34	
Fiona	Female	4	1.05	18	None

This bedroom is 18.24m^2 (3.8m×4.8m) with 2.8m high. The bed size for each child will be 1m×2m. The size of a reading table is 1m×0.5m×0.6m, The dimensions of the room are shown below."

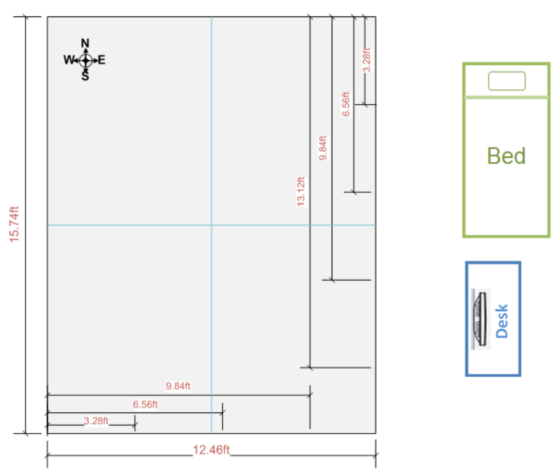


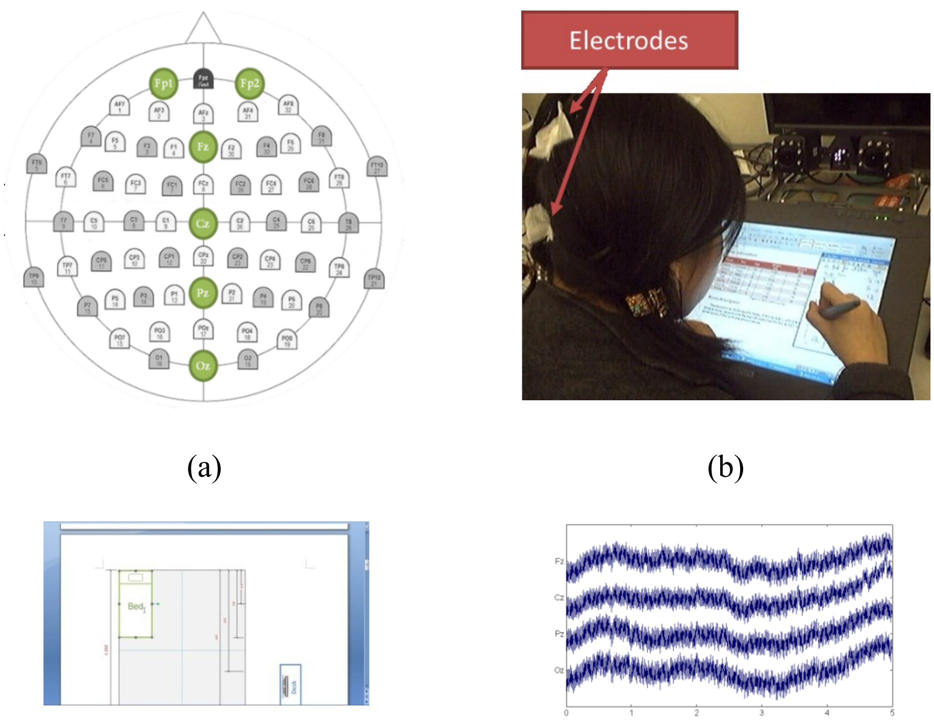
Figure 29. Layout design task.

7.1.2. Layout design task

Participants were instructed to give solution to a layout design task shown in Figure 28.

7.1.3. Data collection

The EEG data (Figure 30(d)) were recorded at six channels: Fp1, Fp2, Fz, Cz, Pz, and Oz. The exact location is presented in Figure 30(a). Designer's computer screen and webcam were also recorded as shown in Figure 30(b), (c).



(a) (b)

(c) (d)

Figure 30. (a) Recorded EEG channels (in green circle) in the layout design task, (b) webcam, (c) screen activity, and (d) EEG signals.

7.2. Procedure

Before the experiment starts, the subject was informed of the experiment procedure in details and then was asked to read and sign a consent form. Only after the consent form was signed, could the experimenter proceed to conduct the experiment.

During the first five minutes of the experiment, the subject was asked to relax. The purpose of these five minutes is to measure the resting state which can be served as the baseline to evaluate the cognitive state during design activities. After the resting state, the subject was given the design problem description. While designing, the subject was not interrupted; however s/he could ask questions. The subject informed the experimenter after completing the design. Another five minute resting state was taken before the experiment actually ended.

7.3. Data processing and data analysis

Because protocol analysis is the most popular method in design research and EEG data can be considered as "protocol", we followed the approach in protocol analysis to analyze EEG. The steps in protocol analysis are: (1) choose or develop coding scheme, (2) segment data and label the segments according to the coding scheme (Ericsson & Simon, 1993).

7.3.1. Developing coding scheme

First, from our observation of the recorded videos, we categorized design activities into four types (see Figure 31): problem analysis (PA), solution evaluation (SE), solution generation (SG), and solution expression (CE). Problem analysis includes problem understanding and problem formulation. Solution evaluation refers to activities that involve comparing, calculating, and analyzing. Solution generation includes activities that precede solution expression. Solution expression is sketching or writing solutions.

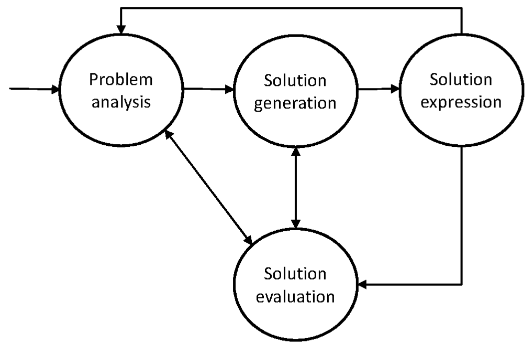


Figure 31. Four types of design activities.

7.3.2. Segmentation and coding

The design and EEG data were segmented, each segment corresponding to an action. The segments were then coded according to four types of design activities. Actions that did not clearly show designers' intention or were not related to design activities were labeled with letter O. The analysis was performed for one subject. There were 287 segments in total but only 260 are valid segments. Figure 32 shows some of the segments and their labels.

7.3.3. EEG analysis

EEG was band-pass filtered from 1Hz to 30Hz. EEG power spectral density (PSD) corresponding to each video segment were computed using EEGLab (Delorme & Makeig, 2004). The power of resting phase was subtracted from that of each design-related EEG segment to show the change in power during design activities relative to the resting state. The EEG power for theta (4-8Hz), alpha (8-13Hz), and beta (13-30Hz) was computed.

Segment No.	Start Time	End Time	Duration	Description of activity	Label
1	0:00:29	0:02:24	0:01:55	Check the software	O
2	0:02:24	0:07:22	0:04:58	Relax	O
3	0:07:22	0:09:44	0:02:22	Read problem description	PA
4	0:09:44	0:10:09	0:00:25	Scroll up and down	O
5	0:10:09	0:10:21	0:00:12	Move bed 1	SG, CE
6	0:10:21	0:10:28	0:00:07	Rotate bed 1	SG, CE
7	0:10:28	0:10:34	0:00:06	Move bed 1	CE
8	0:10:34	0:10:35	0:00:01	Brief idle	SE
9	0:10:35	0:10:55	0:00:20	Read problem description	PA, SG
10	0:10:55	0:11:03	0:00:08	Make copy of bed 1	CE
...	...	...	...	...	...
283	0:30:30	0:30:36	0:00:06	Resize bed 2	CE
284	0:30:36	0:30:40	0:00:04	Evaluate bed 8, complete the design	SE
...	...	...	...	...	

- O: activities that are not related to design
- PA: problem analysis
- CE: solution expression
- SE: solution evaluation
- SG: solution generation

✓ Total segments: 287

✓ Valid segments: 260

Figure 32. EEG segments and coding result.

The segments were then grouped into sets of sub-design problems as seen in Figure 33, each of which was comprised of a sequence of design activities starting from problem analysis/solution evaluation (PA/SE) to solution generation (SG) and ending with solution expression (CE).

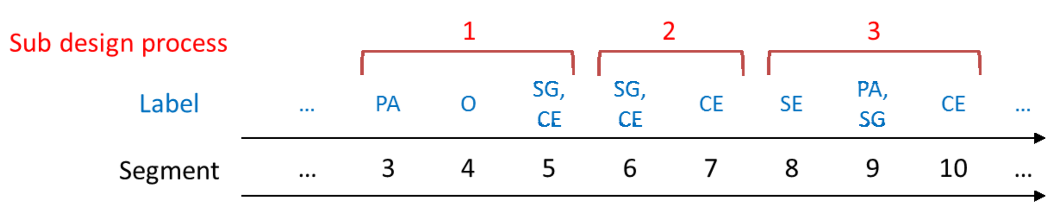


Figure 33. Design activities grouped into sub design processes.

Next, each coded activity in a sub-design process was assigned a weight value based on its EEG power. Activity associated with highest EEG power assumed a weight value of 3, the next highest assumed value 2 and the lowest assumed value 1. If an activity has two labels such as segment 5 in Figure 33, the weight value is divided in half. An example is given in Table 17. This weight value assignment was performed for each channel and each EEG band (theta, alpha and beta). Then for each channel and each band, average was taken for all activities of the same type across the sub design processes.

Table 17. Weight values

Sub design process	Seg.	Label	Fz			Cz		
			Theta	Alpha	Beta	Theta	Alpha	Beta
1	3	PA	3	3	3	3	3	3
	5	SG	1.5	1.5	1.5	1.5	1.5	1.5
		CE	1.5	1.5	1.5	1.5	1.5	1.5
2	6	SE	1.5	2.5	1.5	1.5	1.5	1.5
		SG	1.5	2.5	1.5	1.5	1.5	1.5
	7	CE	3	1	3	3	3	3

7.4. Results

Since beta band is associated with active thinking (Dietrich & Kanso, 2010), we focused on beta band. The result of beta band is shown in Figure 34. From Figure 34(a), it can be seen that mental activity is high in front lobe, which is responsible for decision making, planning, calculation, judgment, during PA/SE (Thompson *et al.*, n.d.). This means that subject spent most of the mental efforts in reflection and judging during problem analysis and solution evaluation. Figure 34(b) show high mental activity in parietal lobe and occipital lobe, which are responsible for shape interpretation, visual processing and eye focusing, during PA/SE and SG. This may suggest that the subject spent more efforts in visual thinking during problem analysis/solution evaluation and solution generation than solution expression. In fact, the beta in SG shows a little higher than the beta in PA/SE (Figure 34(b)), which seems to be in line with the finding of the role of visual design thinking in solution generation (Goldschmidt, 1994).

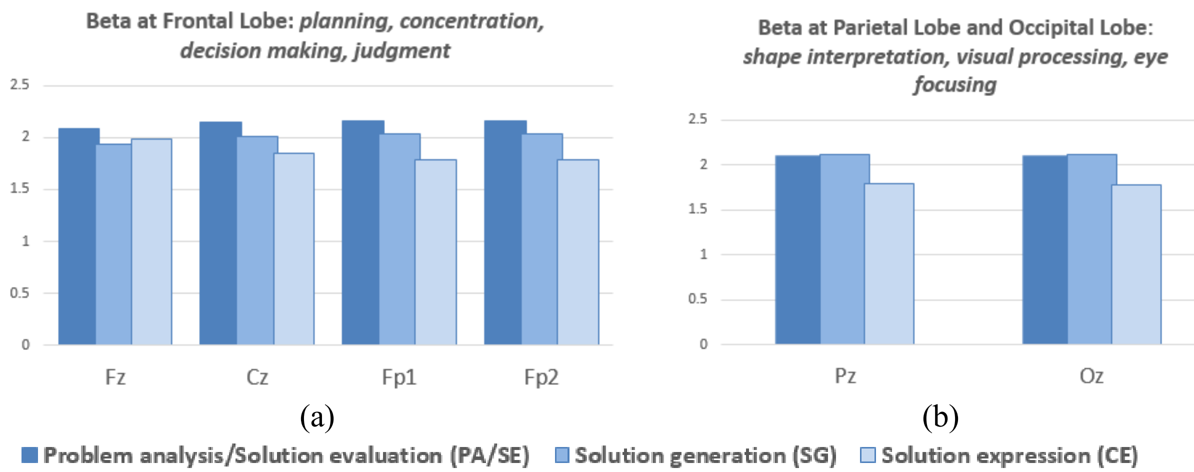


Figure 34. High mental activity in the frontal lobes responsible for decision making and judgment during PA/SE, and in parietal, occipital lobes associated with visual processing during PA/SE and SG.

Thus, the results obtained from EEG data show the feasibility of using EEG to study design cognition and as a complementary method to protocol analysis in understanding design activities.

7.5. Limitations

Limitations of the experiment:

(1) Preparation was very time consuming. It took around 30 to 45 minutes to obtain reasonable quality for the signals.

(2) The recording was extremely susceptible to power line noise and subject's movement.

(3) The electrode paste held the electrodes in place but it tended to dry out after 30 minutes.

(4) Impedance of EEG electrodes could not be checked. A high impedance of an EEG electrode indicates a poor contact of the electrode to the scalp or the worn-out electrode.

(5) Synchronization was dependent on the starting time of each device. Experimenters did not have control over data synchronization.

(6) EEG signals are complex. It is better to measure mental stress from other involuntary physiological signals.

Limitation of data analysis: segmentation was time consuming, labour-intensive and coding was very subjective.

Chapter 8.
Mental Effort and Mental Stress

In this section, the aim is to examine a relationship between designers' mental effort and mental stress.

8.1. Experiment

8.1.1. Recording devices and laboratory setting

Devices: we found that the poor quality of the EEG signals was due to the EEG disc electrodes which was not be able to be held steadily on the scalp. Therefore, we purchased an EEG cap from Cortech Solutions and a new set of 14 electrodes compatible with the cap. The EEG cap is made of stretchy fabric and has plastic holders placed according to the 10-20 standard system. After subjects put on the cap, the electrodes covered with electrode paste were plugged into the holders one by one. With the EEG cap, the electrodes were held perfectly in place. Preparation time still took around 30 to 45 minutes but because the number of electrodes has increased from 8 to 14, we considered this was an improvement in preparation time.

Polar HRV recorder (Polar, n.d.)   Q-see DVR (Q-See, n.d.)   EEG cap and electrodes

Figure 35. Recording devices.

In addition, to facilitate synchronization among video data, we purchased a digital video recorder (DVR) with 8 cameras from Q-See. We also bought a Polar watch to record heart rate variability (HRV) for mental stress measurement.

Experiment room*:* the room was divided into two sections: control and experiment, as illustrated in Figure 36. The experimenter sat in the control room, monitored EEG and video data.

Data storage: a central server was built to simplify data storage, retrieval and backup.

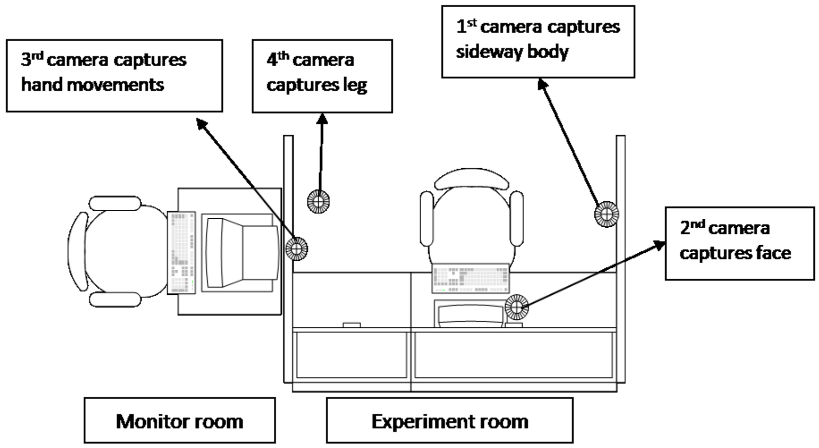


Figure 36. The experiment room (Nguyen & Zeng, 2014a).

8.1.2. Design task

We realized that the layout design task was relatively simple. Thus, in this experiment, we proposed the following design problems:

Design Problem 1: "Design a house that can easily fly from one place to another place. There is no budget limit."
Design Problem 2: "Design a vehicle that can transport an object between any two locations on earth within a few seconds. There is no budget limit."
Design Problem 3: "Design a desk that helps a messy university student to keep things organized and tidy. There is no budget limit."

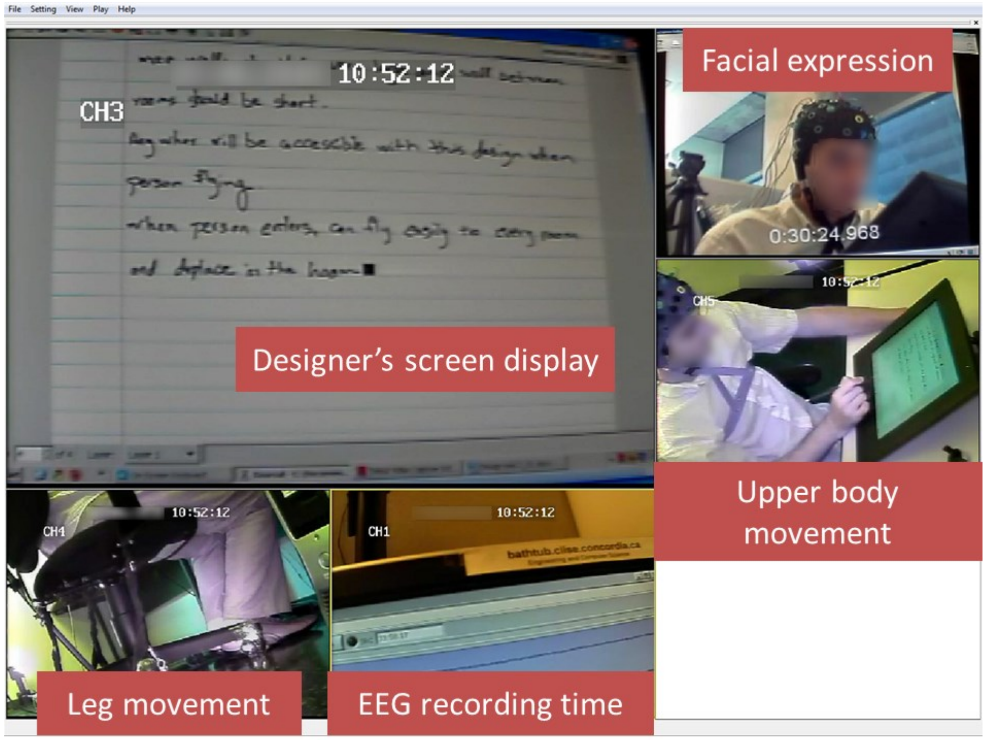


Figure 37. View from the control room.

8.1.3. Data collection

Fourteen channels EEG data were collected by Grass 15LT. The fourteen channels are Fpz, Fz, F4, F3, C4, C3, T4, T3, P4, P3, T6, T5, O2, and O1. All the channels were referenced to left ear. HRV was recorded by Polar RS800G3. Four cameras captured body movements and facial expression, as illustrated in Figure 36. During the experiment, a subject worked in the experiment room and the experimenter watched the subject through cameras in the monitor room. Monitor room and experiment room were divided by an office partition panel. The subject solved the design problem on a tablet using a tablet pen. A screen recorder captured all activities on the tablet's monitor.

8.1.4. Procedure

Eleven graduate students, age ranging from 25 to 35 from Quality System Engineering program at Concordia University volunteered to participate in the experiment. Each subject was asked to solve one of the design problems chosen by the experimenter. The design problems were listed in 8.1.2. The subjects solved the problem at their own pace, no time limit was imposed. Most of the subject was given the design problem 1. In case when the subject had already known about the design problem 1, another design problem was given.

Subject was asked to read and sign the consent form. The protocol was approved by The University Human Research Ethics Committee. The experimenters, then, helped the subject wear HRV chest belt and put on EEG cap. While the experimenters applied EEG gel, the subject learnt to use the tablet. The whole process took around half an hour. After that, the experiment was conducted in the following order:

(1) Resting with eyes open for three minutes.

(2) Resting with eyes close for another three minutes.

(3) Solving a design problem. Internet was allowed. There were no time limit.

(4) Resting with eyes close for three minutes after completing the design.

(5) Retrospective interview.

8.2. Data processing and analysis

EEG data of four subjects were either missing or were too noisy to use. Data of the remaining seven subject were analysed.

8.2.1. Screen recording data

Screen recording data was segmented according to movements that were observable from the video, as illustrated in Figure 38. Typical movements are: write, sketch, no activity, scroll page up, scroll page down, and type.

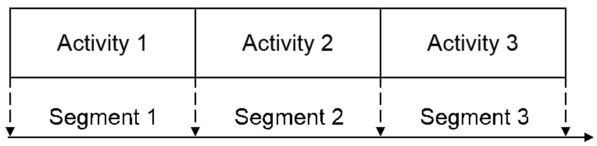
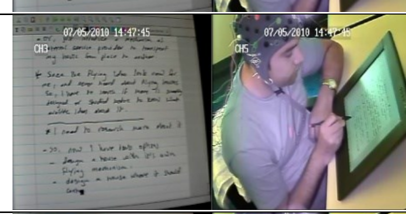
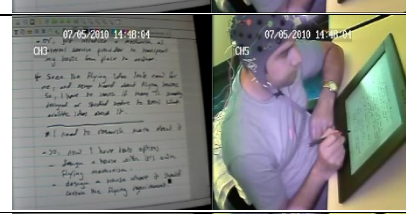
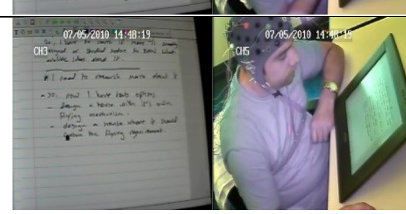


Figure 38. Segmentation rule.

Table 18. Example of some segments

No.	Start time	End time	Duration (seconds)	Description	Tablet and Camera
...					
86	42:00.254	42:03.754	3.50	Lift pen	
87	42:03.754	42:44.454	40.70	Write	
88	42:44.454	43:01.224	16.77	Lift pen Look up (briefly)	
89	43:01.224	43:05.694	4.47	Scroll down	
...					

Some segments is presented in Table 18 as an example. Not all the segments were used for analysis. Segments that are not related to design task and segments that have very noisy EEG data were removed from the analysis. The number of segments for each subject is listed in Table 19.

Table 19. Number of segments for each subject

Subject ID	Total number of segments	Number of segments considered	Duration (hh:mm:ss)	Design problem
1	54	49	0:24:20	House
2	211	207	1:08:45	House
3	141	139	0:41:03	House
4	235	233	0:26:36	Desk
5	216	214	0:28:53	Vehicle
6	680	676	1:49:17	House
7	142	140	0:25:43	House

8.2.2. EEG data

EEG data was segmented based on the screen recording data. For each segment, power spectral density (PSD) was calculated. PSD shows the distribution of signal power along a frequency range. AR model Burg method is used to compute PSD (Burg, 1968). To choose appropriate model order, Akaike Information Criterion (AIC) was calculated for the eyes closed relaxing data at Fpz channel using Matlab function aic. The model order was tested from 1 to 40. The chosen order, usually the minimum value, was validated by computing the PSD during resting state with eyes close. It is well known that alpha is dominant during eyes close. Therefore, computing PSD with chosen order at occipital channels should show peak in alpha band.

EEG data sampling at 200Hz was filtered at 0.3Hz low cutoff frequency, zero phase, 12dB/octave and was filtered at 40Hz high cutoff frequency, zero phase, 24dB/octave. A 60Hz Notch filtered was also applied. All the filtering was performed using BESA software.

PSD was calculated for every one second EEG data. The power of each band (θ band from 4-8Hz, α band from 8-13Hz and β band from 13-25Hz) was computed as the area under PSD curve with respect to the corresponding frequency range. EEG index R_{Xk} for each band $k \in \{\theta, \alpha, \beta\}$ at a segment X was computed as:

$$R_{Xk} = \frac{e_{Xk}}{e_{X\theta} + e_{X\alpha} + e_{X\beta}} \; , k \in \{\theta, \alpha, \beta\} \tag{40}$$

where e_{Xk} equals to the summation of the product of the one-second power p_i and its time within segment X.

$$e_{Xk} = \sum_{i=1}^{n} (t_i \times p_{ik}) \, , k \in \{\theta, \alpha, \beta\} \tag{41}$$

For example, the $e_{X\alpha}$ for segment X shown in Figure 39 is computed as $e_{X\alpha} = \sum_{i=1}^{n}(t_i \times p_{i\alpha})$

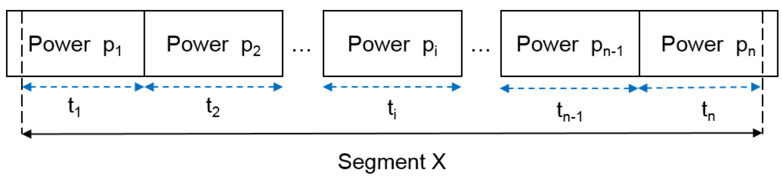


Figure 39. Calculation of e_X.

8.2.3. HRV data

The LF/HF ratio for each 0.5 second is calculated for the whole HRV data using HRVAS software (Ramshur, 2010). Mental stress M_X associated with segment X is computed by dividing the summation of the product of 0.5-second LF/HF ratio r_{ik} and its time t_i within segment X by duration of the segment X:

$$M_X = \frac{\sum_{i=1}^{n}(t_i \times r_{ik})}{\sum_{i=1}^{n} t_i} \tag{42}$$

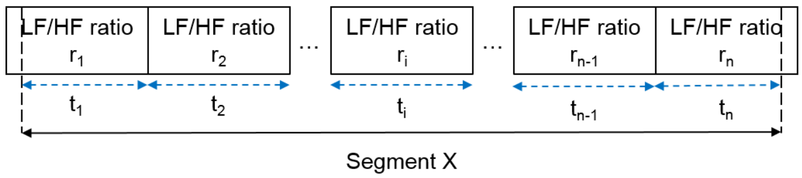


Figure 40. Calculation of M_X.

After mental stress was calculated for each segment, all the segments were clustered into three groups (high, medium and low) based on mental stress using Maltab k-means function. Figure 41 shows the clustering result of one subject.

	Level 1	Level 2	Level 3
Min LF/HF	2.02	92.54	348.43
Max LF/HF	91.88	302.55	726.66
Total segments	557	111	8

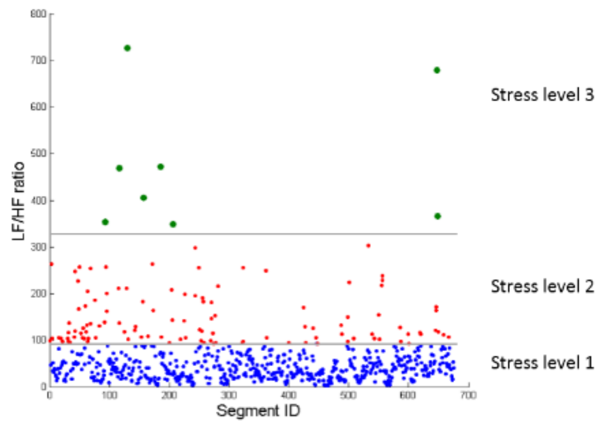


Figure 41. Clustering result of a subject.

8.3. Data analysis

The following factors were computed for each subject at each stress level: percentage of segments, percentage of time, average time per segment, and mental effort.

8.3.1. Percentage of segments at each stress level

How often a designer experienced stress during the design process can be expressed in Eq.(43), where s_l is the number of segments at stress level l and S is the total number of segments.

$$f_l = \frac{s_l}{S} \tag{43}$$

8.3.2. Percentage of time spent at each stress level

$$\bar{t}_l = \frac{t_l}{T} \tag{44}$$

where t_l is the time at stress level l, T is the total design time.

8.3.3. Average time per segment at each stress level

$$\bar{d}_l = \frac{t_l}{s_l} \tag{45}$$

where t_l is the time at stress level l, s_l is the number of segments at stress level l.

EEG energy at each stress level:

$$E_{lk} = \frac{\sum_{j=1}^{s_l}(R_{jk})}{s_l} \quad , k\epsilon\{\delta, \alpha, \beta\} \tag{46}$$

where E_{lk} is the EEG energy of band k at stress level l, s_l is the number of segments at stress level l and R_{jk} is computed according to Eq.(40).

8.4. Results

8.4.1. Percentage of segments at each stress level

Friedman test showed significant difference in the percentage of segments at each stress level. Wilcoxon test showed the percentage of segments at stress level 1 was significantly greater than that at stress level 2 (W(7)=28, p<0.05, one-tailed test), and the percentage of segments at stress level 2 was significantly greater than that at stress level 3 (W(7)=28, p<0.05, one-tailed test). This implies that as stress level increased, the number of activities decreased.

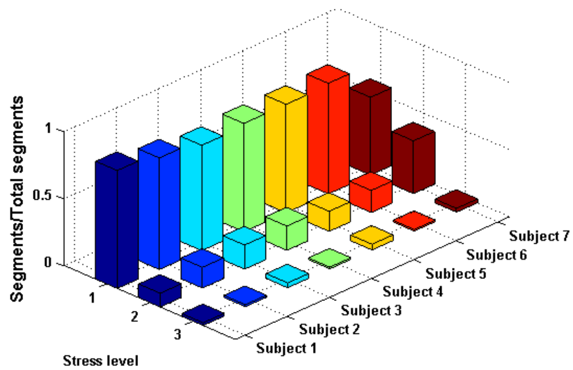


Figure 42. Percentage of segments at each stress level.

8.4.2. Percentage of time spent at each stress level

Friedman test showed significant difference in the time ratio at each stress level. Wilcoxon test showed that the average time at stress level 1 was significantly greater than that at stress level 2 ($W(7)=28$, $p<0.05$, one-tailed test), and time ratio at stress level 2 was significantly greater than that at stress level 3 ($W(7)=28$, $p<0.05$, one-tailed test). This implies that most of the subjects were not very stressed.

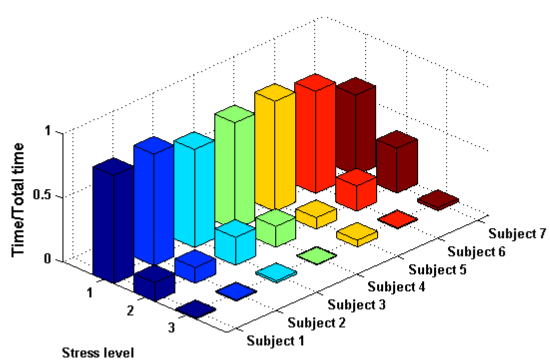


Figure 43. Time ratio at each stress level.

8.4.3. Average time per segment at each stress level

There was no significant difference in the average time (in second) per segment between stress levels. Figure 44 shows the average time per segment for all seven subjects. Among all seven subjects, subject 5 shows a very different trend: average time per segment is very high at stress level 3. Looking into subject 5, we found that subject 5 has a very simple design solution (Figure 45) when compared to subject 1 (Figure 46) who spent less time in the design and when compared to subject 2 (Figure 47) who spent more time in the design. Subject 5 does not seem to “design”. The solution does not solve any conflict. Therefore, we remove data of subject 5 from the analysis.

This time, Friedman test showed a significant difference among stress levels. A Wilcoxon test indicated significant greater time per segment at stress level 1 than at stress level 3 and at stress level 2 than at stress level 3. No significant difference was found between stress level 1 and stress level 2. This implies that the designers did not struggle in stressful situations. This is understood because participation was volunteering and there was no incentive for good design. If difficult situation arises, the designers can probably give up or ignore.

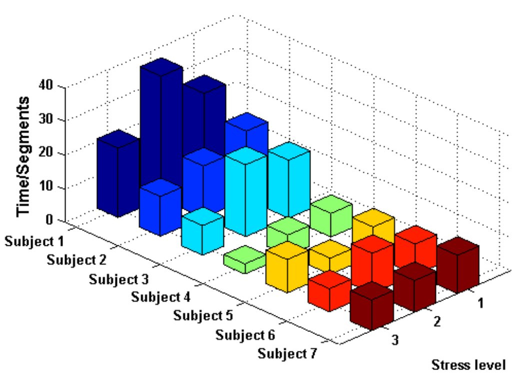


Figure 44. Average time per segment at each stress level.

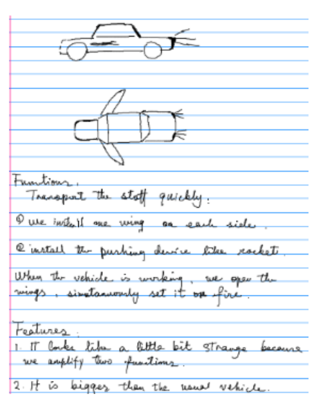
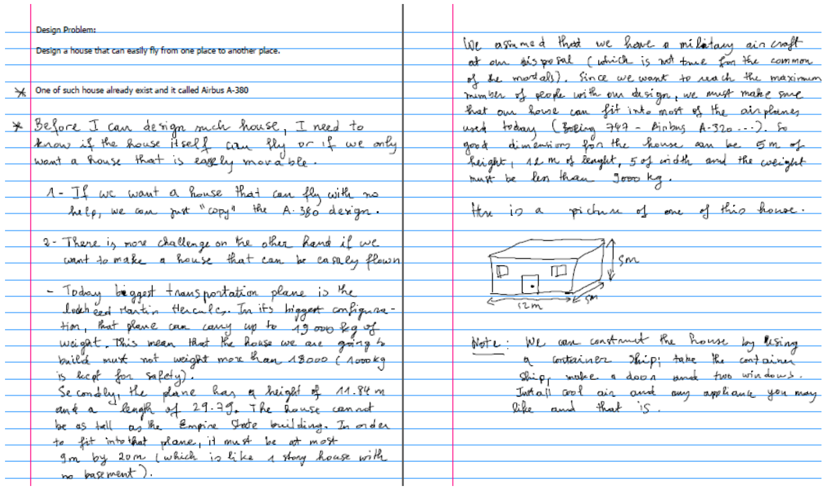


Figure 45. Design solution by subject 5.


Design Problem:

Design a house that can easily fly from one place to another place.

* One of such house already exist and it called Airbus A-380

* Before I can design such house, I need to know if the house itself can fly or if we only want a house that is easily movable.

1- If we want a house that can fly with no help, we can just "copy" the A.380 design.

2- There is more challenge on the other hand if we want to make a house that can be easily flown

- Today biggest transportation plane is the Lockheed Martin Hercules. In its biggest configuration, that plane can carry up to 19 000 kg of weight. This mean that the house we are going to build must not weight more than 18000 (1000kg is kept for safety).
Secondly, the plane has a height of 11.84 m and a length of 29.79. The house can not be as tall as the Empire State building. In order to fit into that plane, it must be at most 9m by 20m (which is like 1 story house with no basement).

We assumed that we have a military air craft at our disposal (which is not true for the common of the mortals). Since we want to reach the maximum number of people with our design, we must make sure that our house can fit into most of the airplanes used today (Boeing 747 - Airbus A-320 ...). So good dimensions for the house can be 5m of height, 12 m of lenght, 5 of width and the weight must be less than 9000 kg.

Here is a picture of one of this house.

Note: We can construct the house by using a container ship; take the container ship, make a door and two windows. Install cool air and any appliance you may like and that is.

Figure 46. Design solution by subject 1.

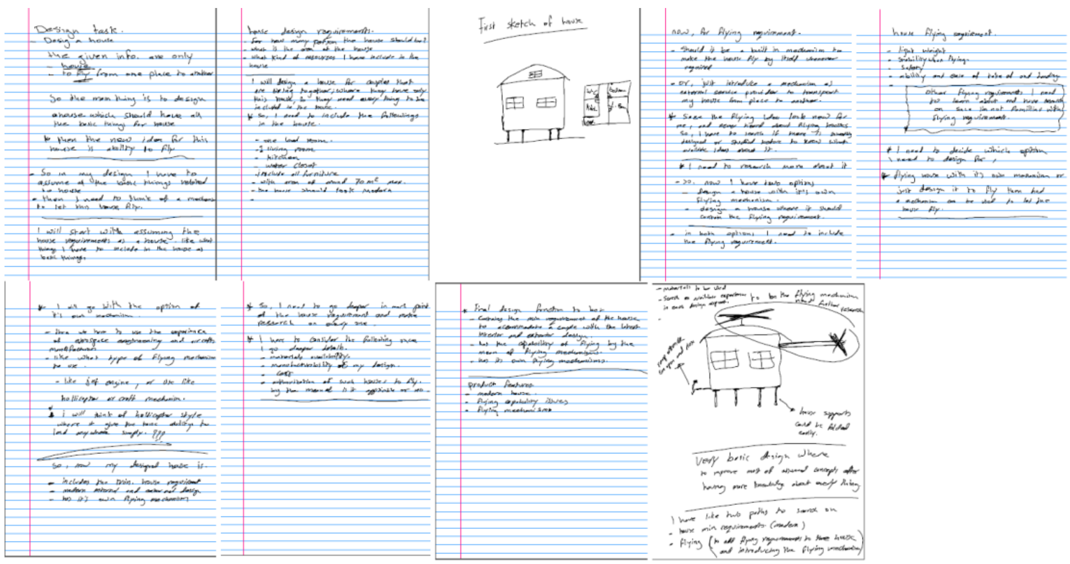


Figure 47. Design solution by subject 2.

8.4.4. EEG energy at each stress level

Friedman test showed a significant difference in theta energy between stress levels (Hypothesis test: H_o: $Md_1 = Md_2 = Md_3, H_1$: $Md_1 \neq Md_2 \neq Md_3$ where Md is the median value of theta energy at a stress level). A Wilcoxon test showed that theta energy at stress level 1 was greater than at stress level 3 in Fpz channel and T3 channel (W(7) =28, p<0.05, one-tailed test).

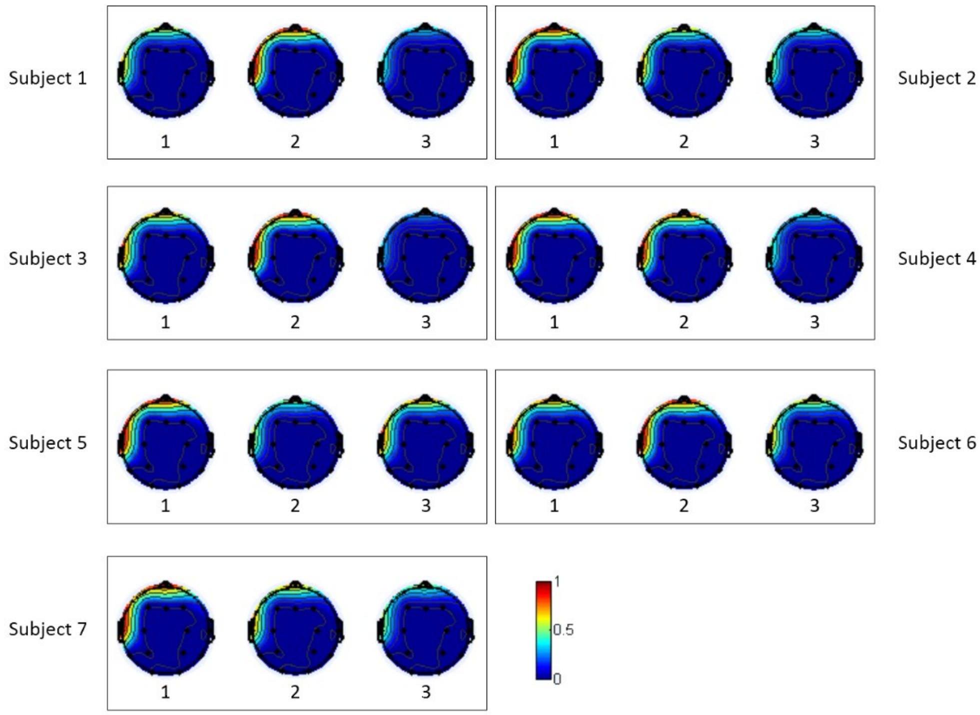


Figure 48. Fpz and T3 channels show significant difference in theta energy between stress level 1 and 3.

After subject 5 was excluded from the analysis, Friedman test showed significant differences in theta band (at all 14 channels), alpha band (at Fz, F3, F4, C3, C4, T3, P3, P4, T5, T6, O1, and O2), and in beta band (at Fz, F4, C3, C4, T3, P3, P4, T5, T6, O1, and O2).

Wilcoxon sign rank tests showed greater energy at stress level 1 than at stress level 3 and greater energy at stress level 2 than at stress level 3 in the following channels: Fpz theta, Fz (theta, alpha, beta), F4 (theta, beta), F3 theta, C4 (theta, beta), C3 theta, T4 theta, T3 (theta, beta), P4 (theta, beta), P3 (theta, beta), T6 (theta, beta), T5 theta, O2 (theta, beta), O1 (alpha, beta). Greater energy at stress level 1 than at stress level 3 are also found at: F3 alpha, C4 alpha, C3 alpha, C3 beta, T4 beta, T3 alpha, P4 alpha, P3 alpha, T6 alpha, T5 alpha, T5 beta, O2 alpha, O1 theta. No significant difference in energy between stress level 1 and stress level 2.

Figure 49, Figure 50, and Figure 51 show the theta, alpha and beta energy. In general, the the energy was higher at stress level 1 and 2 than at stress level 3.

The grand average energy is presented in Figure 52.

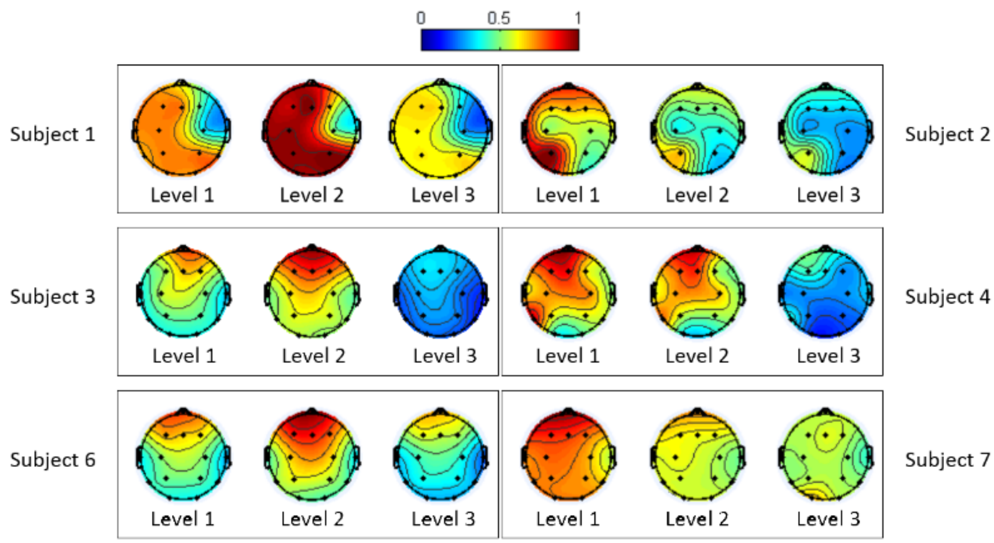


Figure 49. Theta at channels (Fpz, Fz, F3, F4, C3, C4, T3, T4, P3, P4, T5, T6, O1, O2) having significant differences between stress levels.

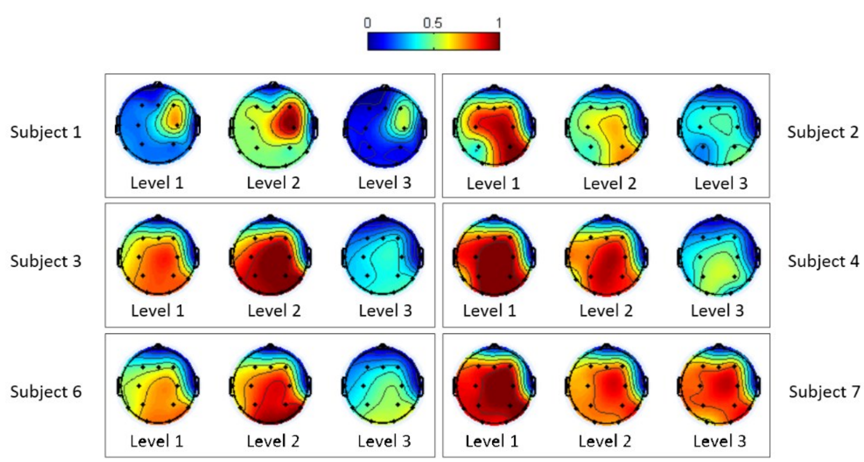


Figure 50. Alpha at channels (Fz, F3, F4, C3, C4, T3, P3, P4, T5, T6, O1, O2) having significant differences between stress levels.

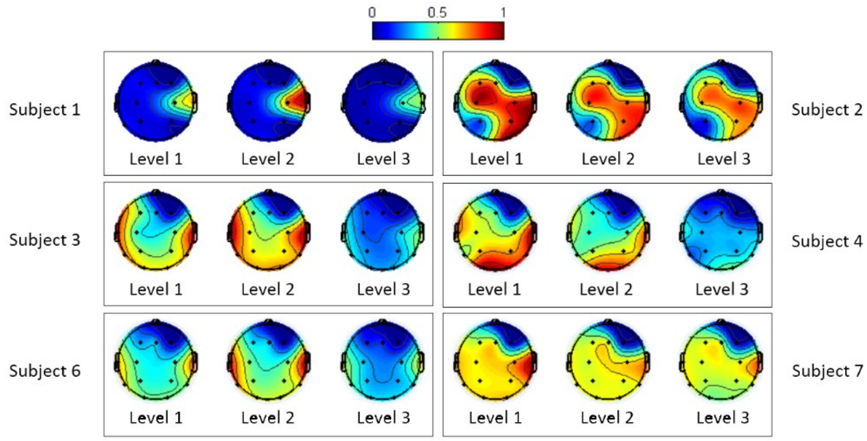


Figure 51. Beta at channels (Fz, F4, C3, C4, T3, T4, P3, P4, T5, T6, O1, O2) having significant differences between stress levels.

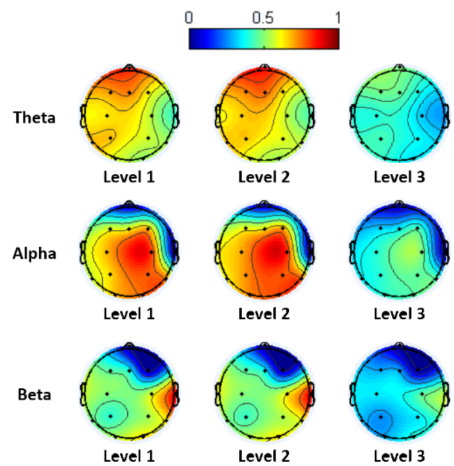


Figure 52. Grand average of energy per segment at theta, alpha and beta.

8.4.5. Comparison of EEG energy between the first and the second half of the design process

Design process was divided into two sections of equal time. Beta at P4 and F4 are significantly greater in the second half than in the first half of the design process. This implies that most of the subjects probably were more concentrated or were more cognitively active in the second half of the process.

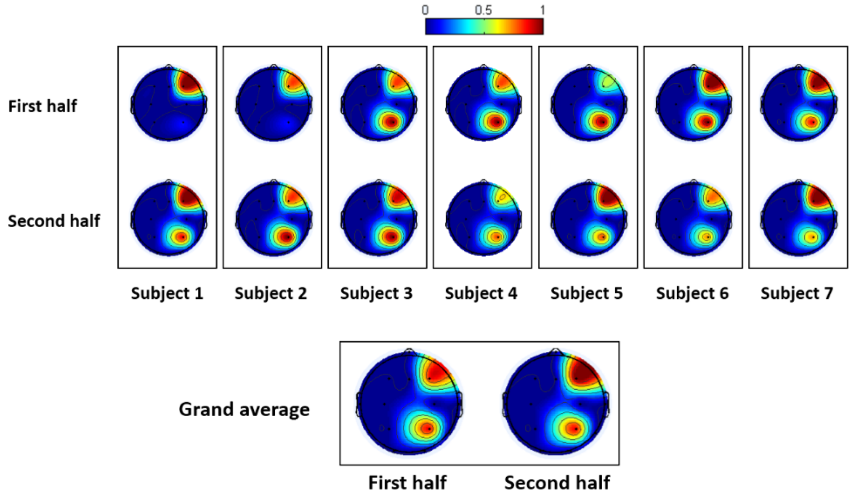


Figure 53. Beta between the first and the second half of the design process.

8.4.6. Comparison of mental stress between the first and the second half of the design process

The percentage of segments at each stress level was computed for each part as presented in Table 20. Although no significant difference was found, five out of seven subjects showed more stress (stress level 3) in the first half than in the second half, as shown in Figure 54.

Table 20. Number of segments at each stress level between the first and the second half of the design process

Subject ID	Stress level 1		Stress level 2		Stress level 3	
	1st half	2nd half	1st half	2nd half	1st half	2nd half
1	0.302	0.698	0.800	0.200	1.000	0.000
2	0.372	0.628	0.375	0.625	0.333	0.667
3	0.661	0.339	0.440	0.560	0.400	0.600
4	0.447	0.553	0.500	0.500	0.667	0.333
5	0.514	0.486	0.781	0.219	0.556	0.444
6	0.334	0.666	0.550	0.450	0.750	0.250
7	0.481	0.519	0.382	0.618	0.750	0.250

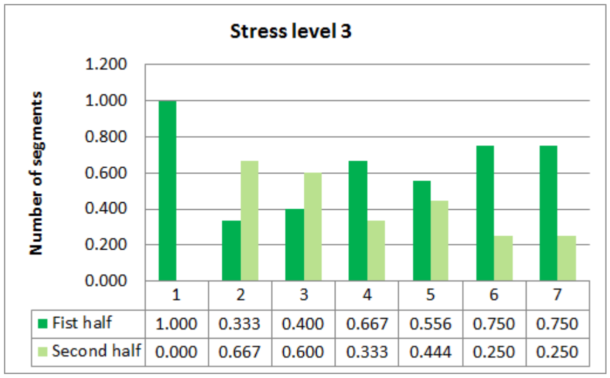


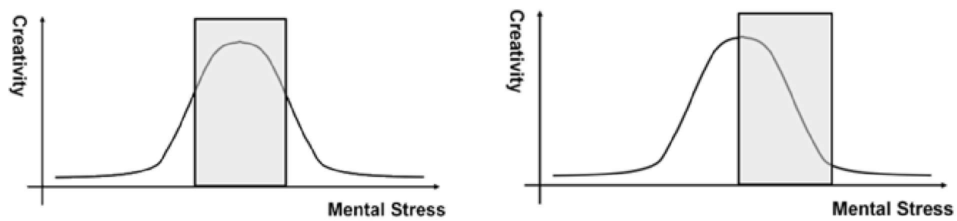
Figure 54. Number of segments associated with stress level 3 in the first half and in the second half of the design process.

8.5. Conclusions and Limitation

EEG and HRV data of seven subjects were analyzed. The result showed that:

- Number of segments at higher stress levels and the time spent at higher stress levels were less than that at lower stress levels. This implies that throughout the experiment most of the designers were not under high stress.
- Average time per segment at stress level 3 was the lowest. Most of the subjects seemed not to stay long in the stressful situation.
- Theta, alpha and beta EEG energy was lowest at stress level 3. There was no difference in EEG energy between stress level 1 and 2. Looking at individual data in Figure 49, Figure 50 and Figure 51, we see that subjects 1, 3, and 6 have mental effort at stress level 2 higher than at stress level 1 and 3 whereas others (subjects 2, 4 and 7) have mental effort decreases as stress level increases. This can be explained that designers perceive the workload (design problem) differently and they have different motivations. These differences will put designers in different sections of the inverse U curve as illustrated in Figure 55.

- Most of the subjects show more activity in the visuo-spatial processing and visuomotor control region of the cerebral cortex in the second half of the design process, reflecting in the greater beta at F4 and P4 channels.
- It is likely that the subjects were more stressed in the first half of the process because five of seven subjects showed higher number of segments associated with stress level 3 in the first half of the process than in the second half.



(a) (b)

Figure 55. Designers' mental stresses distribute within sub regions of the inverse U curve: (a) regions where mental stresses of subjects 1, 3, 6 distribute, (b) regions where mental stresses of subjects 2, 4, 7 distribute.

Theta and beta energy, as index of mental effort, was lowest at stress level 3. EEG energy was not different between stress levels 1 and 2. However, we were unable to show the evidence of inverted U curve relationship between stress level and mental effort. As the next step, we decide to conduct a more structured experiment to examine the relationships between EEG and mental effort and between HRV and mental stress.

Limitations of the study:

- The recording easily picked up power line noise and movements.
- Participants needed to wash their hair right after the experiment.
- Impedance of electrodes could not be checked
- Except the cameras, synchronization was still dependent on the starting time of each device. The experimenter did not have control over data synchronization.

Chapter 9.

Physiological Measurement and Self Report

Self-report is a widely used method in design research. In this chapter, we aimed to answer the question: does subjective measurement of mental stress and of mental effort agree with physiological data?

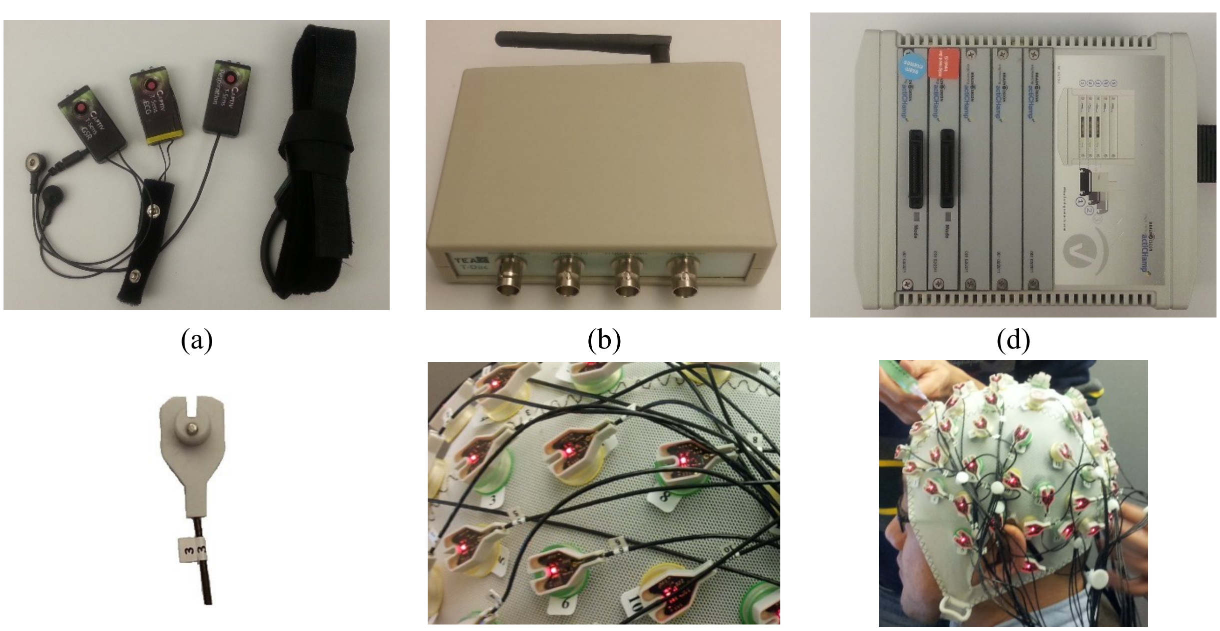
Subjective measures usually comprise a list of items questioning about emotion, mood and events of the respondents in the recent past. The measurement can be in discrete scales (Paas & Van Merriënboer, 1993) as in Subjective Workload Assessment Technique (SWAT) (Reid & Nygren, 1988) or in continuous scales as in NASA-TLX (Hart & Staveland, 1988)

We have devices that can give physiological signals to estimate cognitive effort and stress and we can manipulate design tasks to exert different workloads. Based on this reason, our choice of a self-report tool should meet the following criteria: (1) it can measure perceived cognitive effort, perceived psychological stress and cognitive workload, (2) it is short and easy to do, and (3) it has been validated. Based on these criteria, the unweighted 5-dimensional NASA-TLX was chosen for the current study. First, the NASA-TLX includes mental effort and mental stress in the rating. Although SWAT — another popular rating tool — also includes mental effort and mental stress as subscales, the NASA-TLX is more sensitive than SWAT for low mental workloads (Nygren, 1991) and it collects more information about the task than SWAT. Second, the unweighted NASA-TLX is short and is as effective as the original NASA-TLX (Byers *et al.*, 1989; Moroney *et al.*, 1992). The original NASA-TLX consists of six components: *mental demand, physical demand, time demand, performance, mental effort, and psychological stress*. Each component is weighted according to its importance to respondents (Hart & Staveland, 1988). The simplified version eliminates the weights, which means that the data collection takes less time because the respondents do not need to spend time ranking the components. In our experiment, because the experiment task was not physically demand, we remove the *physical demand* component from the rating to further shorten the procedure. Finally, the NASA-TLX has been widely used and validated (Hart, 2006).

9.1. Experiment

9.1.1. Recording devices and laboratory setting

Devices: to minimize the noise picked up by the electrodes, we purchased a new 64 channel EEG system with active electrodes and three new EEG caps of different head size from Brain Vision. Active electrodes are electrodes with built-in amplifier to increase the quality of the signals. The new EEG system also has built-in impedance check. The new caps allow electrodes to be plugged into the holders before the cap was put on the subject's head. This saved us a lot of preparation time.



(a) (b) (d)

(d) (e) (f)

Figure 56. (a) Heart rate, respiration rate and skin conductance sensors, (b) the wireless recorder, (c) 64 channel EEG, (d) and (e) active electrodes, (f) EEG cap.

We also acquired a CAPTIV system which can integrate the recording of electrocardiography, skin conductance, video, respiration rate and EEG. Moreover, the system enables experimenters to synchronize connected devices at any time through the software's interface. The only problem with this CAPTIV version is that the recorded video file is not compressed which means it takes a lot of disk space. Therefore, we did not use CAPTIV to record video. Instead, we record the video with Q-see DVR.

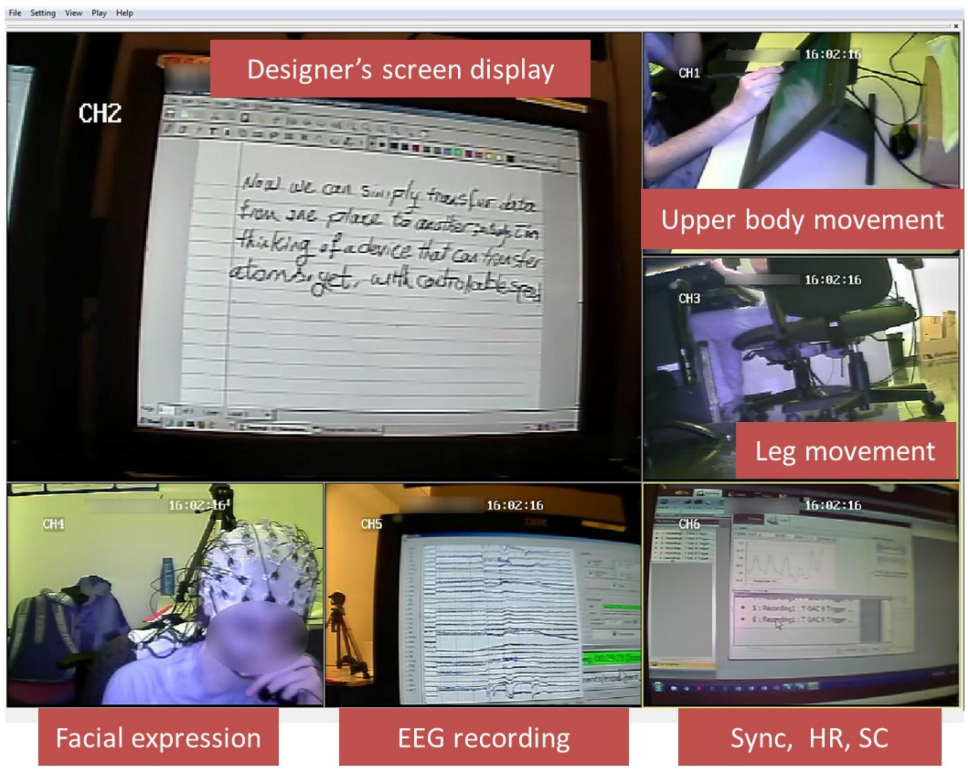


Figure 57. View from the control room.

9.1.2. Design task

Each participant solved 6 design tasks. Each design task consists of five phases as illustrated in Figure 58. In the first phase, participants were presented with a design problem. In the second and third phase, they generated a solution and rated their workload. In the fourth phase, the participants were presented with two different solutions; they had to evaluate which solution was better. Finally, in the last phase, the participants rated their workload again.

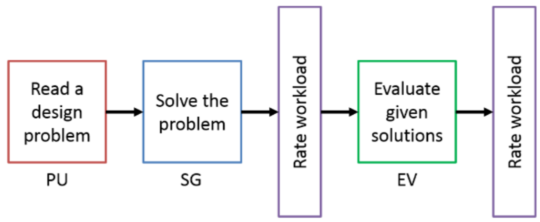


Figure 58. One design task consists of 5 phases.

An example of the 5 phase run is shown in Figure 59. Participants completed all the tasks at their own pace; no time limit was imposed and they could have one or more than one solutions. The six design tasks are listed in Table 21. All the design tasks were presented to the participants in the same order from A to F.

Table 21. The six design tasks

Task	Description
A	Make a birthday cake for a five year old kid. How should it look like?
B	Sometimes, we don't know which items should be recycled. Create a recycle bin that helps people recycle correctly.
C	Create a toothbrush that incorporates toothpaste. (Incorporate = include, combine)
D	In Montreal, people on wheelchair cannot use metros safely because most of the metros have only stairs or escalators. Elevator is not an option because it is too costly to build one. You are asked to create the most efficient solution to solve this problem.
E	Employees in an IT company are sitting too much. The company wants their employees to stay healthy and work efficiently at the same time. You are asked to create a workspace that can help employee to work and exercise at the same time.
F	Two problems with a standard drinking fountain: o Filling up water bottle is not easy. o People who are too short cannot use the fountain and people who are too tall have to bend over too much. Create a new drinking fountain that solves these problems.

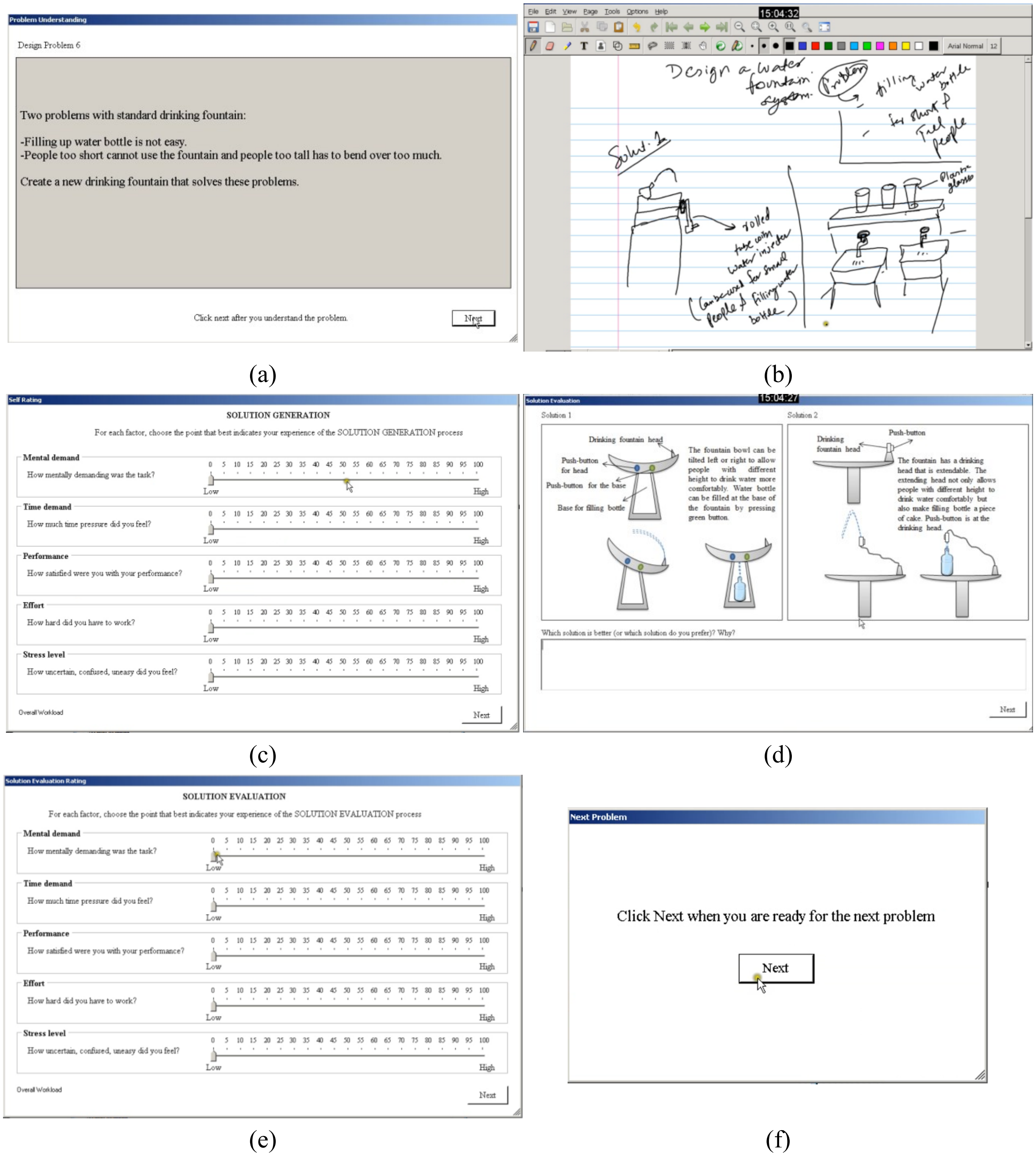


Figure 59. Design task F: (a) read the task, (b) give solutions, (c) rate NASA-TLX, (d) evaluate which solution is better and justify the choice, (e) rate NASA-TLX, (f) rest and be ready for next task.

9.1.3. Data Collection

Subjects sat in front of a Wacom tablet. The tablet display's position could be adjusted to accommodate participants of different heights. Screen recorder recorded design data. Cameras were positioned at different angles to capture hand gesture, facial expression and body movement. Two SC sensors collecting skin conductance at 32Hz were wrapped around the ring finger and the little finger of the subject's non-dominant hand. The electrocardiography (ECG) was collected at 256Hz by a sensor chest strap. A 64 channel EEG was recorded at 500Hz, following the 10-10 system of electrode placement. The recording was referential to Cz. Respiration rate was collected by an abdominal belt. Figure 60 illustrates how a subject wore the devices.

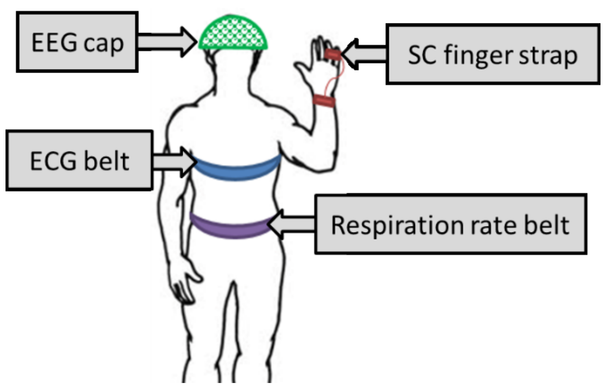


Figure 60. Illustration of how a subject wears physiological recording devices.

9.1.4. Procedure

Forty two students volunteered to participate in the experiment. Data of nine out of 42 students were discarded due to technical failures during the recording.

Among the 33 entered the analysis, 9 were females and 24 were males (age: 30 +/-6years, 3 left-handed). All of the participants had normal or corrected-to-normal vision. Most of them were Engineering students at Concordia University and were taking a design course.

All subjects signed the consent form before taking the experiment. Experimenters helped subjects wear the HRV chest strap, GSR finger strap, respiration rate belt and EEG cap. The experimenters explained the experimental procedure and the experimental tasks to the subjects. Then, the experiment started as follows: the subjects rested for three minutes with eyes closed — referred to as pre-test rest — and then were instructed to start the design. After completing all the tasks, the subjects rested again for three minutes with eyes closed — referred to as post-test rest. At the end of the experiment, the subjects were asked to rank the six design problems from the easiest to the most difficult.

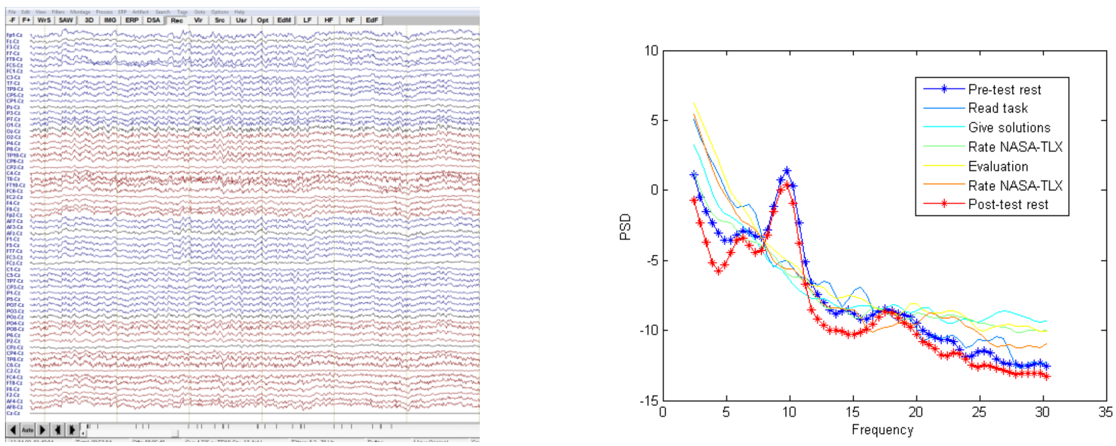
9.2. Data processing and analysis

9.2.1. EEG analysis

In this paper, we used EEG high beta band to measure mental effort because EEG beta is usually associated with active thinking (Dietrich & Kanso, 2010) and high beta from 20 to 30Hz was chosen to avoid individual alpha frequency which may extend beyond 13Hz (Goljahani *et al.*, 2012).

The 64 channel EEG data is shown in Figure 61(a). The Fz channel was chosen for analysis because it reflects the activities of frontal lobe and is less susceptible to muscle movement. The role of frontal lobe in thinking, working memory, and calculating has been widely reported (Sasaki et al., 1994; Stuss & Knight, 2013). EEG was band-pass filtered from 0.3Hz (forward, 6dB/oct) to 70Hz (zero phase, 24dB/oct). Then, ocular artifact was corrected (Ille et al., 2002). The EEG power spectral density was estimated using a Hamming window on 1 second epoch with 50% overlap. Figure 61(b) shows a PSD of a participant, computed for each stage, pre-test rest and post-test rest.

The beta2 relative power was calculated for problem understanding & solution generation (Figure 59(a) and Figure 59(b)), evaluation (Figure 59(d)), pre-test rest, and post-test rest by integrating the power density over 20-30Hz and then divided by the integration of the power density over 4-30Hz.



(a) (b)

Figure 61. (a) EEG data, (b) Power spectral density (PSD) of a participant in task A and two eyes close (EC) sessions.

9.2.2. SC analysis

The raw SC is shown in Figure 62. Zero value in SC was replaced by mean value of neighbouring SC. Each SC point was normalized by subtracting the minimum value and dividing the result by the difference between maximum and minimum value (see Eq.(47)).

$$SC_{normalized} = \frac{SC - SC_{min}}{SC_{max} - SC_{min}} \quad (47)$$

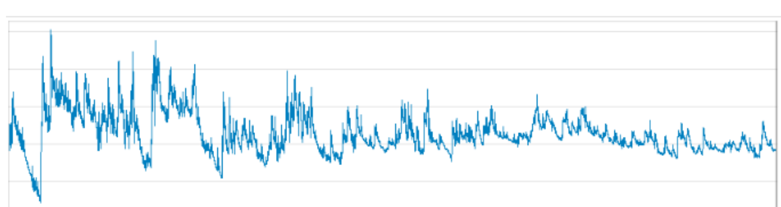


Figure 62. Raw SC data.

For each task, average normalized SC was computed for problem understanding & solution generation (PU&SG), evaluation (EV), pre-test rest and post-test rest.

9.2.3. Data trend and similarity index

From the plots of self-reported effort and EEG beta2 in Figure 63 (data have been scaled for comparison), we observed that the effort (solid red line) and beta2 (dash blue line) change in similar directions in the first three tasks A, B, and C. Therefore, we decided to compare the trends between self-reported data and physiological data. If the trends are similar, there is an association between physiological data and self-rated data.

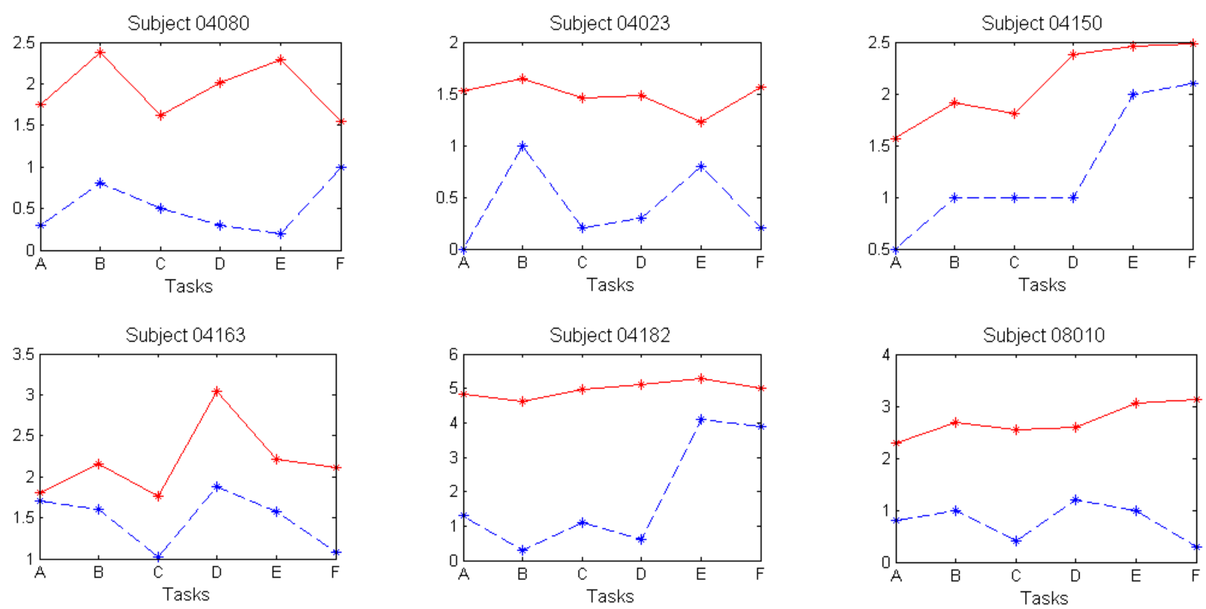


Figure 63. Self-reported effort (solid line) and EEG beta2 (dash line) of PU&SG activities at each design task.

To record the data trend, first, we computed the differences in each variable. For example, for SC variable, the difference between design task j and the preceding design task i is defined as:

$$d_{ij} = \quad SC_j - SC_i, \tag{48}$$

where SC_i and SC_j are SC data collected during task i and j respectively.

Next, the trend of SC for the design task j and the preceding design task i is determined as follows:

$$\Delta_{ij} = \begin{cases} 1 & if\ d_{ij} > 0 \\ 0 & if\ d_{ij} \leq 0 \end{cases} \quad (49)$$

In Eq.(49), value of 1 represents the increase and value of 0 represents the decrease in SC. Thus, the trend is an array of binary data. For each subject, the SC trend consists of 5 points: (B-A), (C-B), (D-C), (E-D), and (F-E).

The trends of EEG beta2, effort rating in NASA-TLX assessment, and stress rating in NASA-TLX assessment are computed in the same manner.

The similarity between the trends of two variables is measured by Simple Matching Coefficient (SMC) (Cheetham & Hazel, 1969; Sokal & Sneath, 1963), which is defined as:

$$SMC = \frac{M_{00}+M_{11}}{\sum M}, \quad (50)$$

where M_{00} is the number of pairs of elements where both have a value of 0, M_{11} is the number of pairs of elements where both have a value of 1, $\sum M$ is the total number of pairs of elements regardless of their values.

The SMC for the trend of beta2 and the trend of self-assessed effort and the SMC for the trend of SC and the trend of self-assessed stress were computed.

For significance test, Monte Carlo simulation was performed with 100,000 number of iterations to find the distribution of the SMC. The estimated distribution is presented in Figure 64.

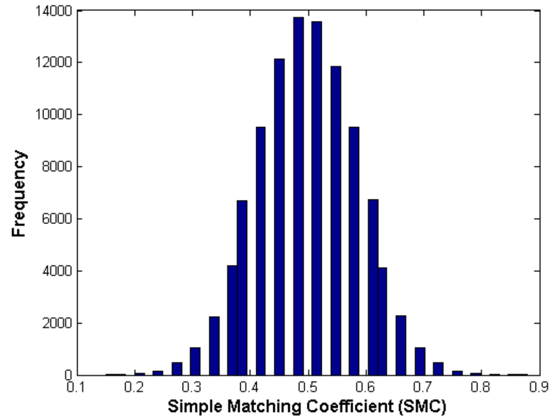


Figure 64. The distribution of Simple Matching Coefficient (SMC) from Mont Carlo simulation with 100,000 runs.

9.3. Results

9.3.1. Pre-test rest and post-test rest

Wilcoxon signed rank test shows that the SC in pre-test rest is significantly lower than the SC in post-test rest ($z = 2.314$, $p = 0.01 \leq 0.01$) but there is no difference between the EEG beta2 in pre-test and the EEG beta2 in post-test rest ($z = 0.87$, $p = 0.19$). The result is presented in Table 22 and Figure 65.

Table 22. Comparison of mean and median between pre-test rest and post-test rest

	Mean		Median		Pre-test rest vs. post-test rest
	Pre-test	Post-test	Pre-test	Post-test	
Beta2	0.161	0.161	0.135	0.141	$z = 0.87$, $p = 0.19$
SC	0.228	0.347	0.139	0.384	$z = 2.31$, ****p = 0.01** ≤ 0.01

The higher SC in post-test rest than in pre-test rest indicates that subjects continued to feel stressed even after the tests were over. This result confirms the delay in stress recovery which has been found to vary among individuals and among tasks (Linden *et al.*, 1997).

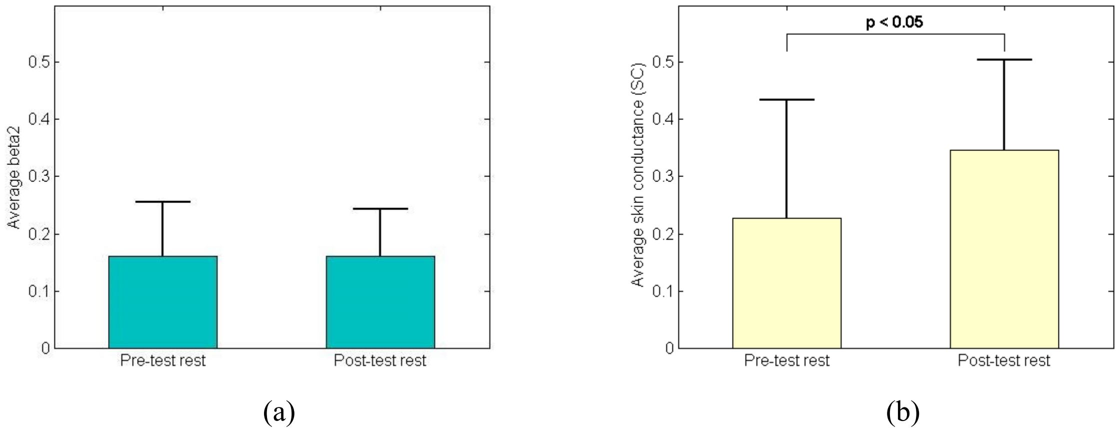


Figure 65. (a) Beta2 between pre-test rest and post-test rest, (b) SC in post-test rest is significantly higher than SC in pre-test rest.

9.3.2. Physiological responses and self-reported data

The similarity coefficients between self-reported data and physiological data are presented in Table 23. There was a significant association between self-reported effort and the EEG-indicated effort ($p=0.02 \leq 0.05$) in the first three tasks A, B and C. No association was found between self-rated effort and beta2 in other tasks as well as no association was found between self-rated stress and SC.

Table 23. Similarity index between physiological responses and self-assessed data

	Design tasks				
	(A, B)	**(B, C)**	**(C, D)**	**(D, E)**	**(E, F)**
SMC (beta2 and self-rated effort)	**0.70**	**0.70**	0.37	0.55	0.46
p-value	**p=0.02***	**p=0.02***	p=0.96	p=0.36	p=0.76
SMC (SC and self-rated stress)	0.36	0.48	0.48	0.45	0.60
p-value	p=0.96	p=0.64	p=0.64	p=0.76	p=0.148

Comparison of SC between rating activities found that SC significantly increased in task D rating (denoted as RD in Table 24), $p = 0.003 \leq 0.01$ and decreased in task E rating (denoted as RE in Table 24), $p = 0.002 \leq 0.01$. Beta2 marginally decreased in task F rating, $p = 0.057$.

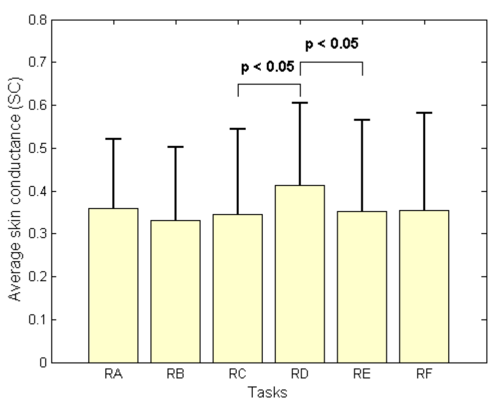
Comparison of beta2 between rating activities found that beta2 decreased in task F rating (p = 0.057) as shown in Table 25.

Table 24. Comparison of SCs between successive rating tasks

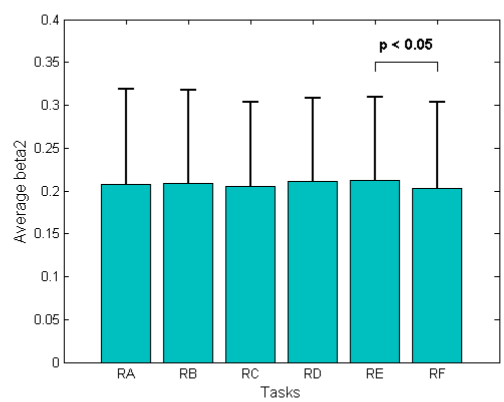
	Mean	SD	Median	RA	RB	RC	RD	RE
RA	0.359	0.161	0.362	-	-	-	-	-
RB	0.332	0.171	0.318	p=0.19	-	-	-	-
RC	0.345	0.198	0.327	-	p=0.41	-	-	-
RD	0.413	0.192	0.417	-	-	****p=0.003**	-	-
RE	0.351	0.215	0.349	-	-	-	****p=0.002**	-
RF	0.354	0.227	0.347	-	-	-	-	p=0.45

Table 25. Comparison of beta2 between successive rating tasks

	Mean	SD	Median	RA	RB	RC	RD	RE
RA	0.207	0.112	0.168	-	-	-	-	-
RB	0.208	0.109	0.183	p=0.2	-	-	-	-
RC	0.205	0.098	0.178	-	p=0.22	-	-	-
RD	0.211	0.097	0.188	-	-	p=0.5	-	-
RE	0.212	0.097	0.188	-	-	-	p=0.2	-
RF	0.203	0.1	0.172	-	-	-	-	$^{+}$**p=0.057**



(a)



(b)

Figure 66. Mean and standard deviation of (a) SC and (b) beta2 during rating tasks.

There was a significant association between self-reported effort and EEG beta2 in the first three tasks A, B and C. However, after task D, this association was no longer observable. A closer look at the rating activities reveals that designers' stress increased significantly during the rating for task D (in Table 24, RD vs. RC, p = 0.003) while the effort did not increase (in Table 25, RD vs. RC, $p = 0.5$). Thus, it is possible that the stress during the rating played a role in the difference between the subjective rating and the physiological signals. The designers were probably under high stress during the task D rating; they did not report their mental state properly, which caused the similarity coefficient to drop in (C, D) and (D, E).

It was expected to see a significant association between beta2 and self-rated effort in (E, F) because designers were not under as high stress in task E rating and task F rating as they were in task D rating. Nevertheless, the similarity coefficient remained low for (E, F) ($p=0.76$, Table 23). We noticed that the effort has marginally decreased during the rating for task F (in Table 25, RE vs. RF, $p = 0.057$) whereas stress remained the same. Therefore, it is possible that the participants did not put much effort into the rating for task F and this might be the reason for the difference between self-rated effort and beta2.

9.3.3. Mental stress between design tasks

Wilcoxon signed rank test showed that during PU&SG activities, stress significantly increased in task D ($z = 2.52$, $p = 0.006 < 0.01$) and significantly decreased in task F ($z = 1.76$, $p = 0.04 < 0.05$). Table 26 and Figure 67 showed the comparison of SC stress between design tasks.

Table 26. Comparison of SC stress between successive design tasks (PU&SG activities), **p≤.01, *p≤.05

	Mean	SD	Median	A	B	C	D	E
A	0.375	0.16	0.369	-	-	-	-	-
B	0.365	0.133	0.354	*p=0.39*	-	-	-	-
C	0.371	0.167	0.374	-	*p=0.23*	-	-	-
D	0.430	0.184	0.434	-	-	*****p=0.006***	-	-
E	0.408	0.199	0.411	-	-	-	*p=0.2*	-
F	0.389	0.217	0.360	-	-	-	-	****p=0.04***

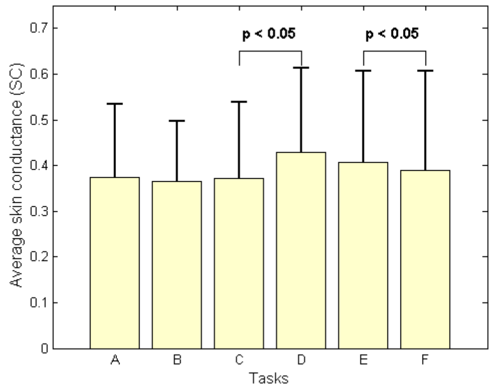


Figure 67. Mean and standard deviation of SC in PU&SG activities.

Table 27. Summary of the difference between change in self-rated data and change in physiological data

	Change in self-rated effort is significantly associated with change in EEG beta2?		**Change in self-rated stress is significantly associated with change in SC stress?**	
	Yes/No	**Possible causes**	**Yes/No**	**Possible causes**
(A, B)	Yes ($p=0.007$)		No ($p=0.91$)	Stress is not significantly different between tasks A and B ($p=0.39$ in Table 26). The designers might not be able to see the difference.
(B, C)	Yes ($p=0.007$)		No ($p=0.5$)	Stress is not significantly different between tasks B and C ($p=0.23$ in Table 26). The designers might not be able to see the difference.
(C, D)	No ($p = 0.04$)	High stress during the task D rating ($p = 0.003$ in Table 24)	No ($p=0.5$)	High stress during the task D rating ($p = 0.003$ in Table 24).
(D, E)	No ($p=0.24$)	High stress during the task D rating ($p = 0.002$ in Table 24).	No ($p=0.64$)	Stress is not significantly different between tasks D and E ($p=0.2$ in Table 26). The designers might not be able to see the difference. Also, stress is high in the task D rating ($p = 0.002$ in Table 24).
(E, F)	No ($p=0.63$)	Decreased effort in the task F rating ($p = 0.057$ in Table 25).	Marginally yes ($p=0.08$)	The difference in stress between E and F is differentiable (E >> F, $p=0.04$ in Table 26) but there is a decrease in effort during the task F rating ($p = 0.057$ in Table 25).

No association between self-rated stress and SC stress was found for (A, B), (B, C), (C, D) and (D, E) (Table 23). The first reason could be that the stress induced by the design tasks A, B, and C was not differentiable enough. The stress was not significantly different in these three tasks as shown in Table 26. The second reason could be that when the stress induced by a task became significantly high such as in task D ($p = 0.006 < 0.01$ in Table 26), the designers did not perform well during the rating because their stress was high (RD >> RC, $p = 0.003$ in Table 24; RD >> RE, $p = 0.002$ in Table 24).

Table 26 shows a significant stress decrease from task E to task F ($p=0.04$), which means that the stress was differentiated enough between tasks E and F. It was presumed that there was a significant association between SC stress and self-rated stress. Nevertheless, there was no association ($p = 0.148$ in Table 23). The reason could be that the effort during the task F rating has decreased ($p = 0.057$ in Table 25), meaning that the raters did not put much effort during the rating.

Table 27 summarizes possible causes of the mismatches between changes in self-rated data and changes in physiological data.

9.4. Conclusions

Data from thirty-three participants were analysed in the experiment. Each participant completed a series of six design problems. The experiment was designed based on two assumptions: (1) a complex design can be recursively divided into a series of similar design problem and (2) each has basic design problem solving activities including requirement identification, knowledge search, solution generation, and solution evaluation. By designing a six consecutive sub-design tasks, we intended to simulate a complex design process, which consists of at least six sub-design processes.

EEG, skin conductance and self-rated data, among others, were recorded. The EEG beta2 power at Fz and average skin conductance were used to estimate cognitive effort and mental stress, respectively. Self-rated mental effort and self-rated mental stress were collected through NASA-TLX assessment.

We found that designers' stress induced during the design process would continue to last even after the design had been completed. The mental effort, however, was not affected by the residual stress. Our analysis also shows that self-rating is a mental activity by itself which may be subject to the effect of stress and the amount of cognitive effort. The result of rating may be incorrect if the raters do not put much effort into the rating or if the raters are under high stress. Therefore, researchers who use self-assessment should take into account the stress and effort of the raters during the rating activities to ensure the validity of the self-report.

Chapter 10. Microstate Analysis of Design Activities

This section presents the ongoing works. The experiment setting, design task, experiment procedure and data collected are the same as that introduced in Chapter 9. The analysis was performed for problem understanding (PU) and reading of given solutions (EV-a). The EV-a, where the subject looked at the given solutions, is part of the solution evaluation (EV) process mentioned in Chapter 9. The other part of EV (see Figure 68(e)) is when the subjects gave their answers by typing in the textbox.

10.1. EEG processing

EEG was band-pass filtered from 1Hz (forward, 6dB/oct) to 40Hz (zero phase, 24dB/oct). Bad channels were interpolated. The data were then transformed to average reference and downsampled from 500 Hz to 128Hz using EEGlab (Delorme & Makeig, 2004).

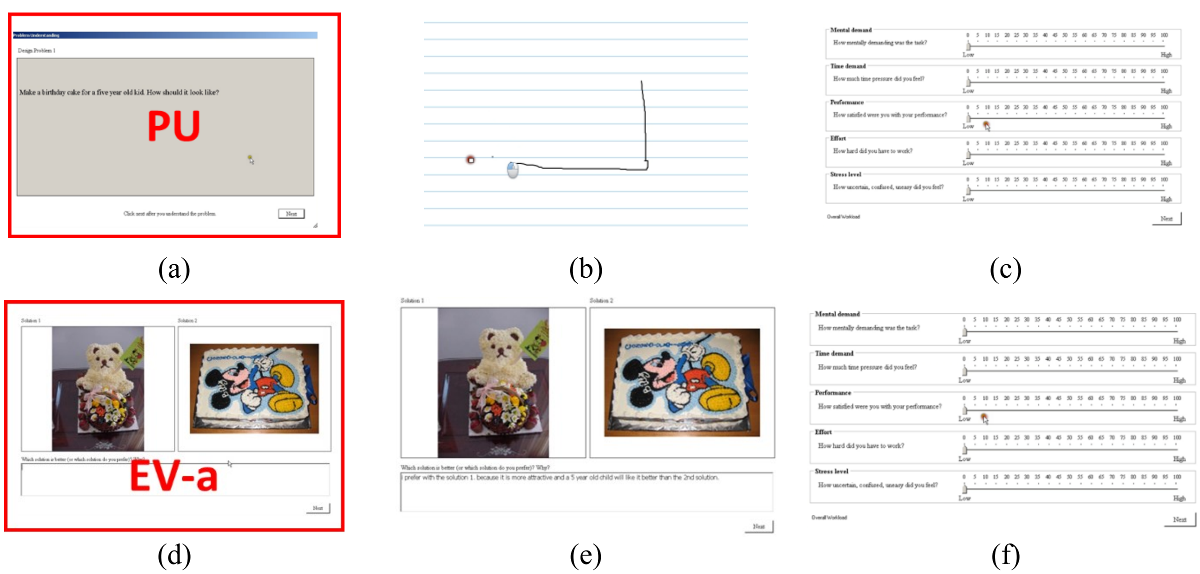


Figure 68. Data analysis was performed for PU and EV-a activities only.

For each subject, local maximum Global Field Power (GFP) was then extracted for PU and EV-a activities separately using Cartool software (Brunet *et al.*, 2011). Figure 69 shows the local maximum GFP of an EEG segment.

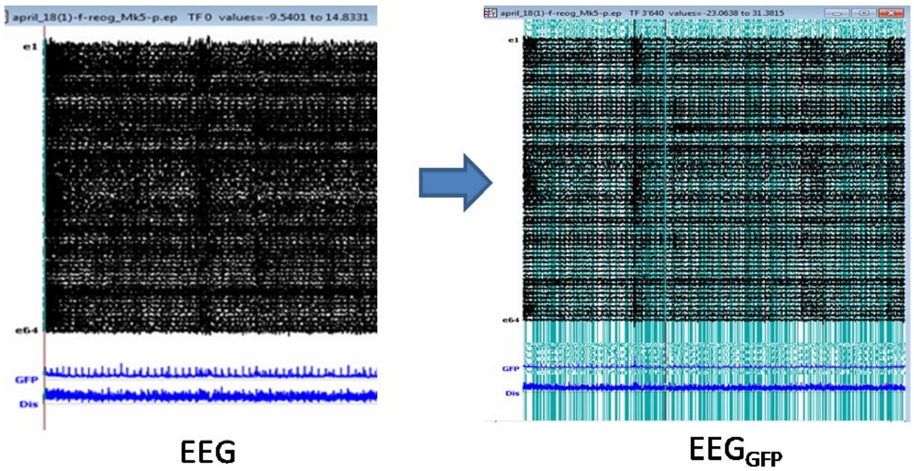


Figure 69. GFP extracted from 63 channel EEG data.

Each subject performed six design task, each design task has PU and EV-a activities. Thus, in total, each subject has 12 sets of extracted GFP.

10.2. Microstate analysis

In this approach, the 12 sets of extracted GFP of each subject were clustered to get individual microstate classes. The number of individual microstate classes can be different among subjects. Next, all the individual microstate classes were clustered again to obtain group microstate classes. The 12 group microstate classes are shown in Figure 70. Then, the group microstate classes were fitted back to the individual EEG data.

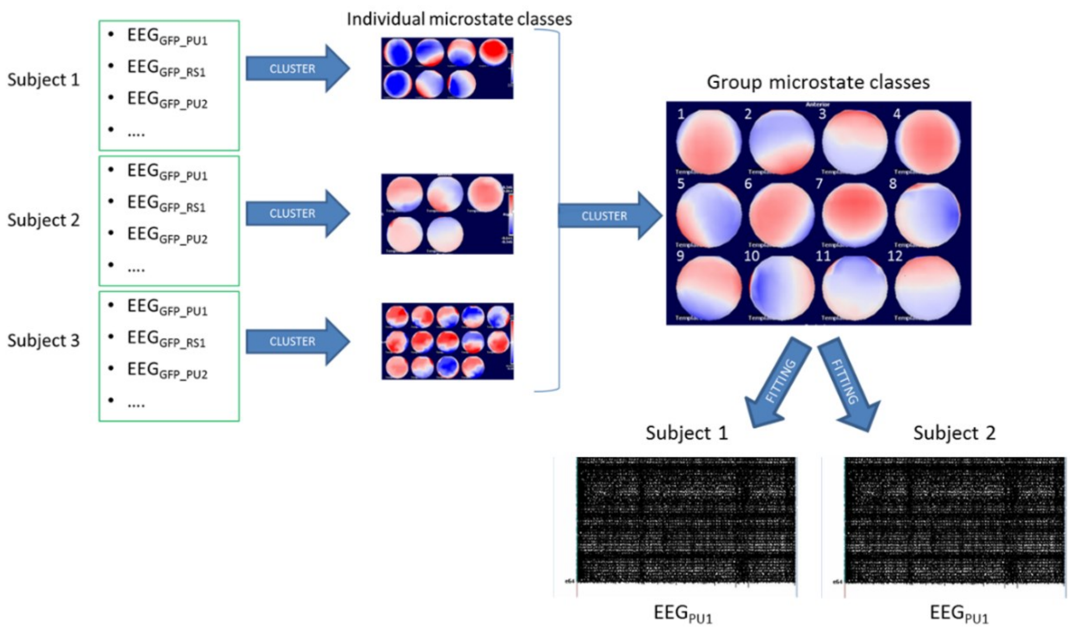


Figure 70. PU and RS were clustered together to get group microstate classes. Theses classes were then fitted back to each individual data.

Percentage of appearance of each map was computed for each subject and each activity. An example of how the percentage of appearance of map 1 in PU activity was computed is depicted in Figure 71.

	PU 1	PU 2	PU 3	PU 4	PU 5	PU 6
map 1	215	458	226	323	738	488
map 2	553	1077	504	761	1716	1074
map 3	19	87	33	73	218	68
map 4	268	616	221	449	940	621
map 5	192	435	238	375	804	548
map 6	336	860	448	628	1306	807
map 7	835	1821	658	1132	2965	1536
map 8	62	287	118	292	300	376
map 9	273	653	318	485	1332	800
map 10	16	37	16	18	32	63
map 11	11	19	8	17	46	22
map 12	147	276	98	142	516	151
Total	2927	6626	2886	4695	10913	6554

% of appearance:

$$\text{Map 1, PU1} = \frac{215}{2927} = 0.074$$

$$\text{Map 1, PU2} = \frac{458}{6626} = 0.069$$

....

Figure 71. Calculation of percentage of appearance for map 1 in PU activity for one subject.

The number of times map i appears more frequently in one activity than in the other activities was computed as the number of times % of appearance of map i in one activity greater than in the other activities. The calculation is illustrated in Figure 72, where PU1 is the PU activity in design task A.

	PU1	PU2	PU3	PU4	PU5	PU6
map 1	0.073	0.069	0.078	0.069	0.068	0.074
map 2	0.189	0.163	0.175	0.162	0.157	0.164
map 3	0.006	0.013	0.011	0.016	0.02	0.01
map 4	0.092	0.093	0.077	0.096	0.086	0.095
map 5	0.066	0.066	0.082	0.08	0.074	0.084
map 6	0.115	0.13	0.155	0.134	0.12	0.123
map 7	0.285	0.275	0.228	0.241	0.272	0.234
map 8	0.021	0.043	0.041	0.062	0.027	0.057
map 9	0.093	0.099	0.11	0.103	0.122	0.122
map 10	0.005	0.006	0.006	0.004	0.003	0.01
map 11	0.004	0.003	0.003	0.004	0.004	0.003
map 12	0.05	0.042	0.034	0.03	0.047	0.023

	EV-a1	EV-a2	EV-a3	EV-a4	EV-a5	EV-a6
map 1	0.09	0.09	0.081	0.09	0.09	0.083
map 2	0.177	0.16	0.175	0.157	0.162	0.172
map 3	0.009	0.013	0.009	0.016	0.011	0.011
map 4	0.106	0.095	0.115	0.096	0.09	0.105
map 5	0.067	0.078	0.073	0.076	0.098	0.081
map 6	0.116	0.138	0.115	0.123	0.108	0.123
map 7	0.23	0.218	0.239	0.211	0.238	0.221
map 8	0.036	0.048	0.039	0.053	0.031	0.058
map 9	0.093	0.107	0.116	0.122	0.125	0.105
map 10	0.008	0.005	0.007	0.005	0.006	0.01
map 11	0.003	0.005	0.003	0.007	0.005	0.004
map 12	0.064	0.043	0.028	0.043	0.036	0.026

If PU_{ij} > $EV\text{-}a_{ij}$, m_{ij} = 1, else m_{ij} = 0

map 1	0	0	0	0	0	0
map 2	1	1	0	1	0	0
map 3	0	0	1	0	1	0
map 4	0	0	0	0	0	0
map 5	0	0	1	1	0	1
map 6	0	0	1	1	1	0
map 7	1	1	0	1	1	1
map 8	0	0	1	1	0	0
map 9	1	0	0	0	0	1
map 10	0	1	0	0	0	1
map 11	1	0	0	0	0	0
map 12	0	0	1	0	1	0

Number of times map i appears more frequently in PU than in EV-a

		> 3		
map 1	0		map 1	-
map 2	3		map 2	-
map 3	2		map 3	-
map 4	0		map 4	-
map 5	3		map 5	-
map 6	3		map 6	-
map 7	5		map 7	5
map 8	2		map 8	-
map 9	2		map 9	-
map 10	2		map 10	-
map 11	1		map 11	-
map 12	2		map 12	-

Figure 72. Calculation of frequency of appearance.

Table 28. Result of frequency of appearance

	Map 1	Map 2	Map 3	Map 4	Map 5	Map 6	Map 7	Map 8	Map 9	Map 10	Map 11	Map 12
PU	9	9	16	11	16	16	11	15	12	12	13	17
EV-a	14	13	8	13	11	10	13	11	14	14	11	9

Table 28 shows the results of the higher frequency of appearance of a map in one activity over the other activity. For example, according to Table 28, there are 9 out of 33 participants who have map 1 appearing more frequently in PU activity than in EV-a activity and 14 out of 33 participants who have map 1 occuring more frequently in EV-a than in PU.

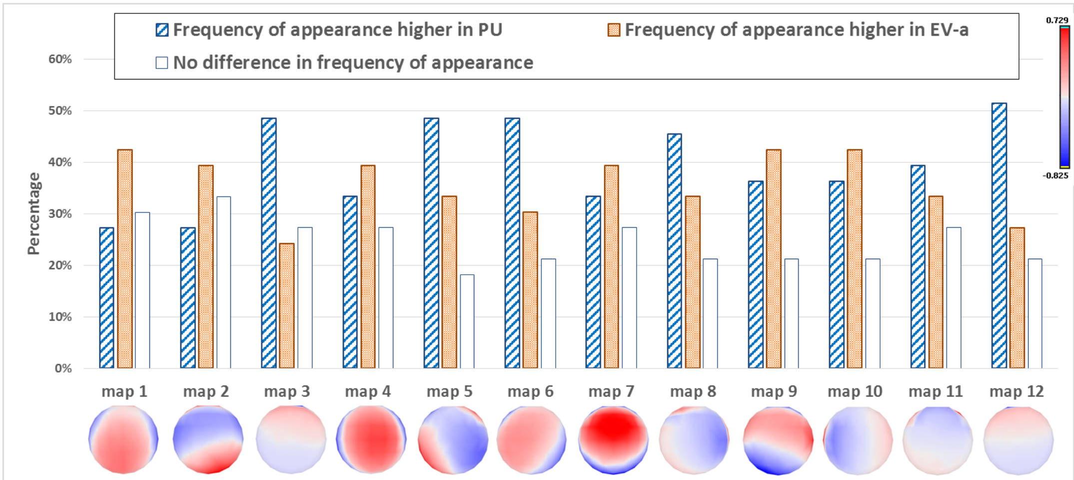
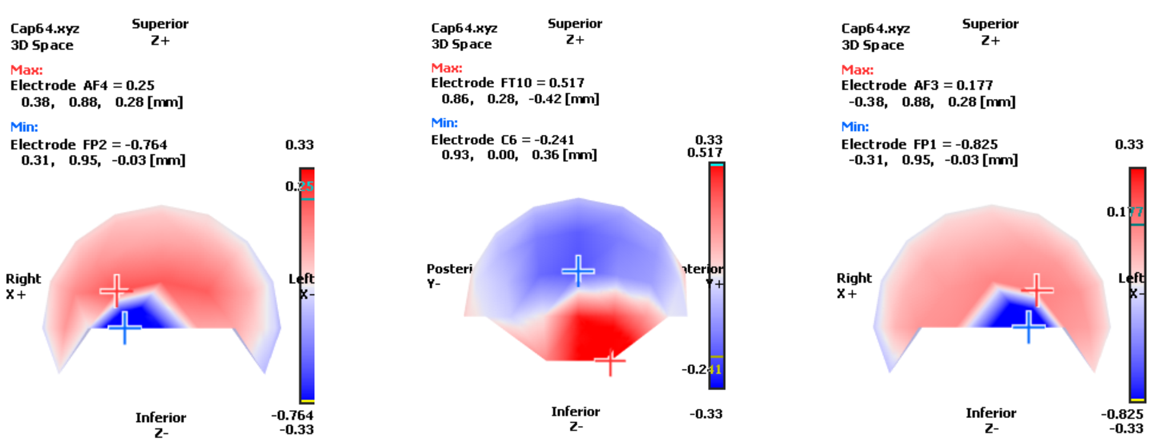


Figure 73. Frequency of appearance of EEG maps.

10.3. Observation and discussion

It can be seen from Figure 73 that more than 45% of the participants show the dominance of map 3, map 5, map 6, map 8, map 12 in PU activities. However, among those, map 3, map 8 and map 12 seem to relate to artifact because the EEG maps show focal activity as seen in Figure 74. Between map 5 and map 6, map 6 shows larger difference between PU & EV-a (46% vs 37%).



(a) (b) (c)

Figure 74. (a) Map 3, (b) map 8, and (c) map 12 may relate to artifact as the maps show focal activity.

Map 1, map 9 and map 10 all have frequency of appearance in EV-a higher than 40% and higher than in PU; among those, map 1 shows the largest difference between PU & EV-a (43%).

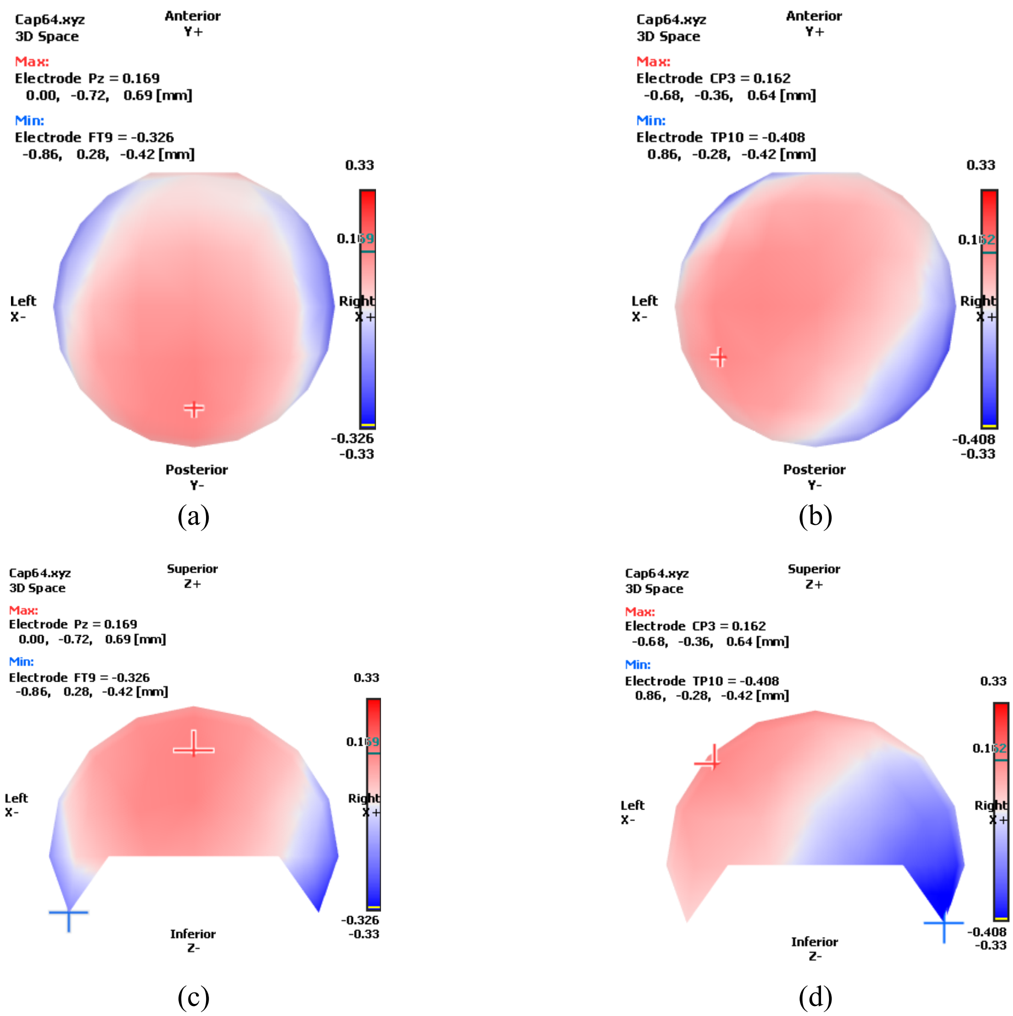
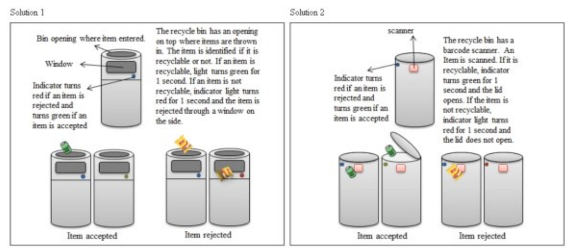


Figure 75. Map 1 appears more frequent in EV: (a) top view, (c) side view; map 6 appears more frequent in PU: (b) top view, (d) side view.

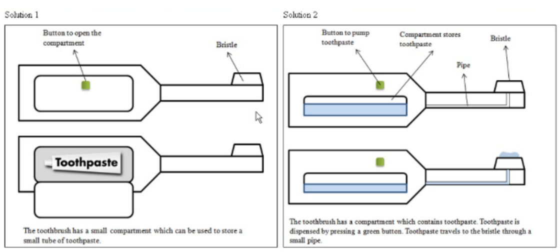
Thus, for future analysis, we may want to perform source localization to further investigate the cognitive sources of microstate. In the meantime, we tempt to say that the peak in map 1 locate in the posterior of the cortex which is responsible for visual processing and cognitive activity in map 3 locates in the left hemisphere which is linked to language processing (see Figure 75).

This makes sense to us as in EV-a task, participants had to evaluate two solutions in pictures and in PU task they had to read and understand task requirements. Furthermore, while all design requirements (PU tasks) were given in texts, not all evaluation (EV-a tasks) were given in sole pictures. Some EV-a tasks include product description next to the product pictures as shown in Figure 76, participants might need to read these descriptions to understand the given solutions, which means that visual information was not always dominant during EV-a tasks. This may explain why the number of subjects showing map 1 dominant (visual processing) during EV is lower than the number of subjects showing map 6 dominant (language processing) during PU.

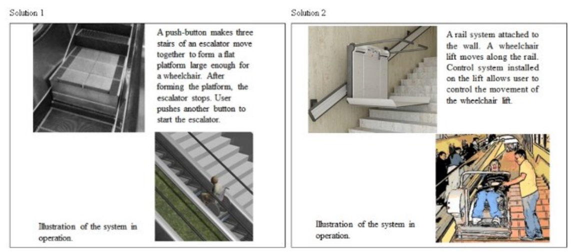
Evaluation: task A



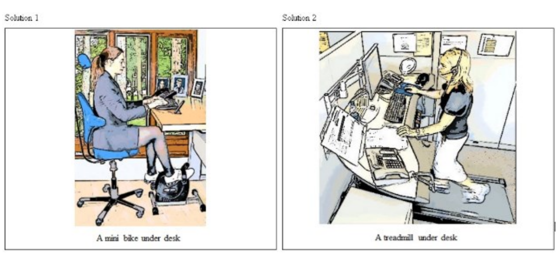
Evaluation: task B



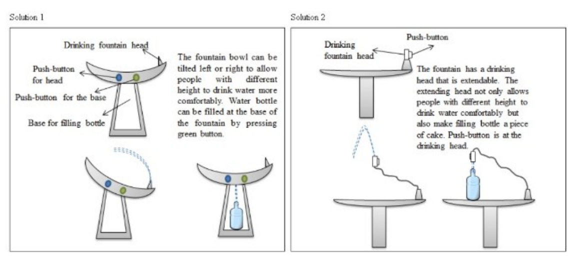
Evaluation: task C



Evaluation: task D



Evaluation: task E



Evaluation: task F

Figure 76. Evaluation tasks: some solutions given in pictures and some solutions given in pictures and words.

Chapter 11. Preliminary Study of Creativity

11.1. Experiment design

11.1.1. Recording devices and laboratory setting

The experiment design is the same as the one introduced in Chapter 9.

11.1.2. Design task and data collection

The experiment consists of two main tasks. In the first task, participants were presented to a sketch. They were instructed to write down what they intuitively saw from the sketch and they could add additional details to the sketch to clarify their ideas. In the second task, the same sketch was given. This time, the participants were required to think creatively. They were instructed to create a concept that was different from what they originally perceived. Participants had maximum three minutes to complete each task. The test was developed based on the Torrance test of creativity thinking (Torrance, 1966) which was modified to fit our aim. According to (Luo & Knoblich, 2007), an experimental task for neuroimaging studies of creativity must satisfy the following requirements:

(1) The task has to elicit cognitive process of interest.

(2) The cognitive event has to happen within a known period of time.

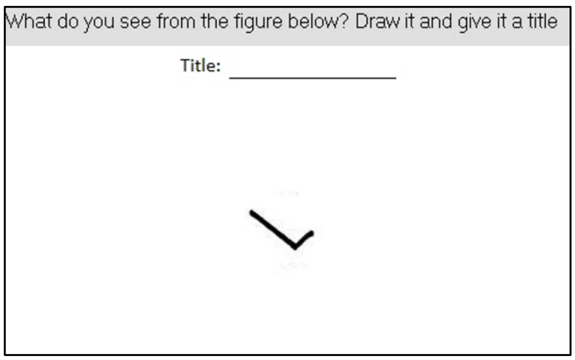
(3) The test should be flexible to enable researchers to test alternative hypotheses (general and specific hypotheses).

(4) Control state must be comparable with the target state (similar problem elements and solution procedures).

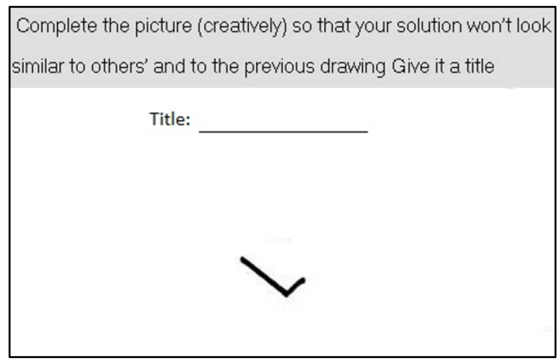
(5) The test should allow internally and externally triggered insights (to compare between internally and externally triggered insights).

In addition to the above requirements, for our experiment, we need the task to be short (maximum 10 minutes), and domain and language independent (many of our participants come from different countries).

Figure 77 shows an example of the two tasks. After completing the second task, participants have to rate their experience, as shown in Figure 78.



(a)



(b)

Figure 77. (a) First task, (b) second task.

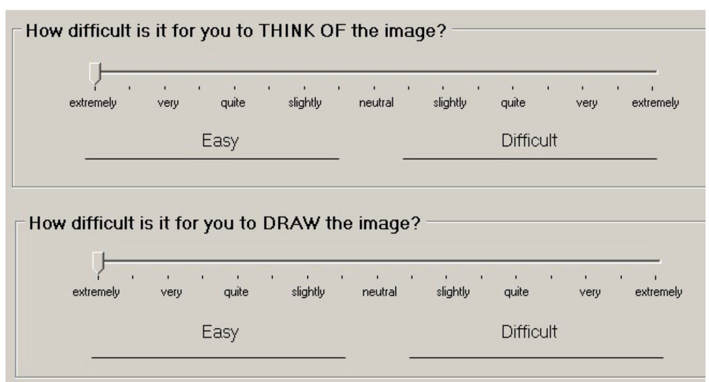


Figure 78. Rating.

Participants had to repeat the whole process three times with different sketches each time. The sketches used in the experiment were presented to all the participants sequentially, in the same order as shown in Figure 79. Data captured include EEG 63 channels, ECG, SC, respiration rate, body movement and design data.

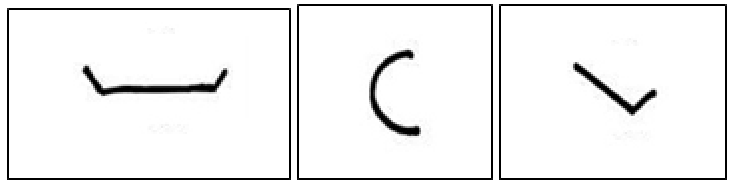


Figure 79. Sketches presented to the participants in the experiment.

11.1.3. Procedure

Twenty nine graduate students from the Concordia Institute for Information Systems Engineering volunteered to participate in the experiment. They all followed the procedure listed below:

(1) Rest for 3 minutes with eyes closed.

(2) Perform task 1, task 2 and do the rating.

(3) Repeat step 2) two more times with different pictures (as shown in Figure 79).

(4) Rest for 2 minutes with eyes closed.

11.2. Observation

In general, we found that the drawings in task 2 contain more details than the drawings in task 1 and that it took the participants longer (approximately 14 seconds) to start giving solutions in task 2 than in task 1. Some answers given by the participants are presented in Table 29.

We also notice that what is creative to one might not be creative to others. One subject drew a book (non-creative response) in task 1 but another subject drew a book (creative response) in task 2, as shown in Table 30.

Table 29. Answers from participants

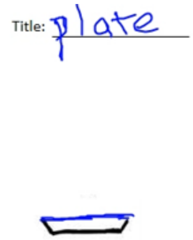
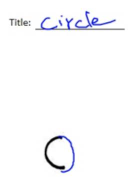
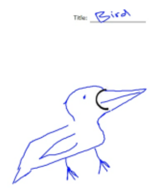
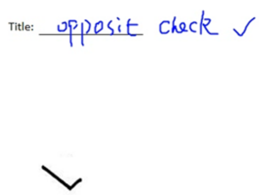
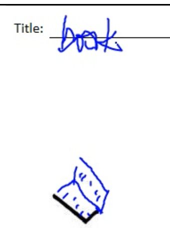
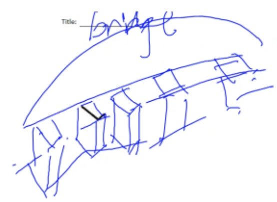
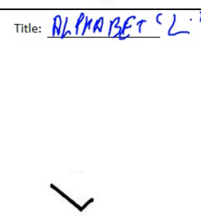
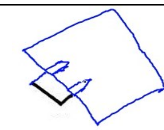
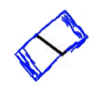
Initial sketch	Task 1	Task 2
		
		
		

Table 30. The solution "book" is considered as creative for one subject but not for another

Subjects	Task 1	Task 2
S020514_2		
S031314		

Some subjects have very similar responses. An example is shown in Table 31. In general, there are more similar responses in task 1 than in task 2. As shown in Figure 80, for the first picture, in task 1 four ideas are found common among subjects whereas only two ideas are found common in task 2.

Table 31. Similar solutions to task 1

Subjects	Task 1	Task 2
S021714_2	 Letter L	 Suitcase
S031314	Title: ALPHABET 'L' 	Title: BOOK 

Task 1

Answer	# ans.
Boat	9
Tray/plate	6
Bathtub	2
Bowl	3

Answer	# ans.
Letter C	8
Ball	5
Mug	2
Ice-cream	2
Circle	3

Answer	# ans.
Tick mark	4
Box	2
Stick	3
Letter L	3
Wave	2
Mountain	2

Task 2

Answer	# ans.
Boat	7
Crown	3

Answer	# ans.
Face	2
Ear	4
Flower	3

Answer	# ans.
Mountain	3
Leg	2
Roof	2

Figure 80. Common answers.

11.3. EEG analysis

11.3.1. Individual frequency

Research has shown that the traditional division of band frequency (i.e. theta from 4-8Hz, alpha from 8-13Hz, and beta from 13-30Hz) may obscure the research result (Klimesch, 1999), especially when the individual's band frequency does not fall into the traditional range. Therefore, in this analysis, we re-compute the exact range of each band for each subject.

We used the program developed by (Goljahani *et al.*, 2014) to calculate individual alpha frequency. After the alpha frequency range is identified, other bands are computed as: theta = [alpha lower bound – 2Hz, alpha lower bound], beta = [alpha upper bound, 30Hz].

The individual alpha frequency range is computed by finding the intersection between the alpha during eyes closed resting and the alpha during eyes open as illustrated in Figure 81.

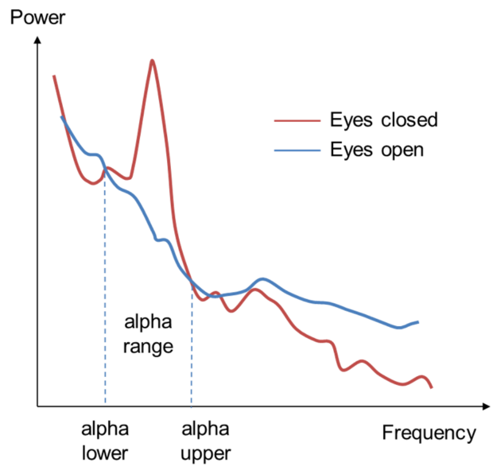


Figure 81. Individual alpha frequency range.

In the current analysis, the EEG eyes closed is the one minute resting EEG extracted from the 3 minute pre-test resting and the EEG eyes open is the one minute EEG extracted from the first creative task (task 2). Alpha frequency was computed for all lobes together.

11.3.2. Time-frequency analysis

EEG data was filtered from 0.3Hz to 70Hz using BESA software. The EEG spectrogram for each task was computed using spectrogram function in Matlab 2011.

For one subject, we visually found that his Fz channel seemed to reflect his behavior data. The frequency bands of this subject are: theta (4.8-6.8 Hz), alpha (6.8-11.60 Hz), and beta (11.60 -30 Hz). The subject showed strong alpha in the posterior area during resting as illustrated in Figure 82.

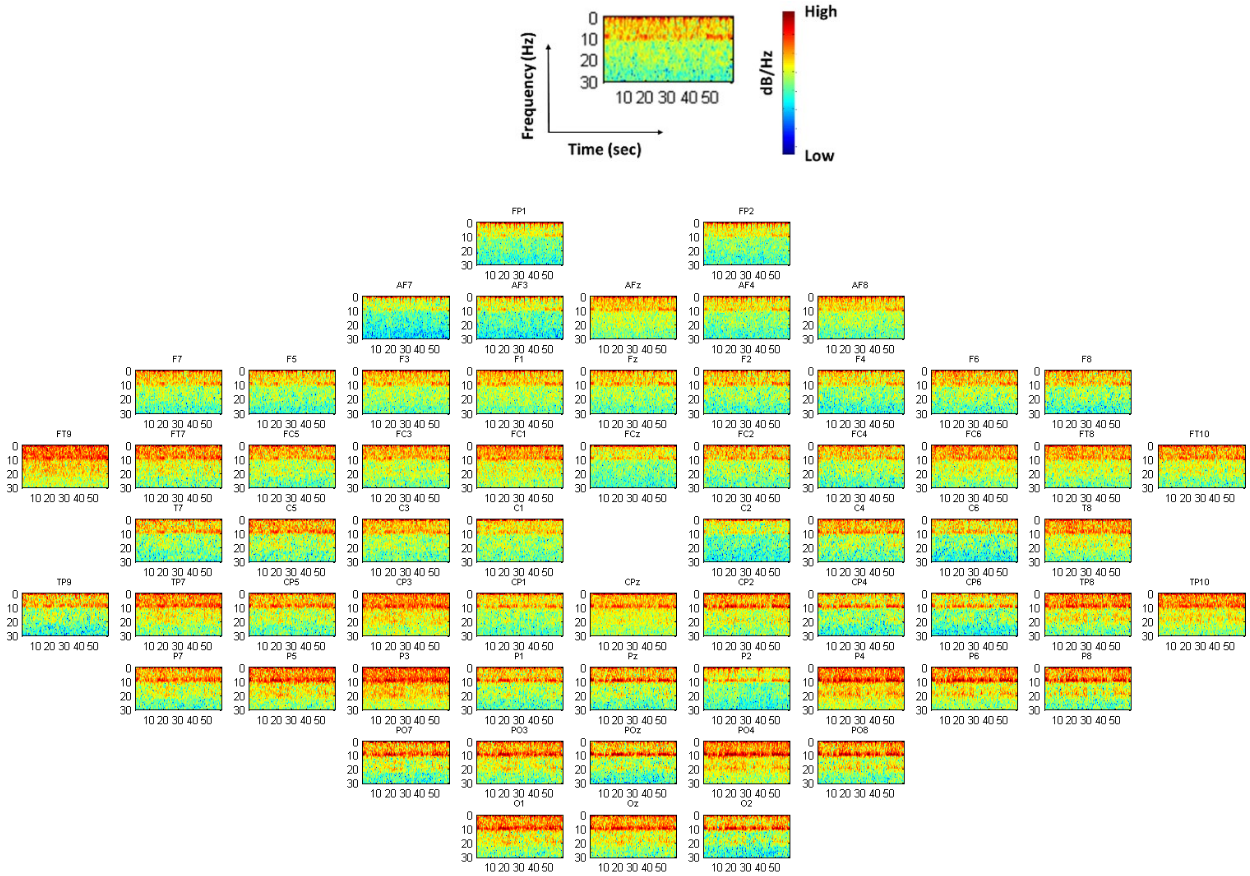
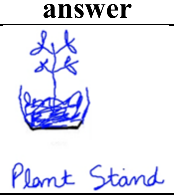
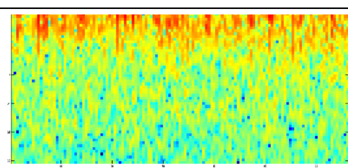
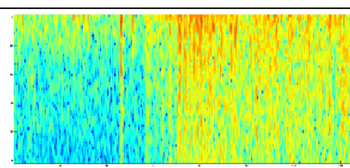
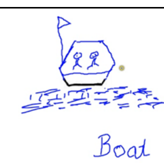
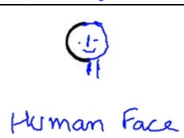
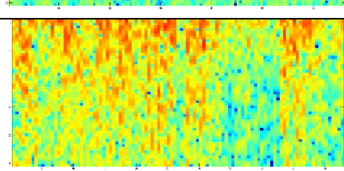
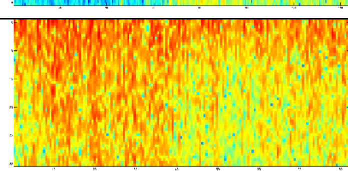
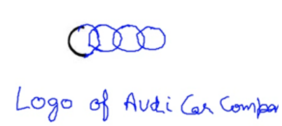
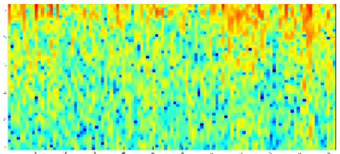
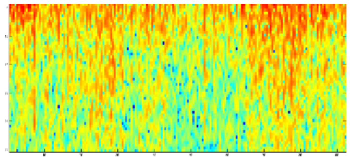
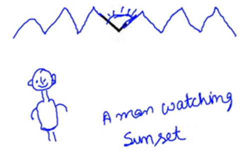


Figure 82. EEG spectrogram of 63 channels during resting state with eyes closed.

For the subject, beta power in task 2 is stronger than in task 1, as seen in Table 32.

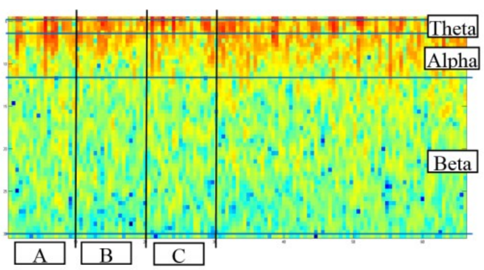
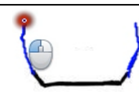
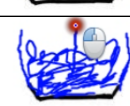
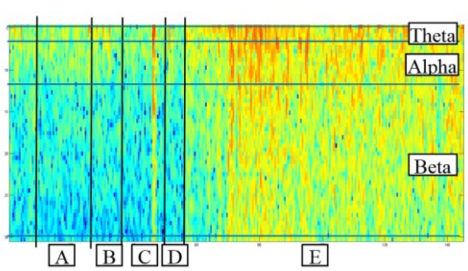
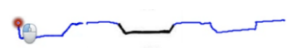
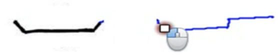
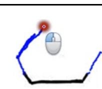
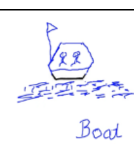
Table 32. Sketches and the corresponding spectrogram of the subject (Nguyen & Zeng, 2014b)

Non-creative answer	Non-creative	Creative	Creative answer
			
			

Looking into his entire solution generation process in detail, we found that beta was strong when the subject appeared to put efforts into the thinking. For example, for the first sketch, in task 2, when the subject drew a simple repeating pattern, the beta was low in segment A, B, C and D (see Table 33). Segment E shows high beta, this is where he drew a boat, a more "complex" idea.

Table 33. First sketch: the creating process and corresponding spectrograms

Spectrogram	Segment (Seconds)	Activity	Description
Non-creative answer 	A (0-10)		Moves the pen around but not drawing
	B (10-20)		Draws the vase
	C (20-30)		Fill the vase with random strokes
			Final solution
Creative answer 	A (8-26)		Draws a repeating pattern
	B (26-36)		Pauses and looks at the sketch
	C (36-50)		Erases the sketch
	D (50-56)		Pauses and looks at the figure
	E		Draws
			Final solution

For the second sketch, in task 1 (see Table 34), where the subject erased and re-wrote the word "Human" (segment A and segment B), beta was lower than in other segments. Apparently, the subject did not need to put much effort or thinking into to the rewriting. In task 2, overall the power in all bands was strong except there was a weak/medium power in beta band around 50 to 60 seconds (region B and C). The subject was erasing and redrawing the picture during this time

Table 34. Second sketch: the creating process and corresponding spectrograms

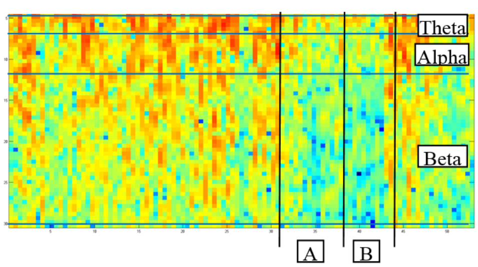
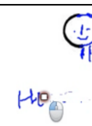
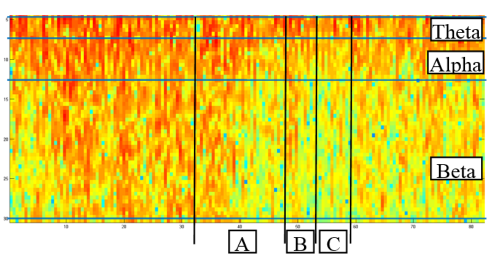
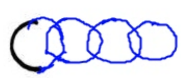
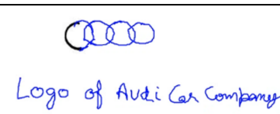
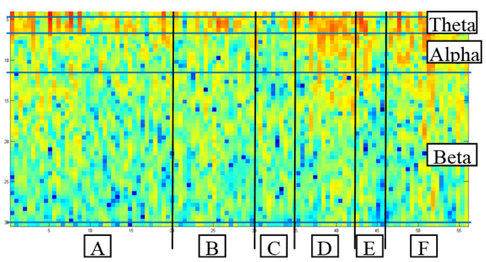
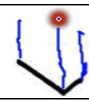
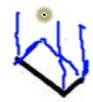
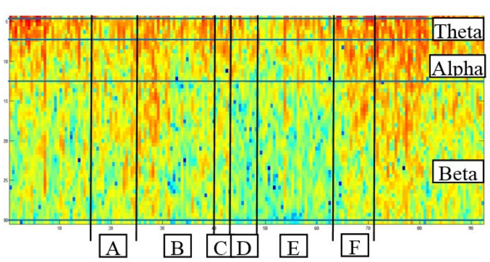
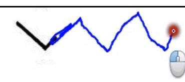
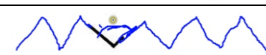
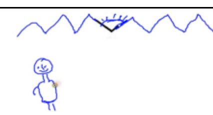
Spectrogram	Segment (Seconds)	Activity	Description
Non-creative answer 			Draws and writes "Human"
	A (31-38)		Erase "uman" in the word "Human"
	B (38-44)		Write again "uman"
			Final solution
Creative answer 			Moves pen around but not drawing
	A (32-48)		Draws circles
	B (48-53)		Erases
	C (53-59)		Draws again
			Final solution

Table 35. Third sketch: the creating process and corresponding spectrograms (Nguyen & Zeng, 2014b)

Spectrogram	Segment (Seconds)	Activity	Description
Non-creative task 	A (0-20)		Moves the pen around the picture but not drawing
	B (20-30)		Draws 3 vertical lines
	C (30-35)		Draws horizontal lines for the bottom
	D (35-40)		Draws horizontal lines for the top
	E (42-46)		Draw another vertical line
	F (46-end)		Write "Box" to complete the task
Creative task 	A (16-25)		Draws repeating patterns
	B (25-40)		Add the sun to the picture
	C (40-43)		Add another stroke to the mountain
	D (43-48)		Moves the pen but not drawing
	E (49-63)		Draw a human figure
	F (63-67)		Add ears to the human figure
			Final solution

For the third sketch. It was not very clear how EEG spectrogram related to behavior data in task 1. In the task 2, beta are relatively weak in segment D and E compared to other segments. In E, he drew a human figure. A strong beta burst in the middle of E occurred when he completed the face which was drawn in previous round. After this strong beta burst, which might indicate a "new idea" came to his mind, he drew the body of the human figure that he did not draw before. After E, beta got stronger. This is where he added ears — a "new" feature (he did not draw ears in his previous drawing) — to the human figure and wrote the description for the sketch.

11.4. Discussion

Beta was weak when the subject did not put much effort in the task. For instance, beta was very weak when the subject fixed a small mistake (e.g. erased and rewrote a word as shown in task 1 in Table 34, or erased and redrew a line as shown in task 2 in Table 34) or when he redrew a concept that he generated previously (e.g. redrawing a human face which was drawn in task 1 Table 34 results in low beta, as shown in region E in Table 35). In general, beta was higher in creative tasks than in non-creative tasks.

Due to individual differences, subjects may not show similar patterns. Research also shows that EEG signals are affected by personality-trait (Mizuki *et al.*, 1992; Mizuki *et al.*, 1984). Therefore, in the future we possibly need to classify subjects into groups based on their resting EEG or other baseline physiological signals.

Some limitations of the experiments are:

1) One participant seemed to use the time in the first question to think of the solution for the second question. So, the signals were mixed between the first and the second questions.
2) Some participants perceived different concepts from a picture at the first sight. For example, a participant might see a letter L and a tick mark from the sketch. So, he/she answered letter L in task 1 and then answered tick mark in task 2. In this case, the participant did not act creatively in task 2. To address this problem, we

tried to explain the experiment task and its purpose to the participants. We emphasized the importance of being creative and being different in the second question.

3) The signals were sometimes destroyed by subjects' extreme movements such as yawning or head turning.
4) The signals on a certain part of the cortex were sometimes not strong enough to be captured.
5) For 3 minutes, it was hard to create something "out of the box".

Chapter 12. Discussions and Conclusions

12.1. Summary and contribution of the research

The extension of ATDM and its application were presented. Specifically, the inverted U curve relation of stress/creativity was introduced as the second postulate in ATDM. The aim is to give ATDM explanatory power. To demonstrate its explanatory power, the impact of sketching on design performance was explained using design governing equation, mental capability, the inverse U relationship between psychological stress and creativity introduced in ATDM.

ATDM was continued to use to identify conditions leading to and develop formal model of design fixation, a phenomenon where designer use a known solution to solve a problem even when the solution is not suitable or irrelevant. Being fixated on the wrong solution results in poor quality solutions but being fixated on the right solution may prevent designers from generating creative solutions. The conditions are as follows: 1) the designer is too attached to a solution that s/he is unconsciously or consciously unable to abandon it or make major changes and 2) the designer does not have the right perception of the current problem because s/he applies his pre-occupied solution/knowledge to frame the design problem. The application of the model is demonstrated using data from existing research studies.

Another contribution of the present thesis is an integrated experimental environment which was developed for the physiological study of design cognition. The environment enables researchers to synchronously collect video data, EEG, ECG, skin conductance, and respiration rate during a design process. It should be noted that setting up the experimental environment is a design process where problems and solutions recursively updated as depicted in Figure 84. Solutions to a problem at one state change the environment and a new problem emerges. For instance, to obtain good signals, besides having active electrodes, we increase the number of EEG electrodes. On the one hand, the large number of electrodes will be helpful in data interpolation when the signals in some channels turn bad. On the other hand, we encounter another problem, i.e. more electrodes means longer preparation time and inconvenience to participants as participants need to wash their hair right after the test to remove electrode gel.

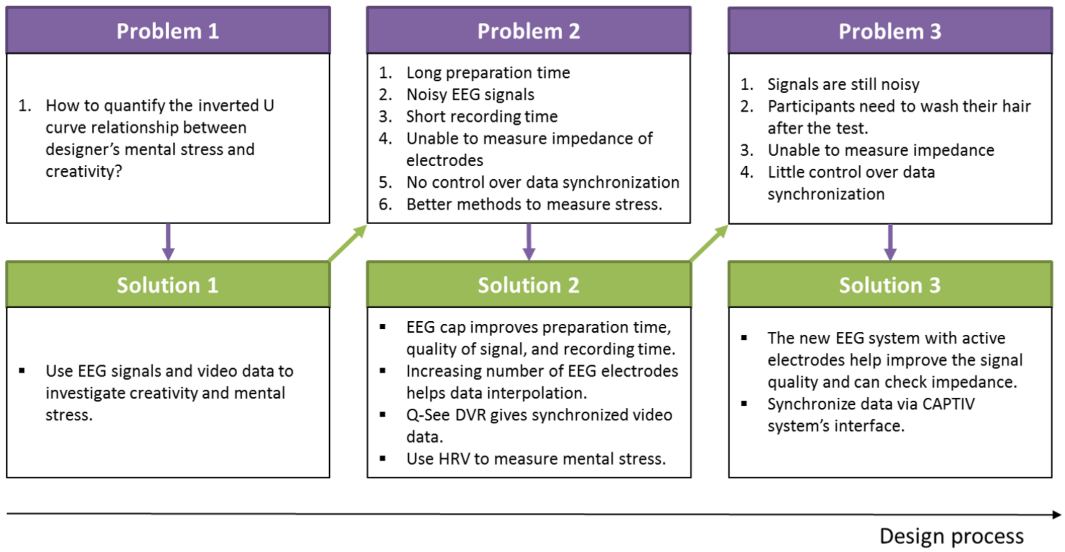


Figure 83. The design process of building the experimental environment.

Methodology for analyzing physiological signals such as EEG, heart rate variability, and skin conductance for design tasks was proposed. As a result, a Matlab program to facilitate the analysis process was built. Figure 84 shows the interface of the program.

From the analysis of physiological signals, the following findings were reported: 1) designers' stress induced during the design process would continue to last even after the design had been completed. The mental effort, however, was not affected by the residual stress, and 2) self-rating is by itself a mental activity which may be affected by psychological stress and may be influenced by the amount of cognitive effort allocated. Researchers who rely on subjective rating should take into account the stress and effort of respondents during the rating activities to ensure the validity of the self-report.

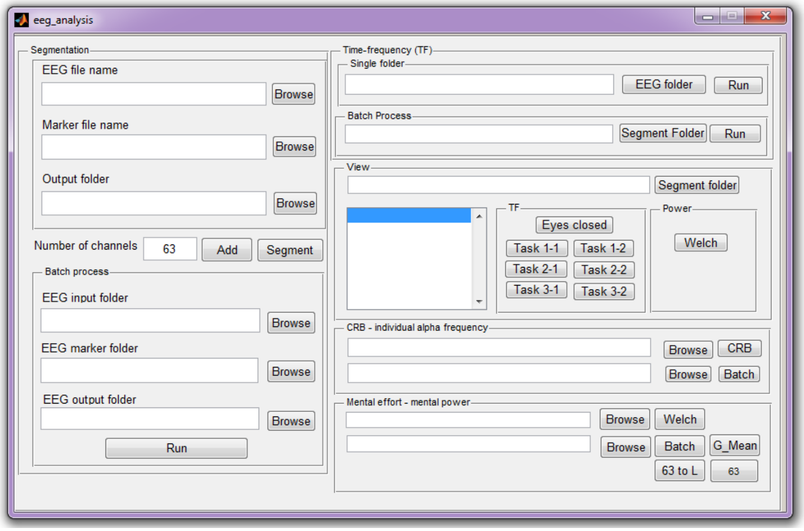


Figure 84. Matlab program to streamline the EEG analysis process.

The thesis also demonstrated the feasibility of using physiological data in design research. In particular, EEG was adopted to measure mental effort, HRV and skin conductance were used to quantify mental stress of designers during the design process.

12.2. Future work

Although ATDM has been showed to be able to interpret some design phenomena, more design phenomena need to be explained using ATDM to show its scope and capacity. In addition, in our work, models derived from ATDM were validated with past findings in the literature. In the future, empirical tests that are attempted refutations will be conducted to further validate the models.

Some experimental data were recorded but have not been used such as respiration rate and electrocardiography. Therefore, more analyses will be performed to take advantage of these available data. Microstate analysis of EEG will be continued. This approach has a potential to deliver some fascinating results. Other techniques such as source localization can also be considered.

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APPENDIX A: APPROVAL OF EXPERIMENTS INVOLVING HUMAN SUBJECTS

UNIVERSITÉ Concordia UNIVERSITY

CERTIFICATION OF ETHICAL ACCEPTABILITY
FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant: Dr. Yong Zeng

Department: Faculty of Engineering and Computer Science \ CIISE

Agency: Natural Sciences & Engineering Research Council

Title of Project: Cognitive Studies of Design

Certification Number: 10000041

Valid From: March 10, 2016 to: March 09, 2017

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

Dr. James Pfaus, Chair, University Human Research Ethics Committee

APPENDIX B: CHARACTERISTICS OF PARTICIPANTS

Study	Total participants	Participants analysed		
		Gender		Age
		Male	Female	
Preliminary study (Chapter 7)	2	-	1	25
Mental effort vs mental stress (Chapter 8)	14	5	2	25-35
Physiological measurement and self-report, microstate study (Chapter 9, Chapter 10)	44	24	9	24-36
Preliminary study of creativity (chapter 11)	29	1	-	(unknown)

APPENDIX C: PUBLICATIONS

Journal papers:

1. **Nguyen, T. A**. & Zeng, Y. (2016). A Theoretical of Design Fixation. *International Journal of Design Creativity and Innovation* (accepted).
2. **Nguyen, T. A**.& Zeng, Y. (2016). Effects of Stress and Effort on Self-Rated Reports in Experimental Study of Design Activities. *Journal of Intelligent Manufacturing*, 1-14. doi: http://dx.doi.org/10.1007/s10845-016-1196-z
3. **Nguyen, T. A**.& Zeng, Y. (2014). A Physiological Study of Relationship between Designer's Mental Effort and Mental Stress During Conceptual Design. *Computer-Aided Design, 54*(0), 3-18. doi: http://dx.doi.org/10.1016/j.cad.2013.10.002
4. Christophe, F., Mokammel, F., Coatanéa, E., **Nguyen, A.**, Bakhouya, M., & Bernard, A. (2014). A Methodology Supporting Syntactic, Lexical and Semantic Clarification of Requirements in Systems Engineering. *International Journal of Product Development, 19*(4), 173-190.
5. Yi, H., **Nguyen, T. A.**, & Zeng, Y. (2013). Humour and Creative Design: Twins or Partners? *J. Integr. Des. Process Sci., 17*(4), 81-92. doi: 10.3233/jid-2013-0020
6. **Nguyen, T. A.**& Zeng, Y. (2012). A Theoretical Model of Design Creativity: Nonlinear Design Dynamics and Mental Stress-Creativity Relation. *Journal of Integrated Design and Process Science, 16*(3), 37-60.
7. Dubois, S., Tate, D., Conrardy, C., **Nguyen, T. A.**, Guioa, R. d., & Gaik-wad, A. (2012). Comparing the Strategies and Outputs of Designers Using Algorithm of Inventive Problem Solving, Axiomatic Design, or Environment-Based Design. *J. Integr. Des. Process Sci., 16*(3), 89-110. doi: 10.3233/jid-2012-0018
8. He, G. Q., **Nguyen, T. A.**, & Zeng, Y. (2010). Experimental Approach to Curve Reconstruction Based on Human Visual Perception. *J. Integr. Des. Process Sci., 14*(1), 51-66.
9. **Nguyen, T. A.**& Zeng, Y. (2010). A Vision Based Graphical Password. *J. Integr. Des. Process Sci., 14*(2), 43-52.

Conference papers:

1. Liu, L., **Nguyen, T.A.**, and Zeng, Y., (2016). *Identification of Relationships Between Electroencephalography (EEG) Bands and Design Activities*. Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Charlotte, North Carolina, USA.
2. Nguyen, P., **Nguyen, T.A.**, and Zeng, Y., (2016). *Quantitative Analysis of the Effort-Fatigue Tradeoff in the Conceptual Design Process: A Multistate EEG Approach*. Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Charlotte, North Carolina, USA.
3. Tan, S., **Nguyen, T.A.**, and Zeng, Y., (2016). *Role of perception in engineering design*." Proceedings of the Proceedings of Tools and Methods of Competitive Engineering (TMCE) 2016, Aix-en-Provence, France.
4. Nguyen, P., **Nguyen, T. A.**, & Zeng, Y. (2015). *Measuring the Evoked Hardness of Design Problems Using Transient Microstates.* ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, V007T006A029-V007T006A029
5. Nguyen, P., **Nguyen, T. A.**, & Zeng, Y. (2015). *Physiologically Based Segmentation of Design Protocol.* DS 80-11 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 11: Human Behaviour in Design, Design Education, , July 27-30, Milan, Italy
6. Wang, X., **Nguyen, T. A.**, & Zeng, Y. (2015). *Influence of Information Collection Strategy in Problem Formulation on Design Creativity through Mental Stress: A Theoretical Analysis.* DS 80-11 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 11: Human Behaviour in Design, Design Education.
7. Xu, X., **Nguyen, T. A.**, & Zeng, Y. (2014). *Galvanic Skin Response as Index of Mental Workload in Design Activities.* Proceedings of Tools and Methods of Competitive Engineering (TMCE) 2014,
8. **Nguyen, T. A.**& Zeng, Y. (2014). *A Preliminary Study of Eeg Spectrogram of a Single Subject Performing a Creativity Test. Innovative Design and Manufacturing (ICIDM).*

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9. **Nguyen, T. A.**, Xu, X., & Zeng, Y. (2013). *Distribution of Mental Stresses During Conceptual Design Activities*. Proceedings of 19th International Conference on Engineering Design (ICED'13), Seoul, Korea.
10. **Nguyen, T. A.**& Zeng, Y. (2012). *Clustering Designer's Mental Activities Based on EEG Power*. Proceedings of Tools and Methods of Competitive Engineering, 7-11 May, Karlsruhe, Germany.
11. Rodica, P., **Nguyen, T.A.**, and Zeng, Y., (2011). *ROM based understanding of ISO standard."* Proceedings of the SDPS Transdisciplinary Conference on Integrated Systems, Design, and Process Science, Seoul, Korea.
12. **Nguyen, T. A.**& Zeng, Y. (2010). *Analysis of Design Activities Using Eeg Signals*. ASME Conference Proceedings, 2010(44137), 277-286.
13. Petkar, H., Dande, S., Yadav, R., Zeng, Y., and **Nguyen, T.A.**, (2009). *A Pilot Study to Assess Designer's Mental Stress Using Eye Gaze System and Electroencephalogram.* Proceedings of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, pp. 899-909.