To investigate power of brain activity using EEG comparison between creative and non-creative design task

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Abstract

To investigate power of brain activity using EEG comparison between creative and non-creative design task

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In recent times, neurophysiological measurement methods such as EEG and fMRI are widely used in an Engineering field to study designer's brain activity during creative thinking. In literature, many researchers reported the synchronization and desynchronization of EEG activity in specific brain cortex during creative thinking. However, we do not find many studies associated to comparison of designer's brain activity during creativity/non-creativity related task demands. The chief objective of present thesis is to investigate the power of brain activity using EEG comparison between creative and non-creative design task. For psychometric measures of creative thinking, Torrance Test of Creative Thinking (TTCT) (Torrance, 1966) is widely used. In present thesis, we use modified TTCT according to our experiment requirement. The test was decomposed between creative and non-creative design task. In creative design task, designers were instructed to think creatively whereas in non-creative design task they were required to think intuitively. When designers were performing these design tasks, their EEG recordings were obtained to investigate brain activity during design tasks. The EEG powers are calculated through spectral analysis. We aggregate electrode positions to identify distribution of EEG powers among brain regions during cognitive task performance. In order to compare EEG between creative and non-creative design task using cortical area to area approach, we perform repeated measure ANOVA for within-subject factors such as design task and brain areas. However, we found non-significant interaction effect between creative/non-creative design task and cortical areas.

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Chapter 1. Introduction

1.1 Conceptual design

Conceptual design is the first phase of an engineering design process, which is primarily divided into three phases: conceptual design, preliminary design, and detail design (Birkhofer, 2011; Mayer, 2012) as shown in figure 1.1. In conceptual design, searching for ideas is the primary activity for designers (Sarkar & Chakrabarti, 2014). An ability to combine these ideas in such a way that can result in a creative design, which is both novel and useful, highly relies on designer's creative thinking (T. M. Amabile, 1996; Finke, Ward, & Smith, 1992). It can be said that quality of design depends on designer's performance during design process.

1.2 Design creativity

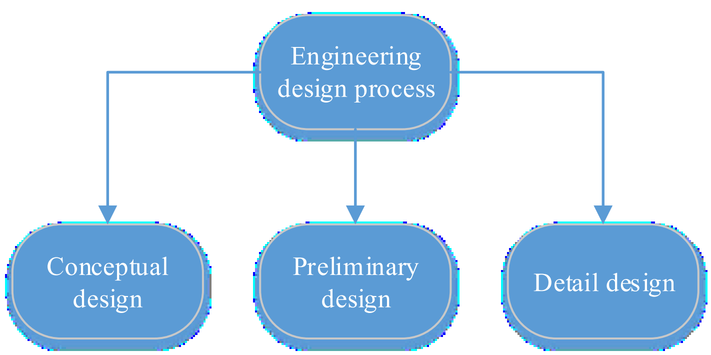


Figure 1-1: Engineering design process (Birkhofer, 2011; Mayer, 2012)

Design is an activity driven by designer's knowledge. Design process includes design knowledge and design information to be tackled by designer (Tomiyama, 2006). Design process is recursive in nature where all the design components (i.e. design problem, design solution, design knowledge, design process and specifically designers) integrated to achieve design creativity and/or creative performance. Designer's performance during conceptual design process largely depends upon his/her emotional state (i.e. mental stress). There is U curve relationship between designer's mental stress and mental efforts (Nguyen & Zeng, 2014a). These studies are discussed in detail in current thesis. Mental effort (i.e. total use of cognitive resources) is low at high stress level. Mental effort is also associated with creativity. (Nguyen & Zeng, 2014b) investigated the phenomenon that designer's performance is more creative (i.e. provide creative design solutions) in creative design task compare to non-creative design task because they put more mental effort in creative design task.

1.2.1 Creative and non-creative design task

The performance of creative people is characterized by their ability to produce novel output (unique/original ideas), to produce large quantity of ideas (i.e. ideational fluency), to think flexibly (i.e. an ability to generate variety of ideas (divergent thinking)) (Guilford, 1962). Torrance Test of Creative Thinking (TTCT) (Torrance, 1966) empirically tested for psychometric measures of creative thinking (Plucker & Renzulli, 1999). In TTCT, participants required to complete partial drawings. These drawings are then evaluated by experts that if these are creative drawings or not. Divergent thinking is measured by visual TTCT, which is an important aspect of creativity (Wu, Gao, Wang, & Ding, 1981). However in their EEG experiment, (Nguyen & Zeng, 2014b) modifies visual TTCT according to task requirement because they were not focus on evaluation of creativity. The focus of study was to identify areas of brain which are activated during design task. Therefore, they needed two cognitive states to compare. Thus, they use two types of design tasks to compare: creative design task and non-creative design task. In non-creative design task, participants required to think intuitively from the given sketches and give title to them. In creative design task, participants instructed to think creatively and generate original ideas, which they did not use in non-creative design task. The participants had to repeat this process for two more sketches.

1.3 EEG and design task

EEG plays a significant role to understand designer's thinking and cognitive process during design task. The designer's brain electrical signal is recorded by EEG when they work on a design task. It is possible to investigate designer's mental effort through EEG signals during the conceptual design process (Nguyen & Zeng, 2010). EEG used in variety of cognitive tasks and experimental procedures have yielded evidence of possible brain correlates underlying creative thinking (Fink, Benedek, Grabner, Staudt, & Neubauer, 2007). EEG signals are reported in frequency ranges: delta (1-4Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), gamma (30-50 Hz). Spectral analysis is done to obtain EEG powers. Event-related synchronization (ERS) and Event-related desynchronization (ERD) are known as changes in power in time-locked events (Pfurtscheller & Da Silva, 1999). EEG recorded yields ERP response to external stimuli which involves several components that provide information about different cognitive processes (Dietrich & Kanso, 2010). In a number of EEG experiments, (Neubauer, Fink, & Grabner, 2006; Neuper & Klimesch, 2006) studied the impact of different cognitive processes specifically involved in creative idea generation task (i.e. visual TTCT). They reported strong increase in EEG alpha activity (i.e. alpha power) during creative idea generation (i.e. creative thinking). (Schwab, Benedek, Papousek, Weiss, & Fink, 2014) also reported that EEG alpha power is sensitive to creativity related demands. (Fink et al., 2009; Martindale & Mines, 1975; Olga M Razumnikova, 2007) testified that higher creative individual has strong alpha synchronization in right parietal sites compare to less creative people. However, (Pellouchoud, Smith, McEvoy, & Gevins, 1999) reported decrease in posterior alpha and an increase in frontal midline theta to reflect mental effort. (Gola, Magnuski, Szumska, & Wróbel, 2013) found that beta band increased over occipital lobe (i.e. visual cortex) during highly visual attention task. Therefore, researchers widely used neuroscientific approaches such as EEG and fMRI to find the neural activation in brain areas during cognitive tasks performance (i.e. TTCT, AUT (Alternative Uses Task), RAT (Remote Association Test)). Thus, we choose to analyze EEG data based on modified TTCT to investigate power of brain activity using EEG comparison between creative and non-creative design task.

1.4 Organization of thesis

In chapter 2, we presented cognitive neuroscience studies of creativity, creativity in engineering design, and various creativity measurement methods and tools. Then, we presented design theories and methodologies, and theoretical model of design creativity.

In chapter 3, we presented physiological signals, relationship of mental effort, mental stress and creativity, then objective formulation followed by experimental study.

In chapter 4, we presented the conclusion and future work.

Chapter 2. Literature review

2.1 Definition of Creativity

Creativity can be seen as "multidimensional" (An, Song, & Carr, 2016), according to (M. A. Runco & Jaeger, 2012; R. J. Sternberg & Lubart, 1996) creativity notices if people are able to produce novel and effective ideas. (O. M. Razumnikova & Novosibirsk State Tech, 2005) reported that "social stereotypes" behavior of men/women can be considered as creative thinking, (Hao, Tang, Yang, Wang, & Runco, 2016) suggested that according to an individual's intentions, creativity can reflect both positive and negative purposes. (Perlovsky, Levine, & Ieee, 2010) testified that to present "crisp and conscious cognitive model-representation" at higher level of brain hierarchical required more mental effort or more creativity. (Barron, 1969) characterized creativity in terms of "a constellation of personality characteristics", whereas (Anderson, 1959) termed it as "the realization of an individual potential". (Christiano & Ramirez, 1993) reported that creativity is the "creation of something innovative and useful from pre-existing knowledge and experience". Whereas (E. Torrance, 1974) defined creativity as a "process of understanding the problems, insufficiencies, gaps in knowledge, classifying the difficulty; examining the solutions, making guesses, or formulating hypotheses" (Kim, 2006).

2.2 Cognitive neuroscience studies of creativity

Creativity is positively associated with cognitive process (i.e. divergent thinking) (P. Tierney, Farmer, & Graen, 1999). Cognitive Neuroscience (CN) studies of creativity provides better understanding of cognitive processes related to creativity. These processes in creativity are the mechanisms, traits, and thinking patterns used to guide and direct creative tasks (Ward, Smith, & Finke, 1999). These studies relevant to creativity research divided into five categories (K. Sawyer, 2011).

1. Creative insight: Remote associations, hypothesis generation and set shift, hints and restructuring, and story generation.
2. Mind wandering and incubation.
3. Creative brains versus non-creative brains.
4. Musical improvisation.
5. Differences with training.

2.2.1 Creative insight

The role of insight is very critical in creativity (Cunningham, MacGregor, Gibb, & Haar, 2009), brain imaging technologies are used to identify brain regions associated with creative insight (K. Sawyer, 2011). These insights aid to determine the cognitive processes involved in solving creative problems. (Dietrich, 2004) hypothesized that frontal region of brain is responsible for "conscious and deliberate creativity". However, the cortex such as temporal, occipital, and parietal (TOP) are accountable for emergence of spontaneous insight. The frontal lobe takes input from TOP to enable "higher-level cognitive behavior such as abstract thinking, willed action, planning, attention, and working memory".

2.2.1.1 Remote association

Many CN studies have been conducted to determine the role of insight in solving problems, (Jung-Beeman et al., 2004) try to find brain activities during solving insight problems. (Bowden & Jung-Beeman, 2003) reported that three-word Remote Association Test (RAT) triplets can be solved without feeling of insight, which is decently a subjective feeling of "emotional intensity or excitement" of finding problem rather than solving problem. It is believed that solving problems with or without insight involve identical "cognitive process and neural mechanisms" but Remote

Association is useful for insight solution. Several CN studies reported the increment in "neural activation in the anterior Superior Temporal Gyrus (aSTG) of the Right Hemisphere (RH)" when brain involved in relative tasks (K. Sawyer, 2011). It is evidenced that processing of remote association is supported by prefrontal part of the RH. To testify the role of insight during the RAT triplets and to determine the response of neural activation, (Seger, Desmond, Glover, & Gabrieli, 2000) perform experiment on 13 subjects with fMRI. Participants were presented with 124 RAT triplets and asked to identify each target word within 30 seconds of time. Then, they were supposed to press the button to confirm if they had experienced a feeling of insight attending the solution. It was found that 56% solution out of 59% solved problems had experienced a feeling of insight that also increased neural activation in the RH aSTG compared to the rest of 3% who had not experienced an insight feeling. In another study (Kounios et al., 2006) detected the brain activity pattern prior to the problem was offered. Participant with insight solution showed huge activity of Anterior Cingulate Cortex (ACC) just before the problem was offered. The conclusion was that "ACC activity is responsible for the alpha wave mid-frontal activity".

From the conclusion of these experiments, it can be observed that there are consistent patterns of brain activation in all cognitive tasks included non-creative tasks. However, the patterns (i.e. neuronal activation) remain same even after the solution. So, it is not easy to say that related brain reason is committed to solve remote associations like RAT.

2.2.1.2 Hypothesis generation and set shift

It is a shift in problem space from one state to another, and this transition is not sequential rather very sharp (Vartanian & Goel, 2007). The Guilford's match problem when use anagram problems, found that right ventral lateral PFC of brain was activated when problems were solved without hint (i.e. *"to make a word with CENFAR?")* but this was not the case for getting the solution with a hint (i.e. "*to make a country with CENFAR?").* It is also concluded that hypothesis generation is responsible for the activation of this brain region, which varied with "total number of solution generated in response to match problems". (Kounios et al., 2008) studied the resting state of anagram problems given to two different groups. One group is "high insight group (HI)" who solve problems with insight. The other group "low insight group (LI)" is least expected to have insight during problem solving. Both groups had different EEG resting state, during resting LI had high alpha and beta-1, which represents "less activity in the visual cortex" but focused visual attention respectively. HI group had high RH activity and "low alpha, high beta-2, beta-3, and gamma frequency ranges". The author explained that pre resting state influenced participants to use insights during anagram problem solving. He further explained the findings that identical brain region is responsible for the elevation of neural activity in both creative and non-creative cognitive tasks.

2.2.1.3 Hints and restructuring

Sometimes fixation results in an impasse during problem solving. "Mental restructuring of problem representation" can overcome it by providing hints (Gick & Lockhart, 1995; Kaplan & Simon, 1990). Various CN studies use this "Gestaltist model of insight". (Luo & Knoblich, 2007) found increased neural activation in ACC when presented with "insight problem (i.e. the thing that can move heavy logs but cannot move a small nail; hint: river)" and followed by a restructuring hint. In another study, (Sandkühler & Bhattacharya, 2008) used EEG to analyze RAT triplets results. The participants supposed to press button to get a hint when they stumped. The author found elevated "upper alpha band (8-12 HZ) response in RH temporal region and strong gamma band (38-44 HZ) response in parieto-occipital region" when compared insight and non-insight solutions.

2.2.1.4 Story generation

(Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005) try to assess verbal creativity by examining brain activity during fictional short story generation activity. Participants were supposed to generate story from three given words in 22 seconds. The demand of task was to: (a) "*participants should be either creative or non-creative*", (b) "*the participants should have either three related words (i.e. magician, trick, and rabbit) or unrelated words (i.e. flea, sing, and sword)*". When subtracted two activities of (a) using "paired image subtraction" an increment in bilateral medial frontal gyri and left ACC was observed. For (b) neural activity increased in bilateral ACC and right medial frontal gyrus. From insight studies, it is referred that these brain areas are not considered unique to "creative tasks" as they are involved in broader range of cognitive tasks.

2.2.2 Mind wandering and incubation

Creativity researchers have regularly studied the role of incubation in creative insight (Ellwood, Pallier, Snyder, & Gallate, 2009), it is perceived that an unconscious incubation always leads to a creative idea (Hadamard, 1945). According to cognitive neuroscientist mind wandering phenomenon is when thoughts drift away from primary task to something totally unrelated. (Hotz, 2009; J. Tierney, 2010) hypothesized that this phenomenon can result in high score from creativity test. The brain region related with mind wandering state aid to understand the role of incubation in creative process. (Andrews-Hanna, Reidler, Huang, & Buckner, 2010) suggested that typical life event dominates the mind wandering and it varies with fatigue, alcohol, and difficulty of task at hand and depends upon Working Memory Capacity (WMC). With high WMC, people's "mind wander less if task demands more concentration but mind wander more if task demand is low". It is possible that temporary diversion of attention form difficult task and giving an “opportunity for insight to occur” can lead to a creative thought.

2.2.3 Creative Brains versus non-creative brains

Some of the cognitive studies have scrutinized people’s neural activity using EEG who get high and low scores in creativity tests (i.e. RAT). It is found that creative people in comparison to non-creative people display higher alpha wave activity during creative tasks (i.e. RAT) (Martindale & Mines, 1975). In a study, (Carlsson, Wendt, & Risberg, 2000) used Creative Functioning Test (FAT) to characterize creative and non-creative groups, who are required to participant in three different tasks. During the first task, the activation was expected to be the lowest in frontal lobes (i.e. “*loudly count from 1”*). In the fluency task (i.e. “FAS: speak all words start with F or A or S that strike in mind”) activation was expected to be higher. Final task (i.e. “say as many uses you can think of for a brick”) has higher activation than previous two tasks. They observed that for low creative people (i.e. non-creative group) during fluency task enhanced regional cerebral blood flow (rCBF) in LH whereas for high creative people (i.e. creative group) during brick task enhanced (rCBF) in RH. They determined that for brick test, creative group used “bilateral prefrontal region” and non-creative group used mostly LH.

(Chávez-Eakle, Martindale, Locher, & Petrov, 2007) performed Torrance Test for Creative Thinking (TTCT) for verbal and figural. Participants who get high scores in TTCT verbal had enhanced rCBF in right precentral gyrus, however who get high scores in TTCT figural had enhanced rCBF in postcentral gyrus, right rectal gyrus, left middle frontal gyrus, right Para hippocampal gyrus, and right inferior parietal lobe – signifying that “creative performance is related to bilaterally distributed brain system (i.e. use both hemispheres)” as most of the enhanced activation is in RH. From these studies it can be concluded that for less-creative or non-creative people RH is marginally less active. However, it is deceptive to say creativity is “in” RH (Feist, 2010; Kaufman, Kornilov, Bristol, Tan, & Grigorenko, 2010).

2.2.4 Musical improvisation

Musical improvisation comprises brain regions, which are responsible for sequence generation and comprehension, finding alternatives and making decisions, creating plan for motor execution for selected sequences. These are “domain-general brain regions” recommends a role for “mental process in creativity”. It is to be noticed that not any particular brain area is associated with improvisation, all the areas of brain are involved in several cognitive tasks, many of them cannot be considered as creative (K. Sawyer, 2011).

2.2.5 Differences with training

Brain imaging studies discovered that with training performance of people changes. Some of the discussed studies are as follow:

2.2.5.1 Music training

Brain of trained musicians display different patterns during listening and generating music because they deactivated the right Tempo-Parietal Junction (rTPJ). Hence, musical training leads to a “shift towards inhibition of stimulus-driven attention”, allow musician to more “goal-oriented performance state” (Berkowitz, 2010).

2.2.5.2 Art training

(Bhattacharya & Petsche, 2005) found considerably “different patterns of functional cooperation between cortical regions” for artist and non-artist while mentally composing drawing. During the task, activation in brain region was different for both groups, the non-artist displayed elevated “short-range beta and gamma band synchronization whereas artist displayed elevated delta band synchronization with strong RH dominance but alpha band desynchronization”.

2.2.5.3 Dance training

In comparison of expert and novice dancers response of neural activation in brain, (Fink et al., 2009) found elevated RH alpha synchronization in experts. These studies support the hypothesis that "neuronal activation patterns can vary in response to experience and learning" (Reiterer, Pereda, & Bhattacharya, 2009).

2.2.6 Limitations of cognitive studies

Cognitive studies highly contributed for the understanding of creativity. These CN studies confirmed findings of (Mark A Runco, 2014; R. K. Sawyer & Creativity, 2006) that during creative task any area of brain can be active. It is also confirmed that creativity is not essentially located in RH. However, CN studies seems unable to operationalize creativity in terms of "usefulness" and "novelty". For example, in daily life people speak a lot of words that they have never used before. It reflects that there are novel thoughts and behavior in every cognitive activity. So presently "*in these experiments there is large gap between creativity as operationalized*" (K. Sawyer, 2011). Moreover, the study of mental process was rather small in terms of brain functions. "Useful" creative product involves hundreds of mental events from different neural groups dispersed throughout the brain. It can be possible if "higher cognitive functions such as problem solving, memory, decision making, language and creativity" are appropriately used (Bechtel & Richardson, 2010). So, it seems that to better understand the concept of creativity, we should review studies of operationalize (i.e. define creativity in terms of the operations used to determine or prove it) creativity and measurement of creativity during cognitive activities, which involve higher cognitive functions.

2.3 Creativity measurement theories in different domains

The most important aspect of creativity measurement is the development of procedure of test. To define the subject of creativity measurement (i.e. "person" or "product") and then identify the novelty, personality inventories, self-report survey, unique or complex solution of problems, usefulness, and something new or innovative (Houtz & Krug, 1995), these characteristics can be helpful to find the potentially creative individual or creative product.

There are numerous tests proposed by (Haensly & Torrance, 1990) which "focused on figural, verbal, or general creative abilities in different domains such as mathematics, dance, science, drama, music and arts". These tests use different measuring scales such as "rating and observational scales, personality and attitude measures, and questionnaires". The other tests are Flanagan's Ingenuity Test (1976), Guilford divergent thinking test (Guilford, 1967, 1977), Torrance Test of Creative Thinking (TTCT) (E Paul Torrance, 1965; Ellis Paul Torrance, 1968), Madnick's Remote Association Test (Mednick & Mednick, 1967), and the Wallach & Kogan Test (Wallach & Kogan, 1965a, 1965b).

Flanagan's ingenuity test is based on problem situation, where participants are supposed to complete an "idea with a word or a phrase" from a given first or last letter. One can think about many possibilities (i.e. divergent thinking) before selecting right answer (i.e. convergent thinking). Guilford presents ten individual tests to assess various features of divergent production, which were scored on fluency and originality for both "verbal (semantic) and nonverbal (figural) contents".

Torrance Tests of Creative Thinking (TTCT) was developed to nurture and enhance creativity among students. There are two test under TTCT, named as TTCT-verbal and TTCT-figural. TTCT figural comprises three activities: picture construction, picture completion, and repeated figures of lines or circles. The test has time limit that demands speed rather than artistic quality. TTCT scores are based on flexibility, fluency, and originality for verbal test and on elaboration for non-verbal test (Kim, 2006; Ellis Paul Torrance, 1968).

RAT (Mednick & Mednick, 1967) based on “related theory of ideation” inheres 30 items and each item has three words. These words may or may not be associated with each other. The participants supposed to think about one more word that can associate with given words that can leads to a creative idea in attempt to link the new word with existing words in different or unique way.

The Wallach and Kogan Test (Wallach & Kogan, 1965b) also involves verbal and non-verbal activities. Former activity inheres instances, alternative uses, similarities whereas latter involves “pattern meanings and line drawings” which is then explained by an individual. This test use fluency and uniqueness criteria for scoring.

(Khatena & Torrance, 1976) assess an individual’s self-perception of creativity using self-report inventory test through “Something about Myself (SAM)” and “What Kind of Person Are You (WKOPAY)” report. SAM encourage an individual to explore about themselves such as when they observe any creative potential inside them. WKOPAY encourage an individual to identify what traits or characteristics they realize actually epitomize their own behavior.

These theories for creativity assessment were becoming old, so (Ellis Paul Torrance & Safter, 1990) presents “incubation model of creativity” which focused on “systematically design instructions in creativity”. The word “system” described various new theories of creative process, that different variable of system operate in combination to result the creativity.

Recently many other researchers conceptualize creativity with different models and theories, including divergent thinking, creative expert performance, and self-rating of creativity. The two models of creativity divergent thinking and creative expert performance are predicted by different measures such as general intelligence, domain knowledge, motivation, creative behavior, and creative personality (An et al., 2016). (Zhu et al., 2016) assessed everyday creativity by creative behavior inventory (CBI) with modified 6-point scale using creative achievement questionnaire (CAQ) with 96 items, Divergent thinking was assessed by TTCT figural, and General intelligence was measured by Combined Raven's Test (CRT) with 12 items and scored based on number of correct answers given in 40 minutes. (Hao et al., 2016) developed a new tool known as Malevolent Creativity Behavior Scale (MCBS) to evaluate individual's Malevolent Creativity (MC). (O. M. Razumnikova & Novosibirsk State Tech, 2005) used Torrance test of completing pictures (TCS) for measuring non-verbal creativity whereas verbal creativity was measured by Medinich's Remote Associates Test (RAT), Intelligence characteristics (IQ) were measured by Amthauer's test and Eysneck's test.

2.3.1 Limitation of general creativity theories

In these studies, we try to understand how these measurements theories of creativity involves higher cognitive functions, which can consequences in potential creative behavior, creative personality, and divergent thinking. It seems that most of these creativity measurement tests are person-centered (Batey & Furnham, 2006). Because these results signifying that creativity can be operationalize in terms of "novelty" by applying various theories and creativity measurement tests. However, these theories are not much used to define the subject of creativity as "product" or "process" so that its characteristics (i.e. "innovation" or "usefulness") can be identified to declare it as a creative product. In order to identify the innovative and useful product, we need to review more studies of creativity based designs. Moreover, creativity in this domain may have some real-world applications.

2.4 Creativity measurement theories in Engineering Design

Researcher recommended that to better understand the concept of creativity, it should be decomposed into more precise and experimentally manageable theory (K. Sawyer, 2011), find creative events in a "discipline or subject field" (Houtz & Krug, 1995), in specific domain the precondition for creativity is an actual achievement (Mark A Runco & Albert, 1986). An important theoretical issue is to define creativity, and methods which are used to study creative thinking process and product/outcome (Houtz & Krug, 1995). Creativity and creative thinking needs significant knowledge base and skills that can be obtained from specific domain (Alexander, 1992; T. Amabile, 1987).

2.4.1 Creativity based design

Creativity in design can be defined as unique and innovative product outcome or "usefulness". Different researchers may have different views about the definition of creativity based design. So, it is important to appropriately define creativity in design before defining the criteria of creativity assessment.

2.4.1.1 Definition of creativity in design

Creativity can be defined scientifically if it allows "objective observations and measurements" (E Paul Torrance, 1965). Quality of product and characteristics of process can be defined as innovative and creative properties of design process (Coyne, Rosenman, & Radford, 1987). A novel artifact design or innovative design solution of an engineering problem (Daly, Mosyjowski, & Seifert, 2014). The design concepts which are results from "sudden insight or creative leaps" are often an innovative or novel designs (Cross, 1997a). The ideas and thoughts that fill the voids after brainstorming session eventually leads to creative design solutions (Tomiyama, Breedveld, & Birkhofer, 2010). A novel design proposal made by designer can result in product creativity

(Teresa M Amabile, 1982; Christiaans, 1992). According to (Rhodes, 1987) definition of creativity relies on following four potential research areas:

1. Person who creates.
2. Cognitive processes those involves in creative idea creation.
3. Environment impacts in which creativity happens.
4. The product which is the consequence of creative activity.

Creative design can be attained intuitively or systematically. Brainstorming plays a vital role to enhance the flow of ideas in an intuitive approach, while the systematic approach use design methodologies (i.e. TRIZ) to achieve "creative design more rationally and systematically" (Shah, 1998). "Innovative combinations of existing knowledge" can result in creative design. The author suggested that design knowledge under some constraints helps designers to convert design requirements into creative design solution during design process as shown in figure 2.1. In other words, design that includes functions, features, and show performance that can surprise people, can be defined as creative design (Tomiyama, Takeda, Yoshioka, & Shimomura, 2003).

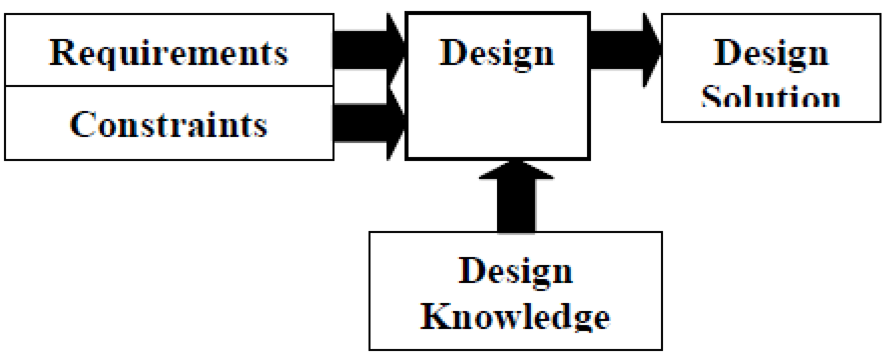


Figure 2-1: Tomiyama's knowledge centered view of design

(Parkhurst, 1999) suggested that creativity displayed quality during problem solving, or generating novel solutions for problems in the hand. The creative product is result of compound collaboration between an environment (i.e. where the product supposed to be used) and designer

(Csikszentmihalyi & Sternberg, 1988). Creativity is designing something useful and innovative in the absence of experience and pre-existing knowledge (Christiano & Ramirez, 1993), however (Sarkar & Chakrabarti, 2014) reported that experience of designer and time duration of design influenced the creativity. Co-evolution of problems and solutions is an 'engine' of creative design (Wiltschnig, Christensen, & Ball, 2013). According to (Guilford, 1967) creativity is when creative engineers design novel solution of engineering problems or produce unique product by utilizing the available resources, (Toh & Miller, 2015) creativity is "uniqueness and originality" of created design, (Chang, Chien, Yu, Chu, & Chen, 2016) ability to create new and innovative product. There are numerous definitions for design creativity by different researchers but still the focus is on core components of creativity such as "novelty and utility" (Batey & Furnham, 2006). To better understand the role of "novelty and utility" in creative design and to understand how these creative design occur, we need to review more independent studies of creativity in design in terms of "novelty and usefulness". Usefulness can be defined as "importance of usage of product" or "duration of usage of product" (Sarkar & Chakrabarti, 2014). Novelty can be expressed as "measure of how unusual or unexpected an idea is from other ideas"(Shah, Smith, & Vargas-Hernandez, 2003)

2.4.1.2 Creative design theories

(E Paul Torrance, 1965) developed creativity test tasks that have features to involve the qualities of creative product, creative personalities, and creative thinking processes. The scores of these tests are based on fluency ("number of applicable ideas produced"), flexibility ("number of changes in thinking"), originality ("statistically occasional ideas"), and elaboration ("detail of ideas"). One of the test is figural test, which involves picture completion (i.e. add lines using pencil into 10 incomplete pictures) to tap diverse functions of creativity. Participants were supposed to think differently and extend the picture to unique final solution that can reflect an interesting story, and then give title to the designed solution. The “repeated closed figure test” inhere figures (i.e. “*circles, squares and triangles”* etc.) needed to be completed in 10 minutes with maximum number of design solutions. The findings and their applications may be considered in two different ways:

1. Creative solution of a problem can be found deliberately.
2. The designer need to analyze what problems can be solved with suddenly ensued findings.

Hence, it seems the author tried intentionally to base the “test stimuli, test tasks, scoring procedure, and instruction” in best from previous findings of creativity research.

(Coyne et al., 1987) believes that knowledge play a key role to simplify the idea of creativity in design. Creativity may be associated with product and process. Quality of the product is measured as creativity of a design process. Quality is further divided in three categories such as value, innovation, and richness of interpretation. If the designed product is considered as of high value (i.e. in terms of marketability, beauty, and sophistication etc.) then the designer may be designated as creative. The designer can be considered as creative if his design is different in some way from other’s product. However, if design is totally new, which never existed before then it can be qualified as creative design but there should be some measuring standards to measure its originality in comparison to others. Finally, a product can be creative if it is multi-valued or it can be interpreted in various ways.

(Dorst & Cross, 2001) reported that iterative process is the foundation of creative design where “design problem and potential solutions co-evolve” in between the ‘problem space’ and a ‘solution space’ as shown in figure 2.2. To validate this, (Wiltschnig et al., 2013) presented a project study of known company wherein an experienced designers are asked to design a product. In order to develop a product collaboratively with the involvement of various groups of designers, the meetings were held to yield the activities such as “problem solving, planning data collection, brainstorming, prototype evaluations, concept development, and sketching”.

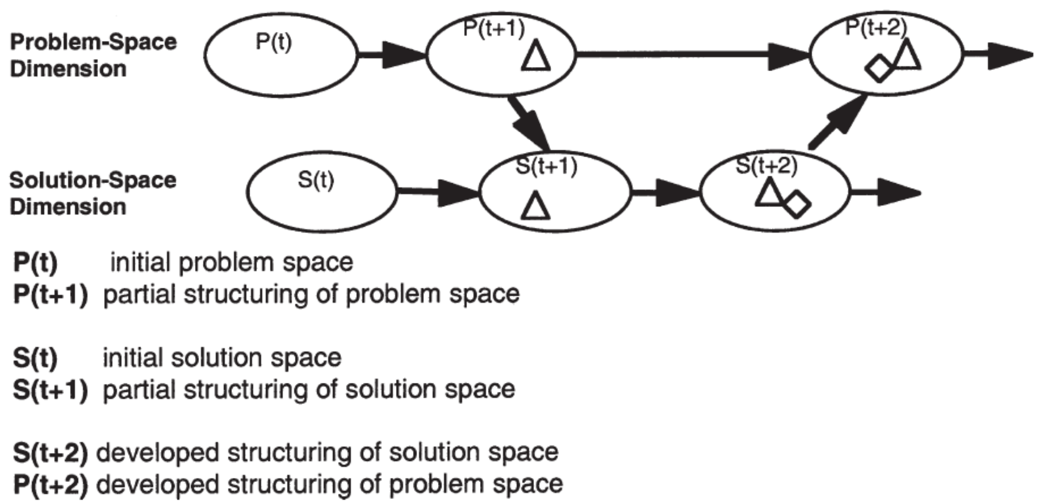


Figure 2-2: Dorst and Cross’s (2001) problem solution co-evolution model as derived from the observations in their study of design creativity

Majority of the episodes of co-evolution were identified such as requirements which were related to problem space were also linked with solution generation activity, and co-evolution of team members of different groups was identified. The author also supported the findings of (Dorst & Cross, 2001) that creative activities (i.e. “analogizing and mental simulation”) are positively associated with co-evolution episodes.

(Goldschmidt & Tatsa, 2005) believes that good ideas are “base of creative design processes” and creative products are the result of ‘good ideas’. They define ‘good ideas’ as one those have links to generate more good ideas that leads to final product. They used (van der Lugt, 2003) theory of measuring the quality of design ideas in idea generation session. They held meetings of design teams for the purpose of idea generation in response to task (“how to make traveling by car fun for children?”). For each session they constructed a linkograph, which record the pattern of an idea builds on a preceding idea in previous session. Then the ideas were appraised by participants at the end of meeting and were associated with their linking scores which "points to the creative qualities of the ideas". The study also supported to the notion that strong interlinking among design ideas is a requirement for creativity.

(Cross, 1997b) presented (Rosenman & Gero, 1993)'s "descriptive model of creative design" in order to understand and to stimulate creative thinking in design. For this purpose two theories such as synectics (i.e. forced association) and brainstorming (i.e. free association) are widely used. The model "suggested four procedures by which creative design might occur: combination, mutation, analogy, and first principles" as shown in figure 2.3. Creative design is represented by potential design solution which is result of a novel concept that emerges in 'creative-leap'. The author presented "*an example of 'creative-leap' which is identified between stage 3 and 4 during an engineering design process based on a conventional model of"*:

1. Explore the problem and write a performance specification.
2. Generate a range of concepts.
3. Evaluate and select the most promising concept.
4. Develop the concept into a detailed design
5. Communicate the final proposed design.

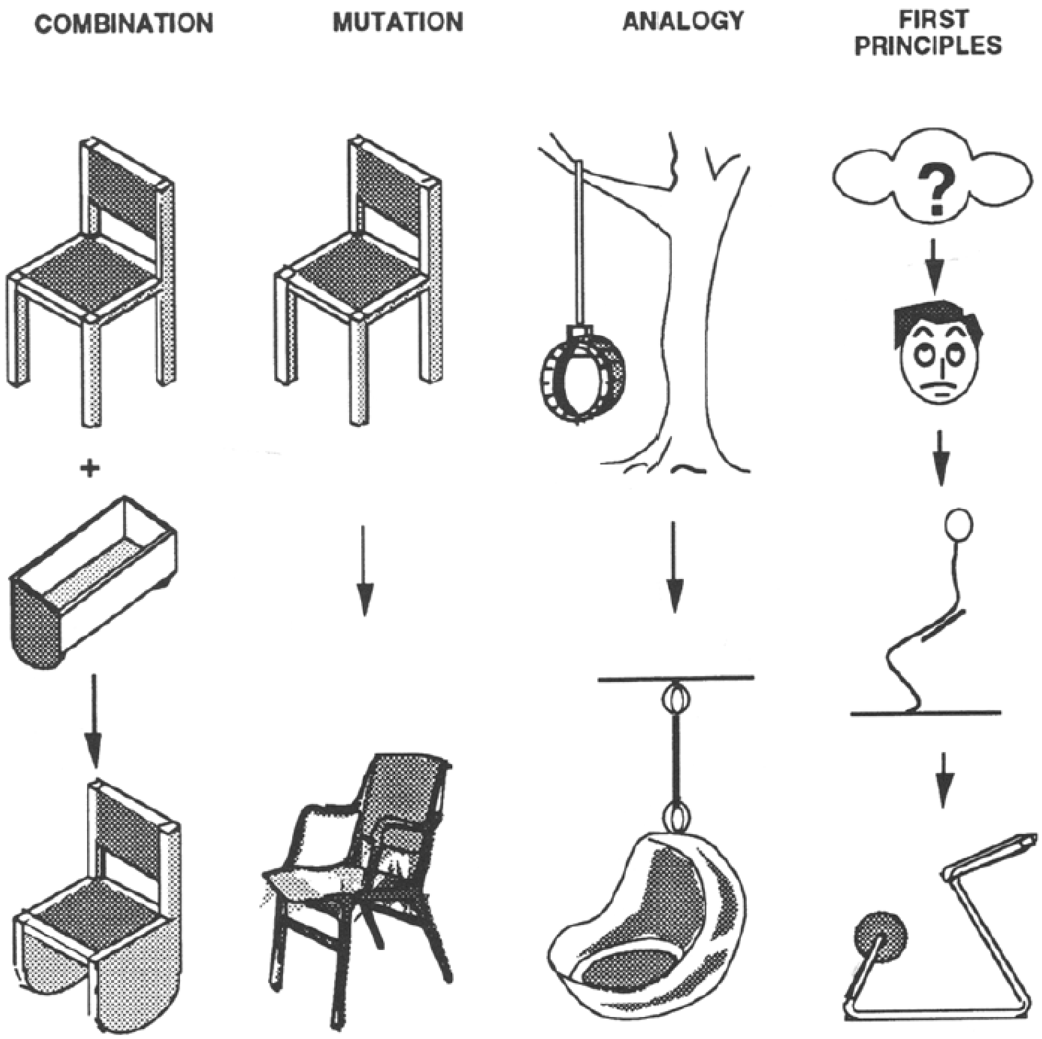


Figure 2-3: Demonstrations of the results of the procedures of combination, mutation, analogy and design from first principles, from Rosenman and Gero (Rosenman & Gero, 1993)

(Christiaans, 1992) reported that if a person use their own reference to form conceptual structure and spend more time to define and understand the problem then he can achieve a creative result. (Dorst & Cross, 2001) find similar implications in their study where 'Dutch Railway' asked an experience designers to design a new litter-disposal system to install in new trains. During the design process, in order to incite a creative response the designers arranged their design assignment to somewhat challenging. Designer 3 is an example of such episode who is rated highly creative.

The designer thought to manipulate assignment by making a hole in train for litter-disposal. Then he received information that there is already a litter system as hole in toilet, but he found it as an ugly solution. He then start to design new litter container that can suck and compress all the litter, this new ideas was considered as original and creative.

(Wei, Weng, Liu, & Wang, 2015) used Keller's ARCS model of "motivational design" and Amabile (1983) model of "social psychology, and a computational model of creativity" to nurture the creativity of students registered in design course through new teaching scheme (i.e. Augmented reality (AR) creative-classroom and AR creative-builder). Keller's model reported that motivation is an important factor in creativity. Amabile's model stated that design solution is expected to be creative if designer use relevant domain knowledge and creative skills. AR helps students to enhance domain-relevant knowledge and creative skills can be improved by learning characteristics of creative design. The experiment to design a bedroom was performed on two groups of students in two different classes (i.e. T1 and T2). The students in both groups study all the aspects of creative design process, which was requirement for a creative design course. At the end of course, the basic knowledge and skills of students were assessed. It was found that T2 group who used "AR creative-builder" to match their design to real world scenario was considered more novel. Thus, it was considered that AR teaching scheme helps designer to learn creative design process which result in better final design solution.

(Sarkar & Chakrabarti, 2014) presented the effects of activities that occur during the conceptual design on final design solution. The chief activity of conceptual design is search for ideas which force designer to look for "new, appropriate, and improved solution". "Search is a process of finding new or improved designs in a design space" where design space inheres set of elements (i.e. problem, solution, or evaluation criteria). They performed two experiments (i.e. Design experiment with and without the use of design methods) with group of experience and novice designers to understand the process of search and their effects on design outcome. The first experiment used four design methods: brainstorming, functional analysis, ideal design, and innovation situation questionnaire to solve two design problems. The second experiment also consider two problems, one problem requires engineering design knowledge, while the other needs general design ability. Design problems is distributed equally among novice and experience designer. They found that for problem understanding, solution generation, and solution evaluation activities, the designer used twelve types of searches. It was also testified that type and amount of search, experience of designer, and duration of designing positively influence the creativity. Thus, the activities performed during conceptual design plays a vital role to achieve creative design solution.

(Toh & Miller, 2015) performed an experiment to determine how engineering teams select design concept and what factors are involved in the selection of creative concept. They consider 37 engineering students who registered in design course. The design task was to develop concept for a new, innovative product that can foam (i.e. overflowing mass of small bubbles) milk in short time duration. The ideas were generated using 20-question "Design Rating Survey" and assessed for creativity by experts. The matrices were developed to assess the novelty of idea and tendency of team to select novel idea during selection process. It was found that engineering students focus more on technical feasibility of product (i.e. to find an 'optimal' solution to design problem) rather than creativity (i.e. identify the factors involved that lead to creative concept selection). The teams who had high frequency of discussions to decompose the generated idea that influence the generation of novel idea.

(Chang et al., 2016) presented the effect TRIZ ("Theory of the Resolution of Invention-related Tasks") methodology on creative processes and creative products designed by engineering design students. TRIZ is knowledge-based design methodology widely used to identify technical solutions and enhancing innovativeness of its system. Creative process can be defined as to design something new (i.e. novel) and useful. The author categorize creative process in five stages: "*identify problems, analyzing problems, and identifying, selecting, and executing a strategy*". Creative product is the innovative outcome of creative design process. The author assessed this component based on following factors: *"novelty (i.e. originality, or being the first), usefulness (i.e. ability to solve any problem), and elaboration (i.e. esthetic considerations, beauty)"*. They performed experiment of "designing and making model solar car" for first-year engineering students. To analyze the effect of TRIZ, multivariate analysis of covariance (MANCOVA) and univariate (ANCOVA) tools were used. The study found positive effect of TRIZ (i.e. selection of strategy) on student's creative process and creative product. The methodology also helps designer to enhance the creativity in terms of design product, develop and implement novel ideas.

2.5 Psychological view of creativity

The number of studies have been presented for creativity by various researchers. Different researchers conceptualized creativity based on different criterion. But the core concept of definition of creativity is involved creative process, creative person, and creative product which is most commonly used. The creativeness of creative product or response is often assessed based on novelty or usefulness of product. The ratings for defined criterion is based on scorer's subjective view. However, the psychologists have disagreement over this definition of creativity. It appears that these definitions are operational rather these are conceptual. In this concern, (T. M. Amabile, 1982; T. M. Amabile & Pillemer, 2012) presented the Consensual Assessment Technique (CAT) to overcome the deficiencies of existing methods. Most of the available creativity assessment methods do not examine the social and environment effects on creativity. CAT is based on an operational definition of creativity where a product is considered creative when expert independently agree upon the judgement. An open ended experiments needs to be performed without any requirement of special skills that can lead to a novel creation. The CAT because of its subjective assessment (i.e. assessment of creativity done by experts) alleviate the problem of "defining ultimate "objective" criteria for creativity". She also emphasized on an intrinsic motivation, which is foundation for the "micro-level social psychology of creativity". The study proposed that *"intrinsic motivated state is conducive to creativity while the extrinsic motivated state is detrimental"*. The former comes from an individual's own perception about task involvement (i.e. finding it more enjoyable or satisfied), whereas the latter arises from outside source (i.e. rewards, threat of failure etc.) (Hennessey & Amabile, 2010)

In another study, (T. M. Amabile, 1983) presented a componential framework for conceptualizing creativity which had three chief components includes "domain-relevant skills, creativity-relevant skills, and task motivation" as shown in figure 2.4.

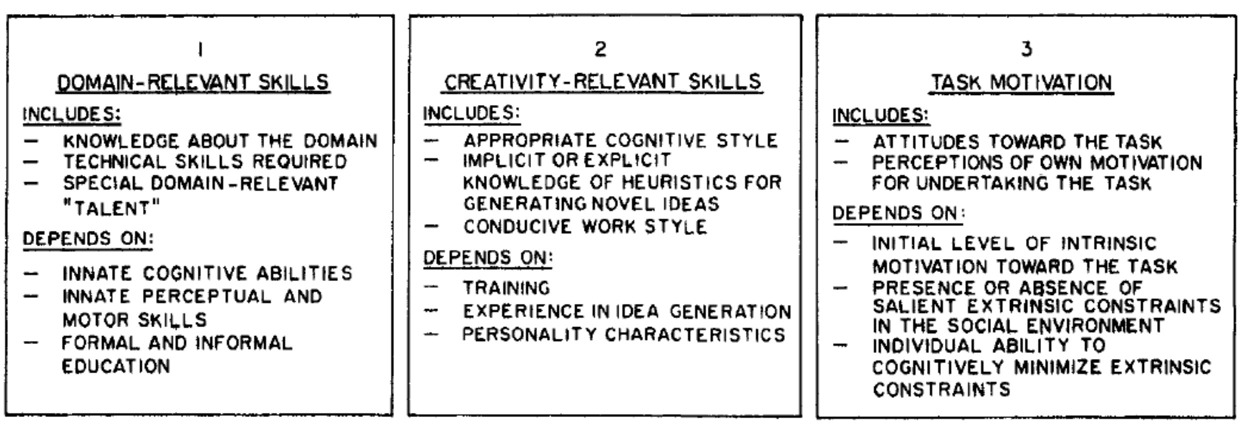


Figure 2-4: Components of creative performance (T. M. Amabile, 1983)

The theoretical framework based on conceptual definition consist two elements to make subjective judgement more relevant:

a) *"A product will be creative if it is both a novel and appropriate, useful, correct, or valuable response to the task at hand".*

b) *"The task is heuristic rather than algorithmic".*

In algorithmic tasks, the path to solution is clear and straightforward but not in heuristic tasks. Hence it is important to consider experimental tasks for creativity assessment in which algorithms are not involved. Different stages of creative process based on componential framework shown in figure 2.5. The level of novelty of product or response found at the third stage of creative process model. The chief difference between presented framework and previous formulations was found that the importance given to the intrinsic motivation and its effects on creativity which was derived from the social psychological theories of motivation. It was also found that *"conceptualization from cognitive psychology can help to apprehend the mechanism by which task motivation influence the third stage of creative process".*

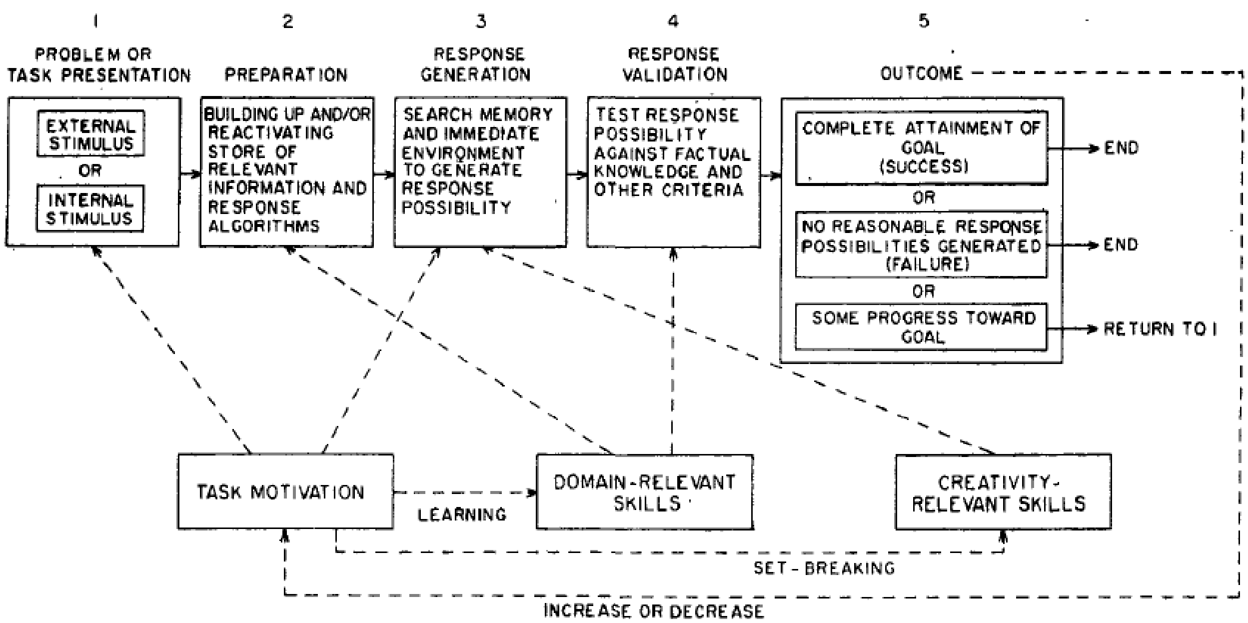


Figure 2-5: Componential framework of creativity (T. M. Amabile, 1983)

(Isen & Reeve, 2005) believes that "positive affect leads to higher level of creativity". It also enables intrinsic motivation, flexible thinking and problem solving. (Vosburg, 1998) reported that positive mood can enables productivity but not the quality of ideas. (Clapham, 2001) found that albeit "positive affect manipulations" can minimize state of anxiety by enhancing mood but it not essentially boost divergent thinking. However, (George & Zhou, 2002) reported that in an organization under certain situations the negative affect are more useful for higher creativity than negative creativity. (Madjar, Oldham, & Pratt, 2002) testified that when employees received support from workplace due to positive affects leads to enhance their creativity and creative performance. (Martin, Ward, Achee, & Wyer, 1993) presented "mood-as-input" model which describes that positive mood ensure an individual about their safety and motivate them to maximize their thinking capabilities. (T. M. Amabile, 1993) reported that under certain conditions rewards can have positive impact on an intrinsic motivation when they push people to achieve something for which they already intrinsically motivated to achieve.

The social psychology of creativity focuses on the impact of work environment (i.e. social environment) on an individual's or organization's creativity. The managers are responsible for positive/negative creation of work environment. (T. M. Amabile, Schatzel, Moneta, & Kramer, 2004) presented a study that "perceived team leader support positively associated to the peer-rated creativity". (Farmer, Tierney, & Kung-McIntyre, 2003) examined that the creativity of an individual is highest when s/he realize that their organization value their creativity. (Madjar et al., 2002) also have some similar findings that support from work (i.e. supervisor and coworkers) and non-work (i.e. family and friends) is positively associated with employee's creativity. (T. M. Amabile, Hadley, & Kramer, 2002) showed that time pressure at work place may have negative impact on creativity. (Baer & Oldham, 2006) reported that time pressure and creativity have an inverted-U relation. (Edmondson & Mogelof, 2006) proposed that for delicate nature of creativity (i.e. risk-taking, frequent failure, and experimentation) psychological safety is very important. (T. M. Amabile, 1996) proposed that creativity is promoted by clearly defined goals for project works. (C. Shalley, 2008) suggested that managers should motivate the employees to commence some creative activities in order to yield creativeness among them. (West, Sacramento, Fay, Thompson, & Choi, 2006) believes that group creativity is negatively influenced by external demands.

Psychology explored the mental processes that involves in creative activities. Cognitive psychologist studied the role of insight in creative process (Robert J Sternberg & Davidson, 1995), striking plays a vital role during intuitive information processing (Bowers, Farvolden, & Mermigis, 1995). Normal cognitive processes results in creativity a well-known mental phenomenon (Ward, Smith, & Vaid, 1997). Visual imagery set the foundation for origination of creative ideas and an open-ended problems leads to genuine creativity (Finke et al., 1992).

2.5.1 Psychological creativity measurement studies

(C. E. Shalley & Perry-Smith, 2001) investigated an impact of expected evaluation and modelling on creativity, two factors of social psychology. The expected evaluation was done in two forms such as controlling (i.e. instructions given strictly to be creative) and informational (i.e. supportive instructions given to be creative) for a given representative management problem. The participants were also provided with hints of solution as no, standard, and creative example. It was discovered that participants had high creativity and intrinsic motivation for informational evaluation as compare to control evaluation. Further, it was found that given a creative example of solution leads to higher creative response. The low intrinsic motivation and low creativity was reported when control evaluation was offered with standard example.

(Choi, 2004) investigated the role of psychological processes, individual characteristics, and contextual factors on creative performance. The experiment was performed on 430 students who took an introductory course in organizational behavior. Questioners were used to assess different set of variable shown in figure 2.6.

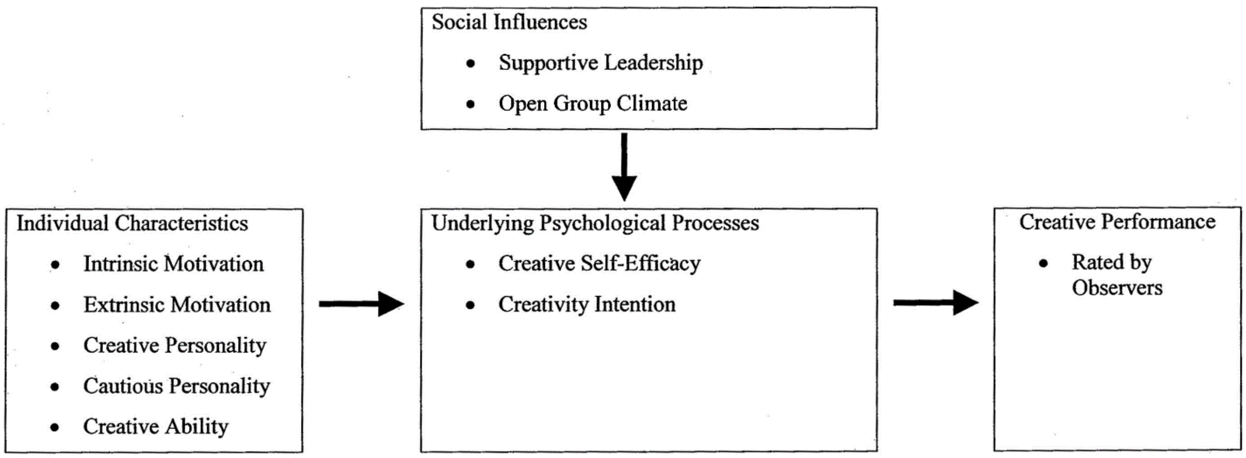


Figure 2-6: Conceptual framework of (Choi, 2004)'s study

The author proposed that psychological processes such as creative self-efficacy (i.e. self-belief that I can behave creatively in a task in-hand) and intention (i.e. degree of motivation an individual require to behave creatively) are predictors of creative performance. An individual's characteristics (i.e. "*motivation, creative personality, cognitive ability*" etc.) and contextual factors (i.e. supportive leadership, open work environment, no time pressure, positive feedback etc.) mediated by psychological processes have positive effects on creative performance.

(Dietrich, 2004) proposed that different combinations of basic psychological processes shown in figure 2.7 can result in creative behavior which is based on prefrontal integration. "Working memory buffer of prefrontal cortex holds the content of consciousness" which is responsible for converting a novel thoughts into an insight (i.e. abstract sense of solution to the problem). Creative thoughts are arisen by two types of processing modes (i.e. deliberate and spontaneous). These modes retrieve information either from emotional content or cognitive analysis stored in working memory (i.e. in TOP (temporal, occipital, and parietal)). Author also proposed that domain knowledge is positively associated with creativity, also both TOP and prefrontal cortex involves in generation of creative insights.

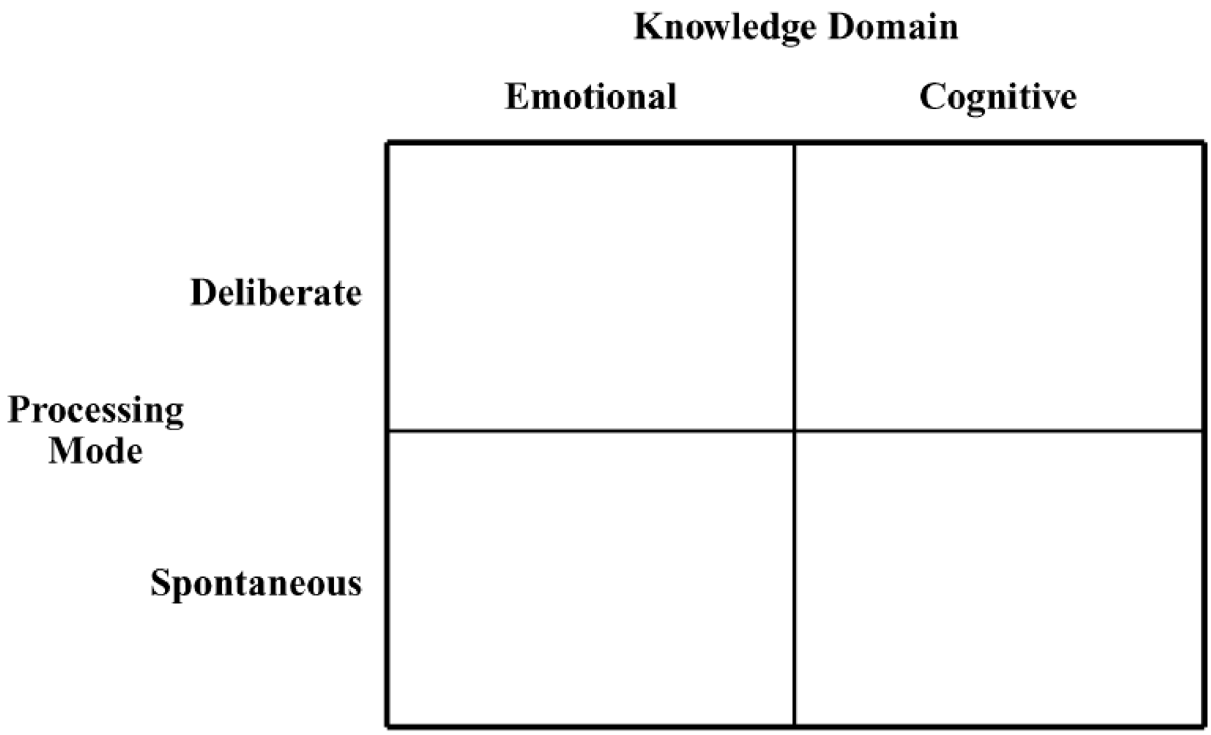


Figure 2-7: (Dietrich, 2004)'s proposed theoretical framework which can result in four different types of creative insights

(Heller, 2007) reported that to describe "the development of individual competencies and excellent performance" cognitive psychological studies are very useful. The scientific ability (i.e. competence) and technical creativity are indicator of exceptional performance. This scientific ability and creativity can be assessed based on cognitive and non-cognitive (i.e. motivation) personality traits. At novice level, an individual's competence for scientific problem-solving depends on their cognitive abilities, however, at expert level it depends on domain-specific knowledge and leaning experiences. In science & technology to generate an "innovative solutions processes and creative products" subject-related expertise are needed. The phases of such an innovative processes in accordance to relationship between system knowledge and system insight illustrated in table 2.1.

Table 2-1: Relationship between self-knowledge and system insight during an invention process (Heller & Facaoaru, 1987)

Prerequisites for individual performance	Phases of the innovative process	Conditions for situational environments and systems
• Creative abilities: – Sensitivity when faced with problems, curiosity, keen observation skills, selectivity. – Cognitive flexibility, originality, imagination. – Ability to analyze and synthesize.	← Problem perception →	• Current information/knowledge state: – State of scientific and technical knowledge. – Existing concepts, principles, functions, materials, components, technological processes, solution strategies.
• Repertoire of knowledge: – Domain-specific as well as general knowledge. – Terminology, structures and outlines. – Existing (available) and new knowledge.	← Information collection →	• Practical necessities of operational companies: – Problems, shortages, imperfections in normal everyday practices.
• Knowledge of behavior patterns and problem-solving strategies: – Creative strategies for receiving knowledge (selectivity, pattern recognition). – Heuristic strategies for processing and generating information. – Using one's own experiences. – Constructing plans of action.	← Production of ideas →	• Occupational demands and tasks: – Objectively allowed degrees of freedom, room to maneuver when making decisions, demands for innovation. • Social and organizational influences: – Group composition and co-worker interaction, communication structures and cooperation. – Organizational characteristics: incentive programs, leadership styles, working atmosphere.
• Creative motivation: – Task commitment and anticipation to give one's all. – Perseverance and concentration.	← Closer examination and elaboration of ideas →	• Target group needs: – Demands made by suppliers. – Regulations regarding patents, patent laws. – Conditions made by potential financial sponsors, undertakers.
• Behaviors and attitude beneficial to creativity: – High expectations of one's performance. – Tolerance of frustration. – Independance.	← Communica-tion and realization of ideas →	• Economic, societal and ecological perspectives: – Costs, reserves, resources. – Competition and competitors. – Criteria for promising evolutionary advances.
Self-knowledge	← Invention →	**System-insight**

In another study, the author found the different roles of "giftedness" among highly intelligent and highly creative students particularly in technology. In the subject of 'math' and 'physics', the intellectually gifted students scored best grades, however, in other subject (i.e. German language) the intellectual as well as creativeness gifted students obtained best grades as shown in figure 2.8.

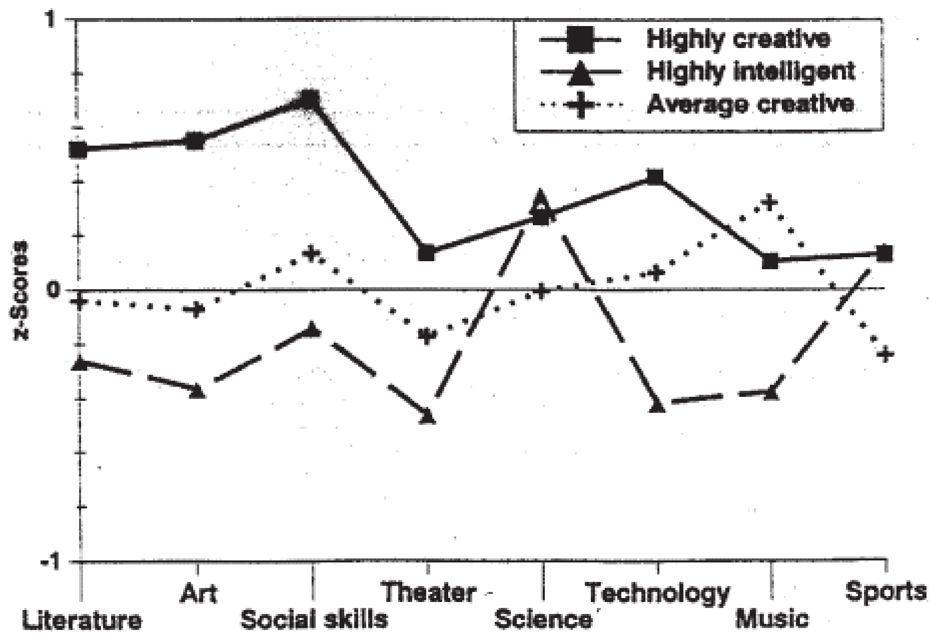


Figure 2-8: Differences between students of high and average creativity as well as high intelligence (Perleth & Sierwald, 2001)

2.6 Existing design theories

2.6.1 Scientific foundation

The "science of design" means to study the design. The fundamental knowledge of science of design is very important to understand this (i.e. study of design). It is well known that this activity of design relies on designer based on their conceived knowledge. They tackled their design knowledge and design information during design process. That is, designer needs Design Theories and Methodologies (DTM) to find, characterize, model, and organize design knowledge and information. There are many design theories, which help designers to utilize their cognitive abilities in order to achieve better design performance. In this section, we discuss existing design theories.

2.7 General Design Theory

GDT is a mathematical theory to formulate the design processes. The theory describes the role of knowledge manipulation to form conceptual design based on axiomatic set theory. Hence, GDT can be recognized as an "abstract theory about design knowledge and its operations" (Tomiyama & Yoshikawa, 1986). Design process operates as "mapping from function space (i.e. first stage of design) to attribute space (i.e. final stage of design)". As shown in figure 2.9, GDT has two important aspects such as an entity (i.e. existing object) and an entity concept (i.e. related to its properties such as function, size, and color that can be abstractly perceived by human). The attributes and functions are included in properties of an entity concept which are also called abstract concepts.

2.7.1 Axioms of GDT

The axioms of GDT defines "knowledge as topology and operations as set operations" (Tomiyama, 2006).

Axiom 1 (Axiom of recognition): attributes or abstract concepts can be used to describe or recognize any entity.

Axiom 2 (Axiom of correspondence): both the important aspects of GDT have one-to-one correspondence.

Axiom 3 (Axiom of operation): the set of abstract concept is a topology of the set of entity concept.

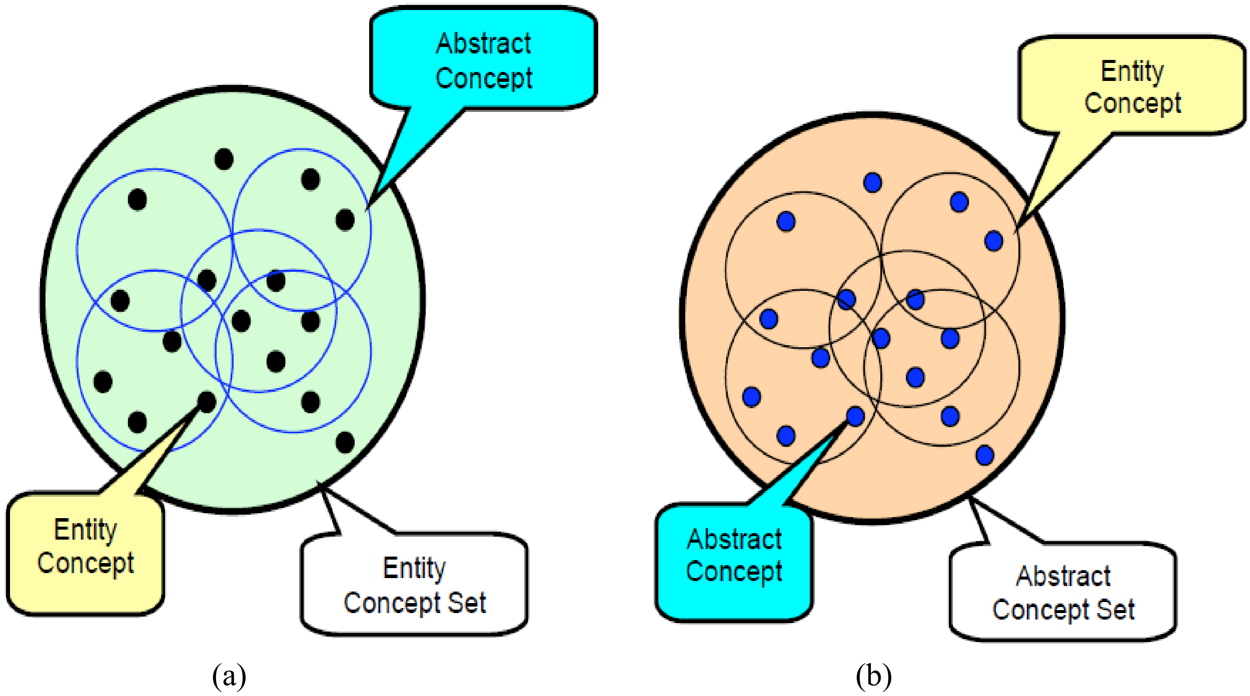


Figure 2-9: (a) Extensional (b) Intentional definition of an entity and an entity concept set (Tomiyama, 2006)

The database of knowledge about entities is represented by an entity and entity concept set. Axiom 2 ensure the existence of a designer who has knowledge about each element in an entity. Axiom 3 ensures the possibility of logical operation of abstract concepts.

2.7.2 Design process in ideal knowledge

In GDT, an abstract concept represents design specifications (i.e. in function space) which are primary requirements of a design solution (i.e. "*in attribute space*"). These specifications are associated with only abstract concepts (i.e. functions) of an entity. An ideal knowledge can describe each element of an entity with abstract concept. Therefore, the design process is a mapping process in an ideal knowledge from "function space to attribute space" as shown in figure 2.10. This situation is also represented by following theorems (Tomiyama, 2006).

Theorem 1: Ideal knowledge is a Hausdorff space.

Theorem 2: In an ideal knowledge, design specifications results in design solution.

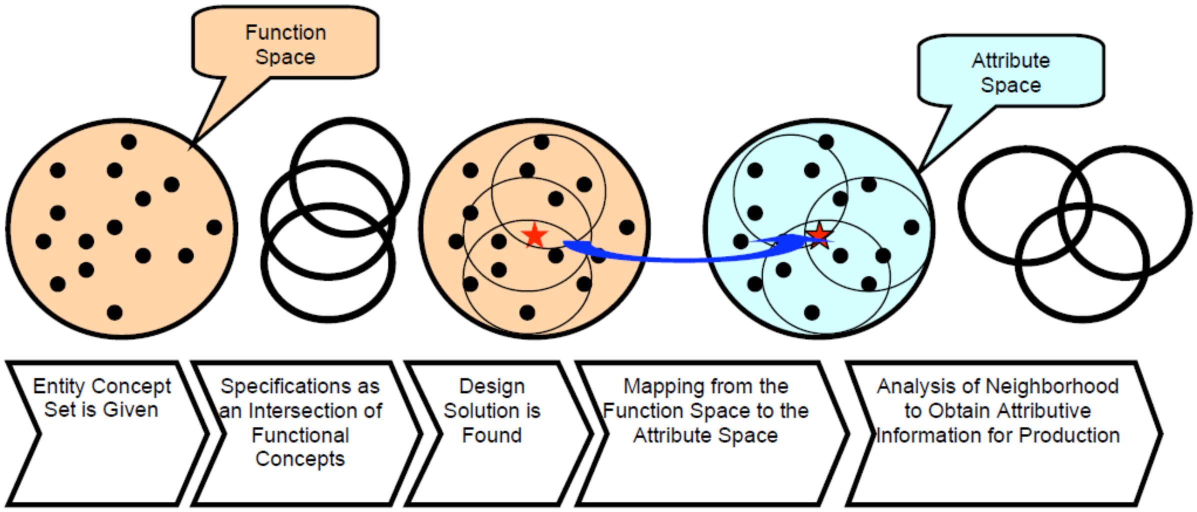


Figure 2-10: Design process in ideal knowledge (Tomiyama, 2006)

How design process works is given as follow:

a) The required usable knowledge of an entity must exist with abstract concepts (i.e. left most in figure 2.10).

b) The existence of a new design solution in a region can be designated as results of abstract concept's logical operations (i.e. second from left in figure 2.10).

c) The requirements designated with abstract concept are fulfilled by an entity which is found by designer. The process becomes the core process of synthesis if no design solution is known (i.e. vacancy in knowledge). This situation leads to pop-up different possible strategies.

d) If an "entity concept" is obtained as design solution, then the solution to the attribute space is mapped from function space. The required attributive information for production (i.e. material, shape, and geometry) is obtained by analyzing the neighborhood of attribute space (i.e. second from right and right most).

2.7.3 Generation of a new design solution using DTM

In case, design knowledge is not enough and existing entities are not able to satisfy the design requirements then a "synthesis" process based on "creativity-based design, modification based design, and combination-based design" strategies can be invited to generate a new design solution (Tomiyama, Yoshioka, & Tsumaya, 2002).

2.7.3.1 Creativity-based design

A new design solution involves new knowledge or combination of existing knowledge which can result in a new element of an entity set. This type of new invention relies on intuitive creativity of human being and a few theories (Coyne et al., 1987). Abduction is a general formalization to explain how a new solution is produced with the combination of multiple known theories (Tomiyama et al., 2003). Intuitive and systematic design methods are two approaches to obtain a creative design. An intuitive approach eliminates the mental blocks and enhances the flow of ideas. It can stimulate designer's imagination by exposing them to "a set of knowledge (i.e. books, museums, different methods for brainstorming) that they never experienced before (i.e. *void in knowledge*)" (Shah, 1998).

2.7.3.2 Combination-based design

The systematic approach is more "rational and systematical" to obtain creative design. This technique applies "design knowledge" by defining design methodologies. These methodologies such as (Pahl & Beitz) and (Hubka) consider an assumption: achieve a new design solution by combining existing building blocks and rules (i.e. combination of known units or components can leads to a new machine) (Shah, 1998).

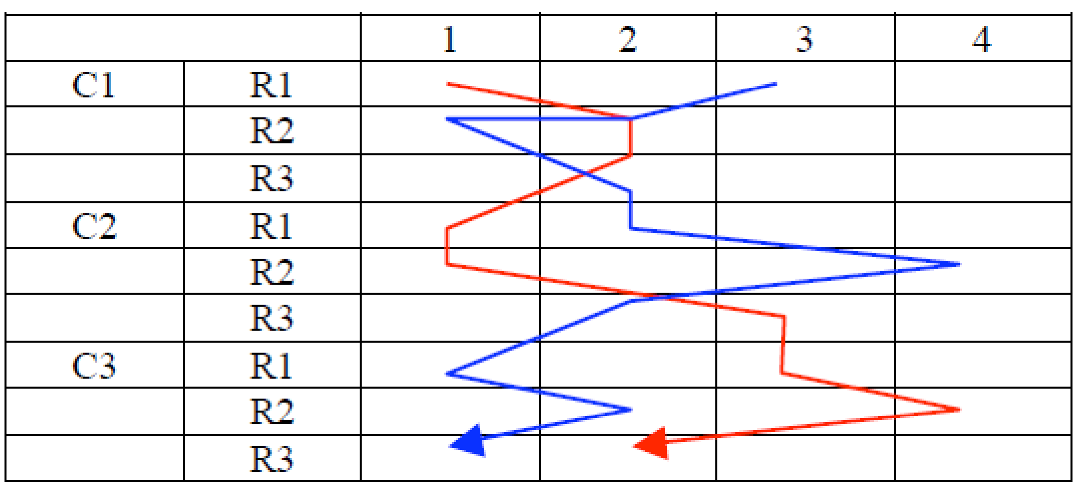
2.7.3.3 Modification based design

This method starts with a solution, which has a close match to the final solution. Parametric design is an example of this method, where database is used to find an unspecified design solution. Then the obtained solution is modified to match with the specified design requirements. TRIZ is an example of this approach (Altshuller, 1984).

2.7.4 GDT to give theoretical foundation to Birkhofer's and Breedveld's method

The one common point in Birkhofer's and Breedveld's method is "search for *voids* in design knowledge". These voids are empty cells in morphological table which corresponds to "creative design solution" those are not thought of or existed before. In case of P&B design methodology, the designers are supposed to intuitively generate (i.e. brainstorming) "*as many solutions as possible"*. These solutions are then classified according to similarities among them. The generated solutions are filled in morphological table and solutions without similarities are left with *voids*. These voids are filled exhaustively and this process to complete the table leads designer to a creative design solution (Tomiyama et al., 2010).

Table 2-2: Classification table (Tomiyama et al., 2010)



		1	2	3	4
C1	R1				
	R2				
	R3				
C2	R1				
	R2				
	R3				
C3	R1				
	R2				
	R3				

Table 2-3: Morphological table (Tomiyama et al., 2010)

Row Parameter	Column parameter				
	C1	C2	…		Cn
R1					
R2					
R3					

GDT describes why *voids* search in above mention methods can facilitate creativity. As, GDT states that voids in the knowledge of "non-existing entities" leads to an innovative design solution by forming specifications using combination of existing entities for a solution that is never existed before.

2.7.5 Limitations

Albeit General Design Theory (GDT) support the design process as knowledge operation to find design solution which can constraint design requirements but design is not merely a mapping process (Takeda, Hamada, Tomiyama, & Yoshikawa, 1990) rather a stepwise refinement process. Moreover, it is not a process where all the design components (i.e. design problem, design solution, design knowledge, design process and specifically designers) integrated to achieve design creativity and/or creative performance. The process must be recursive where design problem, design solutions, and design knowledge should be refined at every stage. (Akin & Akin, 1996) argued that to develop a theoretical model that can derive interpretations of design creativity phenomena and can reason about design creativity is a challenging task. (Y Zeng & Cheng, 1991) argued that such a model should be able to answer two fundamental questions given as following:

1. How to integrate above mentioned design components coherently into design theory?
2. How to investigate a nondeterministic, ill-structured, and unpredictable phenomena of design creativity into a formal, structured, and a deterministic framework?

(Nguyen & Zeng, 2012b) presented such a theoretical model which can answer above asked questions and identifies various factors affecting the creative design.

2.8 Theoretical model of design creativity

2.8.1 Mathematical foundation

It is suggested by (Y Zeng & Cheng, 1991) that design process is a recursive in nature and many other design researchers agreed that design is not a linear process.

2.8.2 Recursive logic

In the initial stage, the designers generate uncertain solutions from original design problem which aid them to better understand the design problem and then they further reformulate the problem to fit the solutions. This iterative process continuous until designer finds a satisfied solution which can fulfil all the design requirements (Nguyen & Zeng, 2012b). Figure 2.11 shows the recursive logic.

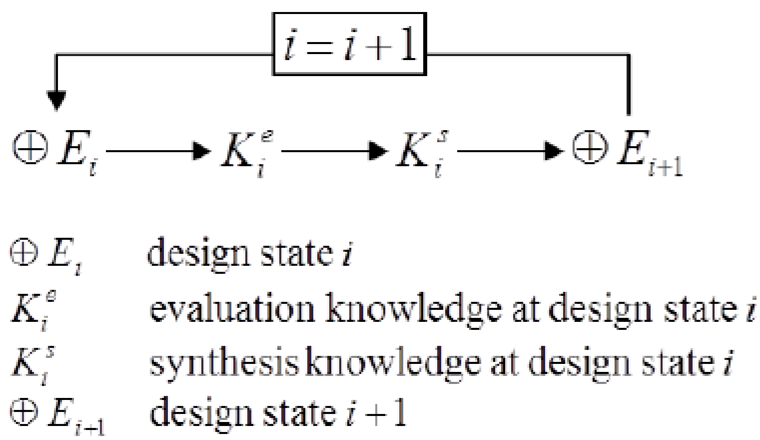


Figure 2-11: Recursive interdependence between design problem, design solutions and design knowledge (Nguyen & Zeng, 2012)

To solve a given design problem in design state ($\oplus E_i$), a designer requires design knowledge (i.e. evaluation knowledge (K_i^e) for screening of candidate solutions against design requirements, synthesis knowledge(K_i^s) to propose set of candidate solutions). The evolvement of design knowledge in present design state leads to a design solution which defines a new design state($\oplus E_{i+1}$), which further in result of a new bunch of design knowledge. Hence, throughout the design process design problem, design knowledge, and design solution are interdependently evolved which is called recursive logic of design (Nguyen & Zeng, 2012b).

2.8.3 Axiomatic Theory of Design Modelling (ATDM)

(Yong Zeng, 2002) developed Axiomatic Theory of Design Modelling (ATDM) to validate recursive logic of design. The theory renders a "mathematical reasoning and representation tool" to study design. To address the nature of human thought process and object representation, ATDM comprises two groups of axiom and mathematical operators such as union ($\cup$), intersection ($\cap$), equality ($=$), relation ($\otimes$), and structure ($\oplus$). The chief operator is structure ($\oplus$) and is defined as union ($\cup$) of an object and relation ($\otimes$) of an object with itself.

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

Where $\oplus O$ is the structure of object O

The structure of an object being designed during design process without the previous knowledge of its concrete structure is represented by structure operator. A group of primitive objects because of human cognitive capacity and scope application can be defined as (Yong Zeng, 2002, 2008):

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

Where O_i^a is a primitive object that cannot or need not to be further decomposed

n is the number of primitive objects

Mathematically, the difference between set theory and ATDM is an elimination of membership operation ($\in$) in the latter which is beneficial to represent unknown design information. For creative design this situation is very critical because the structure of design solution is mostly new and hence it cannot be denoted in a prior defined structure (Nguyen & Zeng, 2012b).

2.8.4 Design governing equation

To identify the conflicts between desired state of design and current state the evaluation operator (K_i^e) is considered; and let design state i (or design environment at state i) is represented by E_i. Then, the design problem at state *i* is defined as:

$$P_i^d = K_i^e (\bigoplus E_i) \tag{3}$$

The description of design solution is represented by the environment structure $\bigoplus E_i$ at design state *i,* relevant design knowledge, design requirement of new design state (i + 1), and other design information (Yong Zeng, 2004).

The synthesis operator K_i^s on design problem P_i^d leads to a new design state (i + 1):

$$\bigoplus E_{i+1} = K_i^s(P_i^d) \tag{4}$$

From equation (3) and (4), we have:

$$\bigoplus E_{i+1} = K_i^s(K_i^e (\bigoplus E_i)) \tag{5}$$

Equation (5) is called design governing equation and it models the recursive logic of design as graphically shown in figure 2.11 (Yong Zeng, 2004; Yong Zeng & Gu, 1999; Yong Zeng, Yan, Chen, & Yao, 2011). The equation shows the recursive nature of design in which previous design state E_i through synthesis knowledge and evaluation knowledge results in current design state (E_{i+1}).

2.8.5 Relation between design states

(Lansdown, 1987) combine the routine design and creative design to model the creative act with "catastrophe theory" in order to understand design creativity. These assumptions inspired Zeng and Cheng to associate design and chaotic dynamics (Y Zeng & Cheng, 1991).

2.8.5.1 Nonlinear chaotic design dynamics

There are two parts involve in any dynamical system: a state and a dynamic (Crutchfield, Farmer, Packard, & Shaw, 1986). A state comprises the vital information of system (i.e. "*components and their relation*"). The evolvement of system with time from initial state to final state is discovered by dynamic rule. An attractor (i.e. chaos) in its state space can be used to characterize the convergence of a dynamical system to a stable motion with passage of time. Unpredictable motions and "sensitive dependence on the initial conditions" are fundamental characteristics of chaos. The system may be effected considerably with the amplification of small fluctuations in its time evolution. The mapping function $f: x_{n+1} = f(x_n)$ is used to illustrate the chaotic motion, where an initial difference is small fluctuation ε between two x's is augmented to the separation of $\varepsilon e^{n\lambda(x_0)}$ as illustrated in figure 2.12. There can be many attractors those may involve to various attractors under various initial conditions in a dynamical system (Nguyen & Zeng, 2012b).

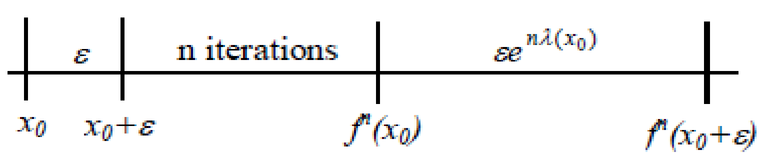


Figure 2-12: Chaotic motion (Nguyen & Zeng, 2012)

However, it is not certain that all the dynamical equations which are nonlinear in nature will consequence in chaotic motion. The stretching and folding operation is very important element in chaotic dynamics. The stretching operation as its name explains is to diverge an orbit exponentially in state space whereas the folding operation forces the orbit to come closer to one another (Nguyen & Zeng, 2012b).

From equation (3) to equation (5), it can be determined that a new design solution redefine each new design state, a refined design problem formulation, and a new design knowledge related to the solution. Hence, equation (5) is further formulated as:

$$\oplus E_{i+1} = K_i^s(K_i^e (\oplus E_i)) = D^i (\oplus E_i) \quad (6)$$

From equation (6), it is reflected that solving design problem is a process to find the fixed point of function D^i. From an initial design state $\oplus E_0$, the next design state $\oplus E_1$ can be determined using equation (6), which updates function D^i and design states. Therefore, during design process at each stage $D^0, D^1 \dots . D^n$ are generated. They redefine the required design knowledge to generate design solution. In accordance with equation (6), the relation between initial $\oplus E_0$ and final $\oplus E_s$ design state can be denoted as:

$$\oplus E_s = D^n D^{n-1} \dots . D^0(\oplus E_0) \quad (7)$$

The above mentioned design process is indeed consistent with the recursive logic of design (Y Zeng & Cheng, 1991). Equation (6) represents that at every stage of design process the evaluation operator K_i^e generates design solution that defines the evaluation operator K_i^s. It means both K_i^e and K_i^s operators are interdependent and interact with one another. Therefore, "*function D^i is nonlinear"* (Nguyen & Zeng, 2012b). In result, it is possible that same design problem may have many fixed points but "convergence relies on the initial design state". In addition, depends upon the design problem, a bunch of possible design solutions are suggested by the synthesis process K_i^s which perform like a stretching operator to expand design state space. Whereas, the evaluation process K_i^e perform like a folding operator to shrink and adjust design state space by investigating the possible design solution against the defined design requirements through identification of undesired conflicts. The final design solution is the result of interaction between these two operators as shown in figure 2.13.

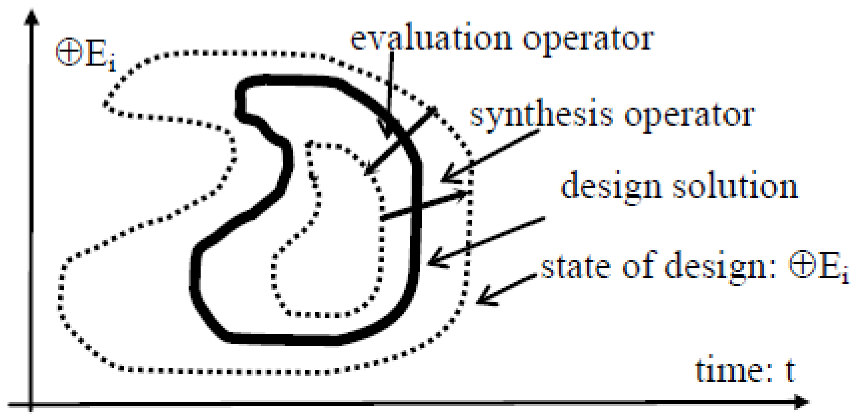


Figure 2-13: State space of design under synthesis and evaluation operators (Yong Zeng, 2004)

Therefore, design process has stretching and folding operations which are essential conditions for

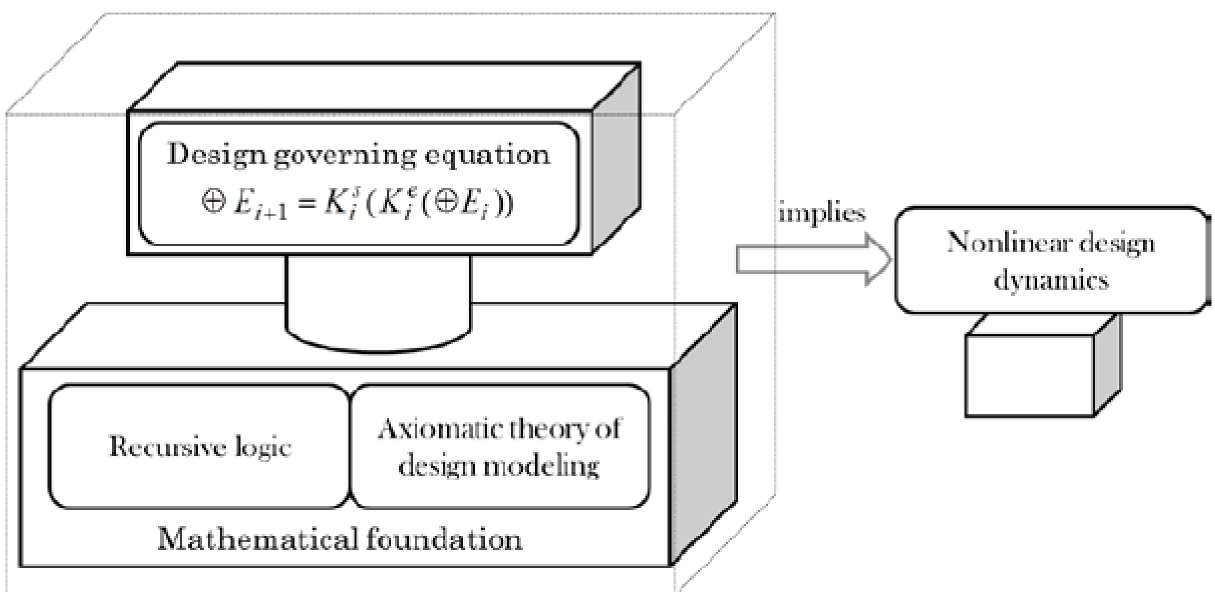


Figure 2-14: Non-linear dynamics underlying design activities (Nguyen & Zeng, 2012)

chaotic motions in a dynamical system. It leads to the postulate of nonlinear design dynamics which is given as follow (Nguyen & Zeng, 2012b).

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

It is discovered that this postulate suggests essential condition for creative design. Design governing equation represents the chaotic design dynamics which are responsible to generate creative design solutions. Figure 2.14 illustrates the relationship among axiomatic theory of design modelling, recursive logic, nonlinear design dynamics and design governing equation.

2.8.5.2 Routes to creative design

The creative design solutions are generated and reformulated continuously under certain initial conditions by design itself. Nonlinear chaotic nature and different initial conditions of design process leads to multiple design solutions for same design problem, it is believed that some of those might be creative. Mathematically, design states inhere these initial conditions.

Let the design environment E_i contains n_e number of environment components and E_{ij} is an environment component, then equation (4) and equation (5) can be further represented as:

$$\oplus E_{i+1} = K_i^s(P_i^d) = K_i^s(K_i^e (\oplus E_i)) = K_i^s \left(K_i^e \left(\oplus\left(\cup_{j=1}^{n_e} E_{ij}\right)\right)\right) \tag{8}$$

$$K_i^e \subset \{K_1^e, K_2^e, \dots \dots K_n^e\}, \exists K_i^e : K_i^s \sqsubset \{K_1^s, K_2^s \dots \dots K_m^s\}$$

Equation (8) describes that it is possible to decompose the design problem into sub-problems and each design problem can be evaluated with different approaches (K_i^e), and to generate solution for each identified problem, different approaches (K_i^s) are presented. Hence, it can observed from equation (8) that three possibilities can be derived which may result in different design states.

1. During design process, define the design problem in different manner. Design problem at each design stage is redefined which amplified initial differences in problem formulation throughout the design process as shown in figure 2.15. It reflects that changes in perception of seeing a design problem may result in a creative solution.

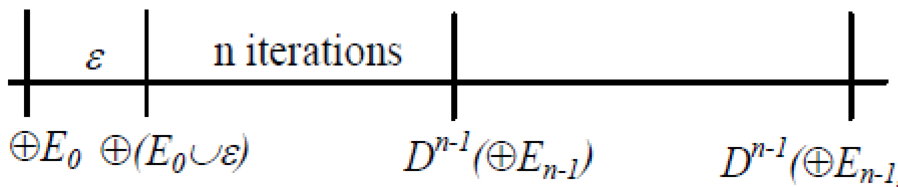


Figure 2-15: Nonlinearity of design process: a small difference in the design problem is amplified (Nguyen & Zeng, 2012)

2. Extend the design knowledge that can deliver the possibility to select different K_i^e and K_i^s which can further consequence in an intermediate design state $\oplus E_{i+1}$ to be different. Therefore, the final design solution would be considerably different as shown in figure 2.16.

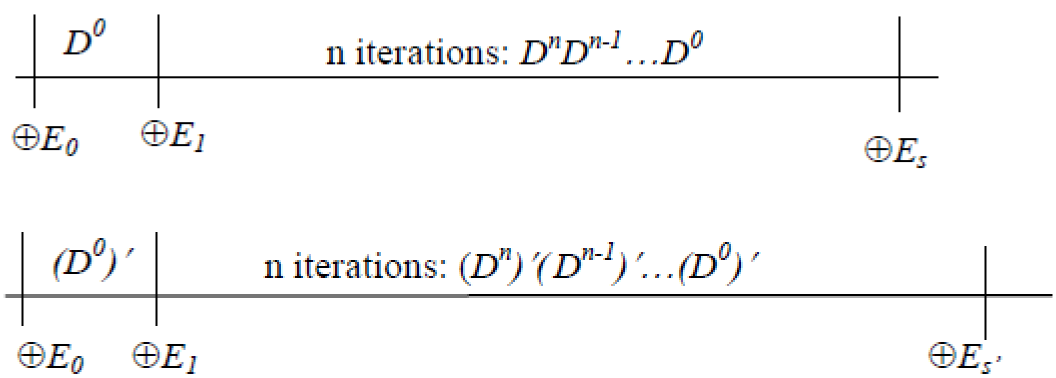


Figure 2-16: Nonlinearity of design process: the same design problem with different design solutions (Nguyen & Zeng, 2012)

3. To decompose a complex problem choose different strategy.

Hence, three routes are identified that can lead to a different design solution. They describe how changes in initial conditions may lead to different final solution during design process.

2.8.5.3 Limitation of ATDM

The explanatory power of ATDM seems to be restricted to the evolution of design states because it is not determined how it explains different phenomena in design as depicts in figure 2.17 (a). The ATDM is also unable to address the role of designer's cognition during the design process as depicts in figure 2.17 (b).

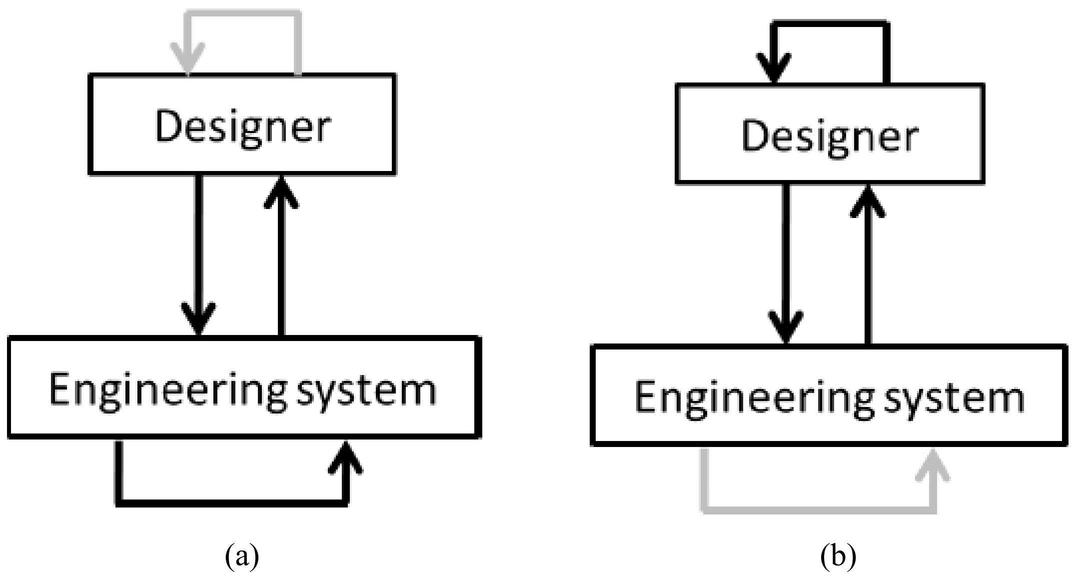


Figure 2-17: Objects of study (Nguyen, August 2016)

2.8.6 Extended ATDM: Relation between design states and designer

The factors of Environment Based Design (EBD) involve in design process that contribute to the changes of initial conditions are identified. Then the role of designer in design process is determined through "an inverse U shaped relationship between mental stress and design creativity".

2.8.6.1 Descriptive design model: EBD

Following the ATDM, the design governing equation is solved using EBD methodology (Yong Zeng, 2002), which comprises three activities – environment analysis, conflict identification, and solution generation as given follow (Yong Zeng & Yao, 2009):

1. **Environment analysis**: the first stage is to define current environment of system $\oplus E_i$.
2. **Conflict identification**: the second stage is to identify undesired conflicts C_i among relationships of environment components by using evaluation operator K_i^e.
3. **Solution generation**: finally synthesis operator K_i^s is used to generate a design solution S_i by resolving a group of chosen conflicts. The design environment and its internal relationships are updates by these three activities to solve a design problem. "The design process remains continue with new environment analysis until no more undesired conflicts exit" (Yong Zeng, 2011). The EBD methodology is shown in figure 2.18.

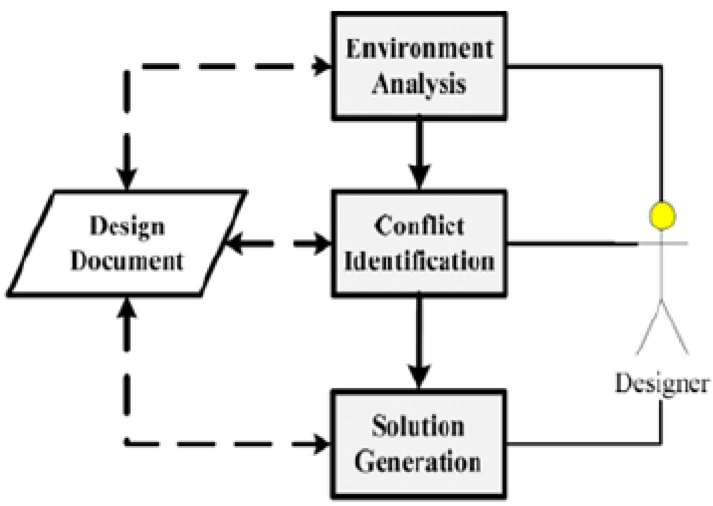


Figure 2-18: EBD: process model (Yong Zeng, 2011)

2.8.6.2 Initial conditions in EBD

The designer perform some design activities those can contribute to the changes in initial conditions of designer are listed in table 2.4. In practice, due to designer's lack of experience, unavailability of cognitive resources and current cognitive state they could not perform all the activities mentioned in table 2.4. The connection between these activities and three possible path that can lead to creative design are listed in table 2.5.

Table 2-4: Summary of information and skills required by design (Nguyen & Zeng, 2012)

	Information					
Skills	**Synthesis knowledge**	**Evaluation knowledge**	**Critical requirement**	**Primitive design solution**	**Partial design solution**	**Conflicts**
Identify		9	1	7		1, 3
Search for	2	4, 6	3			10
Generate				2		
Evaluate				5, 10	10	
Analyze			1	9	9	
Redefine			3, 11			
Recompose				8	8	

Table 2-5: How initial conditions may change (Nguyen & Zeng, 2012)

Routes	Activities
Formulating design problem differently	Search and identify evaluation knowledge Search, identify and redefine critical requirement Generate and update primitive design solution Evaluate, analyze and recompose partial design solution
Extending design knowledge	Search and identify synthesis knowledge Search and identify evaluation knowledge
Changing the strategy of environment decomposition	Search for critical conflicts Search and identify evaluation knowledge

2.8.7 Designer's contribution to the initial conditions through mental capacity

The quality of design depends heavily on designer's performance during design process. The second postulate aims to create a bridge to "integrate designer into this nonlinear design dynamics", as given below (Nguyen & Zeng, 2012b).

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

Research findings from psychology set the foundation to derive the second postulate of designer's mental stress and creativity relationship, shown in figure 2.19.

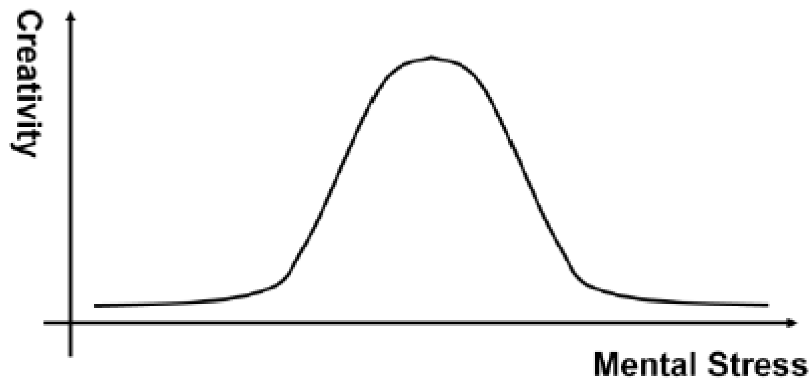


Figure 2-19: Relationship between creativity and mental stress (Nguyen & Zeng, 2012)

Researchers found that there is an inverted U shape relationship between designer's performance and arousal (Wilke, Gmelch, & Lovrich Jr, 1985; Yerkes & Dodson, 1908).

(Tang & Zeng, 2009) hypothesize that the level of mental stress positively associated with workload whereas negatively associated with mental capacity. The relationship is as follow:

$$Mental\ Stress = \frac{Workload}{Mental\ Capability}$$

The definition of workload can be given as "an external load which is entrusted to a person or designer" whereas "the ability of a person or designer to handle that external load" is considered as mental capacity. The source of mental stress is the amount of external workload. Higher the workload may lead to higher mental stress. The workload can be related with the complexity level of problem in hand. In addition, it is possible that under different conditions same individual with same workload may have different mental stress or on the other hand different individuals may feel different mental stress with same workload.

Mental capability comprises three elements – knowledge, skills, and affect. There are many definitions of knowledge (Rowley, 2007) but the most relevant in this context is given by (Rainer & Cegielski, 2010) such as knowledge is "the organized and processed data and/or information that is transfer to understand, accumulate learning, experience, and expertise as they apply to a current problem or activity". Skills denotes the thinking strategy or reasoning, and thinking style. Skill helps to expand the knowledge, and relevant knowledge required to solve a problem can be identified. Affect presents the emotions and mental states related with feeling (Brenner & Salovey, 1997) and it can be determined by belief, attitude, motive, stress, and personality traits. For problem solving, how much an individual's knowledge and skills can be effectively utilized relies heavily on affect. This shows clearly the impact of designers in initial design conditions. Hence, it is noteworthy that three chief factors such as knowledge, skills and affect would affect mental capacity. The relationship among these three factors is shown in figure 2.20.

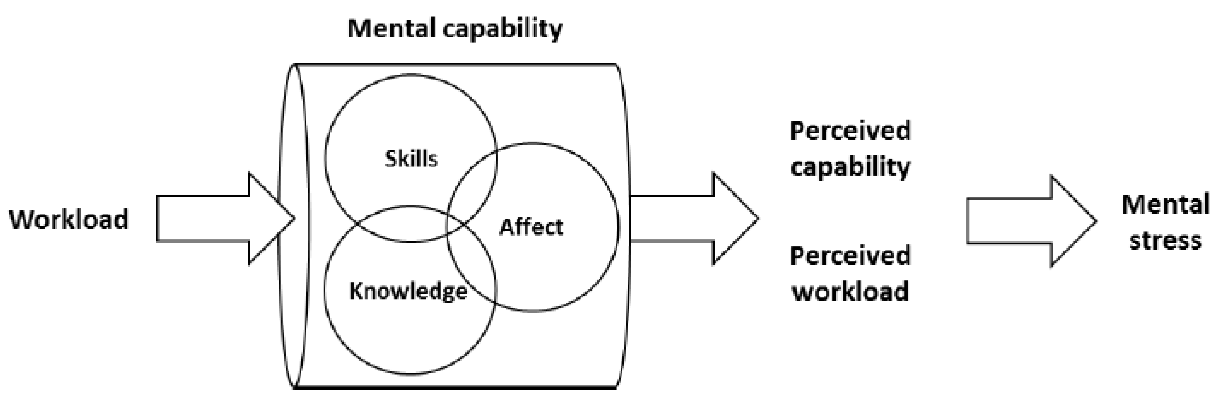


Figure 2-20: Relation between mental capability, workload and mental stress (Nguyen & Zeng, 2012)

To accomplish a design task, the designer must possess knowledge and skills listed in table 2.4. The structure of knowledge (i.e. possibility of how efficiently knowledge can be retrieved from storage) and the availability of cognitive resources (i.e. past knowledge held in working memory to use) are two important factors that influence the knowledge. The lack of knowledge and skills for a design problem in hand can enhance the level of mental stress. Moreover, because of the recursive nature of design, there are many unpredictability and uncertainties exists about the completion of design task which may generate negative feelings such as sense of being lost, frustration, and fear of failure which in result may enhance the level of mental stress (Nguyen & Zeng, 2012b).

An individual's perception about perceived workload can be more or less than the actual workload which completely depends upon the mental capacity. The mental stress is then determined by the mental workload and the level of mental stress affects designer's creative performance.

All the above discus infers that (Nguyen & Zeng, 2012b):

1. Mental capability and workload cannot be viewed as two separate aspects. A designer may reveal different mental capacity while facing different design problem. As designer may lack in knowledge for one design problem but can have vital knowledge about other problem.
2. How effectively knowledge and skills can be utilized in design process is determined by affect.
3. When a designer finds the design problem much more complex and uncertain which is beyond his mental capability, then his level of mental stress will be high. On the contrary, his mental stress will be low when he finds the uncertainty and/or complexity of problem is below to his mental capability.

2.9 Summary

In this chapter, primarily we presented cognitive neuroscience studies of creativity as (P. Tierney et al., 1999) pointed out that creativity is positively associated with cognitive processes (i.e.

divergent thinking). These cognitive processes in creativity are the mechanisms, traits, and thinking patterns used to escort and direct creative tasks (Ward et al., 1999). In nutshell, CN studies confirmed findings of (Mark A Runco, 2014; R. K. Sawyer & Creativity, 2006) that during creative task any area of brain can be active. (Kounios et al., 2008) explained that identical brain region is responsible for the elevation of neural activity in both creative and non-creative cognitive tasks. (Sandkühler & Bhattacharya, 2008) used EEG to analyze RAT triplet's results and found elevated "upper alpha band (8-12 HZ) response in RH temporal region and strong gamma band (38-44 HZ) response in parieto-occipital region". (Martindale & Mines, 1975) used EEG to study brain's neural activity and found that creative people in comparison to non-creative people display higher alpha wave activity during creative tasks (i.e. RAT). Cognitive studies highly contributed to understand cognitive processes which leads to creativity but seems unable to operationalize creativity in terms of "usefulness" and "novelty". Therefore, we presented studies of creativity in engineering design and various measurement methods and tools to assess the creativity. Different researchers used different indexes to measure creativity during cognitive tasks. The idea generation involves various cognitive processes such as memory retrieval, attention, and working memory etc (Schwab et al., 2014). The researchers reported that high cognitive tasks demands additional mental effort (Nguyen & Zeng, 2014a), task difficulty associated with mental effort, task difficulty depends upon Working Memory Capacity (WMC) (K. Sawyer, 2011), and high mental effort leads to creative solution (Nguyen & Zeng, 2014b), creativity requires attention (Zabelina, Saporta, & Beeman, 2016). Several studies also reported that EEG is most sensitive to changes in cortical regions at task difficulty. We observed that the neuroscientific approach such as EEG is highly in demand to analyze designer's behavior during design creativity (i.e. conceptual design process) which is responsible for creative performance. (Akin & Akin, 1996) stressed for the need of a theoretical model that can derive interpretations of design creativity phenomena and can reason about design creativity. In next section, we presented such a theoretical model developed by (Nguyen & Zeng, 2012b) which identifies various factors affecting the creative design. The model consist of two postulates. The first postulate: "*Design reasoning follow a non-linear dynamics which may become chaotic"*. This postulate explains the recursive nature of design process. The second postulate: "*Design creativity is related to designer's mental stress through an inverse U shaped curve".* As the quality of design depends heavily on designer's performance during design process. The second postulate aims to create a bridge to "integrate designers into this nonlinear design dynamics" (Nguyen & Zeng, 2012b). Researchers also reported that there is an inverted U shape relationship between designer's performance and arousal (Wilke et al., 1985; Yerkes & Dodson, 1908). To accomplish a design task, the designer must possess knowledge and skills. The lack of knowledge and skills for a design problem in hand can enhance the level of mental stress which in result affects designer's creative performance.

Therefore, from these studies it is clear that physiological approach such as EEG is most sensitive to changes to the cortical activation at different level of task difficulty. Many studies reported the identification of activated brain area during cognitive task by EEG activity (i.e. synchronization or desynchronization of EEG power). However, there is no study available in literature where two cognitive states are compared based on EEG power distribution between two design tasks specifically to compare creative performance (i.e. level of task difficulty high) with non-creative performance (i.e. level of task difficulty is low). Since, it could be possible to identify area of brain which are activated during creative design task and in non-creative design task based on utilized cognitive abilities to complete two task of different level of task difficulty.

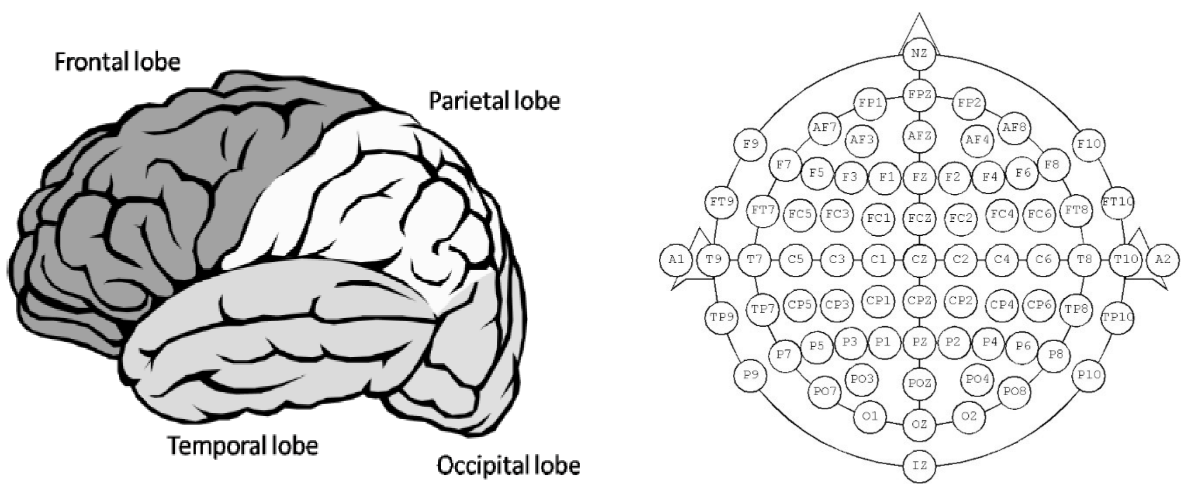
Chapter 3. Physiological approach to investigate creativity in design task

3.1 Physiological signals

In recent times with an advancement in technologies, physiological signals are widely used to study designer's cognitive behavior and design activities. We discuss some of them in this study.

3.1.1 Electroencephalography (EEG)

EEG based approach allows an objective measure of design activities by recording designer's brain electrical signals when they work on design task. EEG signals can be recorded from four different regions of a brain or human scalp: frontal lobe, parietal lobe, temporal lobe, and occipital lobe as shown in figure 3.1 (a). Each lobe is responsible for specific brain functions (Nguyen & Zeng, 2010) as described in table 3.1. The electrodes on the scalp has positions according to the international standard 10-20, 10-10, or 10-5 system. Figure 3.1 (b) follows the 10-10 system.



(a) (b)

Figure 3-1: a) areas of brain (b) 10-10 international system of electrode placement (Nguyen & Zeng, 2010)

Table 3-1: Brain regions and their functions (Nguyen & Zeng, 2010)

Brain region	Functions
Frontal lobe	Planning, judgment, making decision, concentration, emotions, motor
Parietal lobe	Verbal understanding, texture and shape interpretation
Temporal lobe	Auditory processing, auditory memory
Occipital lobe	Visual processing, visual experiences, eye focusing

Electrical brain signals, also called EEG signals, are classified in terms of frequency band. EEG has four main frequency bands: delta (1-4Hz), theta (4-8Hz), alpha (8- 13Hz) and beta (>13Hz). The delta rhythm is present all over the scalp during sleeping state. Theta rhythm dominant during relaxed state and eye open. Alpha rhythm dominant during eye close and beta rhythm appears when the brain is engaged in visual or cognitive activities (Nguyen & Zeng, 2012a). Among theta, beta and alpha, only theta over parietal site can be used to identify low and high task demand (Fairclough, Venables, & Tattersall, 2005; Nguyen & Zeng, 2014a). Regarding beta band, it is often associated with cortical activation. The increase in beta band over occipital lobe (visual cortex) is related to the increase in visual attention (Gola et al., 2013; Nguyen & Zeng, 2014a). (Howells, Stein, & Russell, 2010) testified a positive correlation between perceived mental effort and left parietal beta power during attentional tasks.

3.1.2 Heart rate variability (HRV)

Heart rate variability (HRV) is the variation in time intervals between consecutive heartbeats. Five alphabets P, Q, R, S, and T represents the heartbeat waveform as shown in Figure 3.2. The time interval between two heartbeats is the time between two R and R components generated from the QRS complex. R and R intervals also called cycle length variability where R is a point corresponding to peak of the QRS complex of the ECG wave. ECG is one method used to detect HRV. The HRV spectrum is classified into four bands as shown in table 3.2.

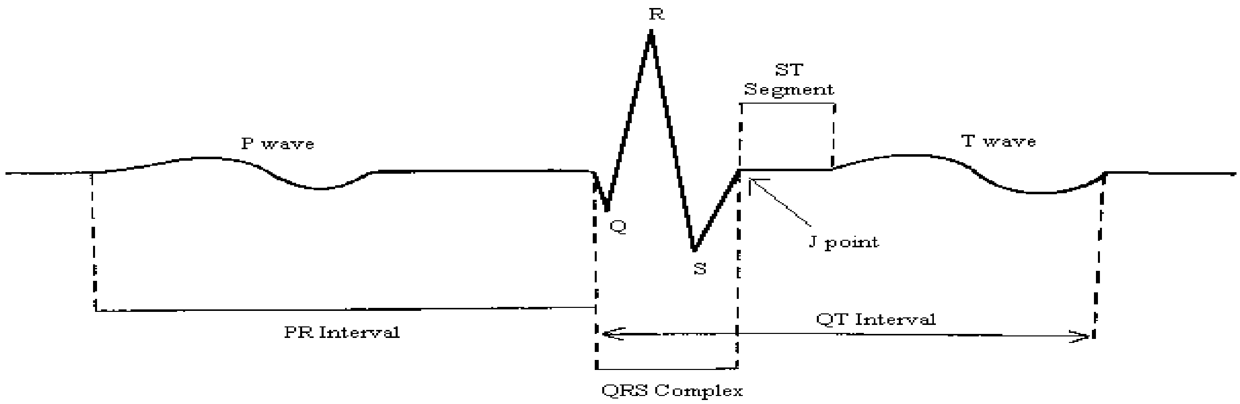


Figure 3-2: Components of QRS complex (http://nps.freeservers.com/ek.htm)

Table 3-2: HRV spectrum

Frequency	Frequency range
Ultra-low frequency (ULF)	Less than 0.003 Hz
Very low frequency (VLF)	0.003 Hz- 0.04 Hz
Low frequency (LF)	0.04 Hz- 0.15 Hz
High frequency (HF)	0.15 Hz- 0.4 Hz

3.1.3 Skin conductance (SC)

Electro dermal response (EDA) is the canopy term used to define autonomic changes in skin's electrical properties. One of the extensively used property is Skin Conductance (SC) which defines the phenomenon that the skin temporarily becomes a better conductor of electricity. EDA compound comprises both background tonic (skin conductance level: SCL) and swift phasic components (skin conductance response: SCR) yielded from sympathetic neural activity which describes that SNS plays chief role in any electrical changes of skin conductance (Stern, Ray, & Quigley, 2001). The state of sweat glands in the skin roots is to fluctuate skin resistance. SNS control this sweating whereas SC is signal of physiological arousal. The highly aroused SNS leads to increment in sweat gland activity which causes skin conductance to augment. So, SC can be measure of sympathetic and emotional responses and can be counted as an indirect way to measure the activity of stress system (Southwick, Yehuda, & Charney, 1997).

3.2 Relationship of mental stress, mental effort, and creativity

(Nguyen & Zeng, 2014a) reported that there is U curve relationship exist between mental stress and mental effort. Mental stress is body's response in critical and/or threatening situations. The stress mechanism is associated with Autonomic Nervous System (ANS) which comprises of two main parts such as Sympathetic Nervous System (SNS) and Parasympathetic Nervous System (PNS). The SNS that reflect low frequency (LF) increases heart rate whereas PNS that reflect high frequency (HF) decreases heart rate. Psychosocial stress is originate to be related with mounting LF or aggregate LF/HF ratio or lessening HF. If the ratio of LF/HF is greater than one, SNS dominant which indicate stress. EEG is most sensitive to changes to cortical activation (Gevins & Smith, 2006) at different level of task difficulty. Physiological parameters such as EEG reflects mental effort to some degree when task demand increases (Mulert et al., 2007). Many researchers have reported that enhancement in task difficulty result in increased theta band and decreased alpha band (Gundel & Wilson, 1992; Smit, Eling, Hopman, & Coenen, 2005).

In an experiment where participants were asked to solve an open ended design problem, (Nguyen & Zeng, 2014a) quantified their mental stress by LF/HF ratio and mental effort was measured by EEG beta energy. Following are the results of her experiment:

1. Designers were under low or medium stress during the conceptual design process.
2. At higher stress level, designers spent less time.
3. At low and medium stress level, mental effort was stronger than mental effort at higher stress level.

They assumed that mental effort is associated with creativity. That is, if the subject put more effort in designing a solution leads to higher possibility that designer can generate a creative solution. To investigate further this assumption, (Nguyen & Zeng, 2014b) analyzed EEG spectrogram study of single subject when he performed creative and non-creative design task. It was found that beta was strong when subject put more efforts. In creative tasks, beta occurred frequently in comparison to non-creative task. The focus of study was also to find some regularities between EEG signals and creative/non-creative design activities. The authors have presented the challenges they faced during data analysis:

Hypothesize: "They hypothesize that creative thinking require more EEG theta and beta power than non-creative thinking" (Nguyen & Zeng, 2014b).

They were expecting to compute EEG power in creative design task and then compare it with EEG power in non-creative design task, and the power in creative design task should be significantly higher than in non-creative design task. However, they reported that it is not possible to compare EEG between creative design task and non-creative design task with (cortical) area to area comparison approach because of following reasons:

Reason 1: The creative and non-creative design task may utilize different cortical regions.

Reason 2: To solve the design problem, different designers implement different approaches that may cause different regions to be activated.

3.3 Formulation of Objective

Therefore, we try to find the roots of this challenge. We try to estimate the power of brain activity during creative design task and non-creative design task. Since, we want to compare EEG power between these two tasks and we are fascinated to determine which brain area is associated with strong EEG power in creative design task compare to non-creative design task. So that we can compare EEG using (cortical) area to area approach. Hence, we formulate an objective "To investigate the power of brain activity using EEG comparison between creative and non-creative design task".

The reason one in previous section reflects that the creative/non-creative design tasks and cortical regions may not have strong correlation. That is, the interaction effect between these two factors may be non-significant. If we find the p-value greater than 0.05 (i.e. standardized value to maintain the probability of type I error) for interaction effect between these two within-subject factors (i.e. design tasks, cortical area). Therefore, it would be not possible to compare EEG power between creative and non-creative design task with (cortical) area to area approach.

For better understanding of an objective, we applied Recursive Object Model (ROM) diagram on it. ROM is a linguistic tool invented by (Yong Zeng, 2008) to represent natural language used in engineering. ROM comprises of five elements such as object, compound object, predicate relation, constraint relation, and connection relation as shown in figure 3.3.

Type		**Graphic Representation**	**Definition**
Object	Object	O	Everything in the universe is an object.
	Compound Object	O	It is an object that includes at least two other objects in it.
Relations	Constraint	•⟶	It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection	- - - ι - - ->	It is to connect two objects that do not constrain each other.
	Predicate	— ρ ⟶	It describes an act of an object on another or that describes the states of an object.

Figure 3-3: Elements of Recursive Object Model (ROM)(Yong Zeng, 2008)

The mathematical foundation is based on two Axioms of the Axiomatic Theory of Design Modeling are given below (Yong Zeng, 2008).

1. *Everything in the universe is an object.*
2. *There are relationships between objects.*

Objective: To investigate the power of brain activity using EEG comparison between creative and non-creative design task.

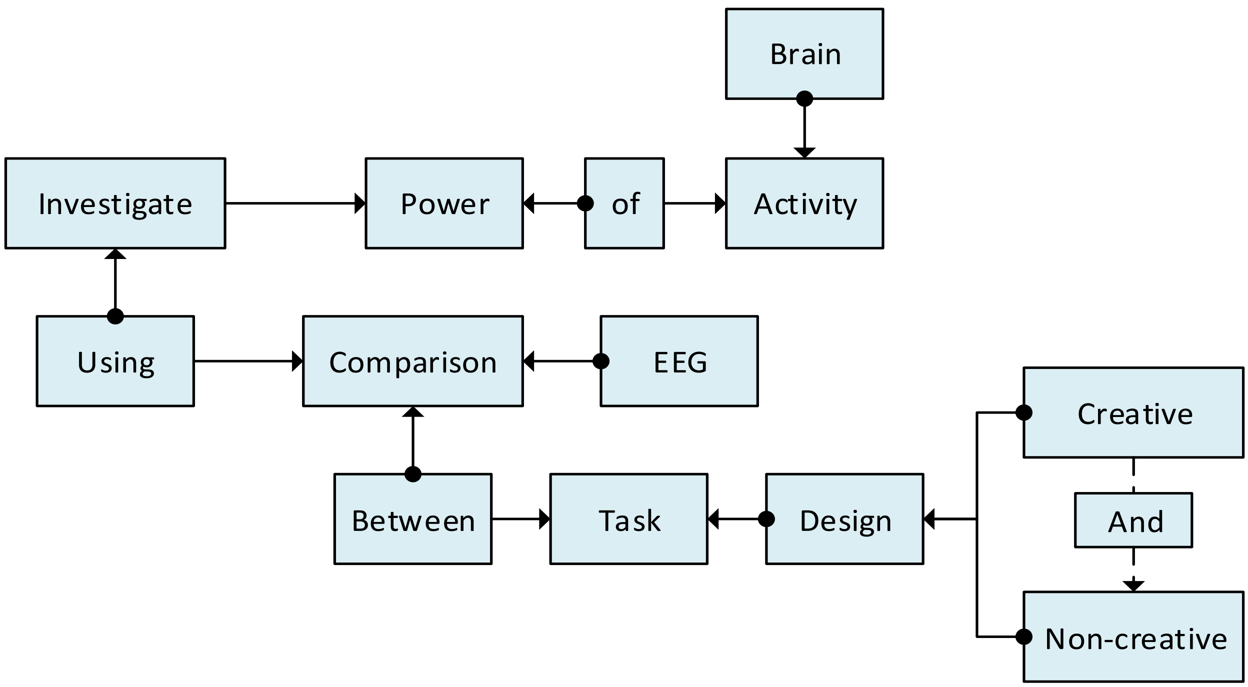


Figure 3-4: Recursive Object Model (ROM) diagram of an objective

The next step is to generate questions based on ROM diagram. For more detail information about ROM and its functioning, readers can check (Yong Zeng, 2008, 2011). The generated questions in the research based on ROM are given below:

1. What is creative/ non-creative design task?
2. What is power of brain activity?
3. What do you mean by EEG comparison?
4. Why to investigate power of brain activity using EEG comparison?

5. How/When/Where/Why to investigate power of brain activity using EEG comparison between creative and non-creative design task?

To best of our understating, we try to answer these questions as follow:

1. *What is creative/ non-creative design task?*

An individuals' mental capabilities are measured by the psychometric tests which are standard and scientific methods. Torrance Test of Creative Thinking (TTCT) (Torrance, 1966) have been developed and empirically tested for psychometric measures of creative thinking. Divergent thinking (i.e. an ability to generate variety of ideas) is measured by Torrance Test of Creative Thinking (TTCT). The two design task such as creative and non-creative design task uses divergent thinking method. These two design task are designed by modifying original TTCT. Because in original TTCT, subjects are asked to complete a partial drawing and the judge will evaluate if the drawing is creative or not. However for EEG experiment, the focus was to identify areas of the brain that are activated in creative task and in non-creative task. Therefore, two cognitive states are required to compare. It is possible to do comparison between rest and creative task, or between non-creative task and creative task, or mathematical test and creative task. The experimenter choose to compare between non-creative and creative tasks.

2. *What is power of brain activity?*

Designer's brain produce certain electrical signals when they work on a cognitive design task. These electrical signals are fired off by neurons. EEG is used to record these signals. The patterns of neuronal activity changes within specific cortex of brain based on task difficulty. The changes are reflected by power changes in different cortex. EEG is most sensitive to these changes to the cortical activation at different task difficulty level. Active area of brain use more power than less active area. The power (amplitude square) is the distributed EEG power of signal over frequencies which is determined by Power spectral analysis.

3. *What do you mean by EEG comparison?*

It is to find the co-relation of EEG power between creative and non-creative design task when designers use their cognitive abilities to complete these two tasks.

4. *Why to investigate power of brain activity using EEG comparison?*

EEG is most sensitive to changes to cortical activation at different level of task difficulty. EEG used in variety of cognitive tasks and experimental procedures have yielded evidence of possible brain correlates underlying creative thinking. We use EEG to calculate power of brain activity. Different power means different brain patterns that means different cognitive states. That is why we want to investigate power of brain activity.

5. *(a) When/Where/Why to investigate power of brain activity using EEG comparison between creative and non-creative design task?*

When participants performed creative and non-creative design task in design lab (i.e. experimental lab) of Concordia University. To compare EEG power between two design tasks by (cortical) area to area approach.

5. *(b) How to investigate power of brain activity using EEG comparison between creative and non-creative design task?*

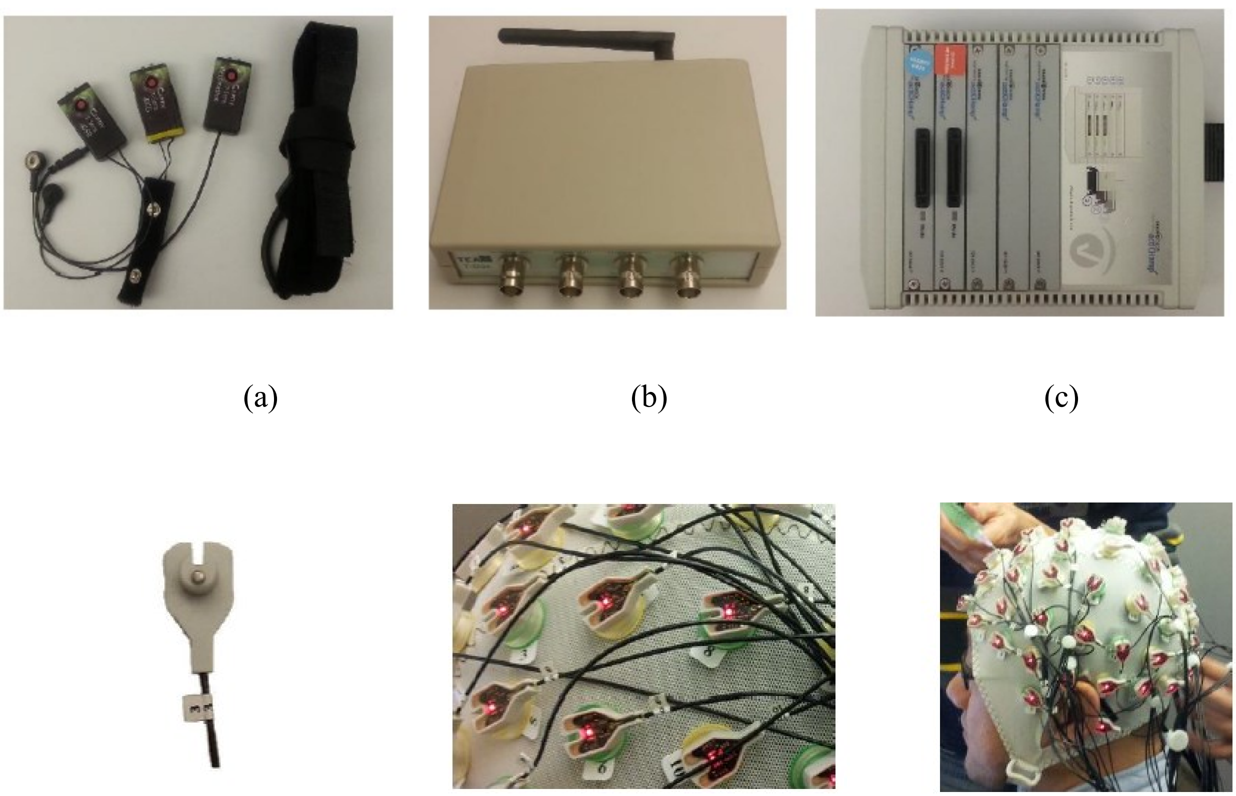
To investigate this study, we use experiment designed by (Nguyen & Zeng, 2014b). Then we perform Power Spectral Analysis and Statistical Analysis using Repeated measure ANOVA.

3.4 Experiment design

The experiment was designed to compare two cognitive states (i.e. creative design task and non-creative design task). This experiment do not use an approach to subtract rest state from cognitive state or by averaging rest state to compare with cognitive state to identify the changes to cortical activation. Therefore, the rest state was set in start and in the end of experiment instead of in-between the cognitive states. Rest state was set for 3 minutes because with longer rest period, participants may tired and shorter duration than this may not be considered as actual rest state.

3.4.1 Recording devices

EEG system of 64 channels with active electrodes was used to reduce the noise picked up by electrodes. Three EEG caps were used in order to fit in different head sizes from Brain Vision.



(a) (b) (c)

(d) (e) (f)

Figure 3-5: (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 (Nguyen, August 2016)

The quality of signal improved due to in-built amplifier in the active electrodes. The new EEG system consists in-built impedance check. The flexibility of putting electrodes into holders before adjusting the cap on subject's head, made this new caps more useful. This aided experimenter to save a lot of preparation time.

3.4.2 Design task and procedure

Twenty nine students volunteered to participate in the experiment from the department of Concordia Institute for Information System Engineering. We use sample of 16 subjects (3 female and 13 male) aged between 25 to 35 years, and all are right handed. The procedure of an experiment is illustrated in figure 3.6.

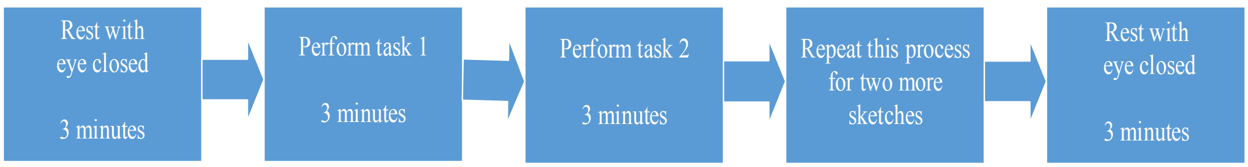
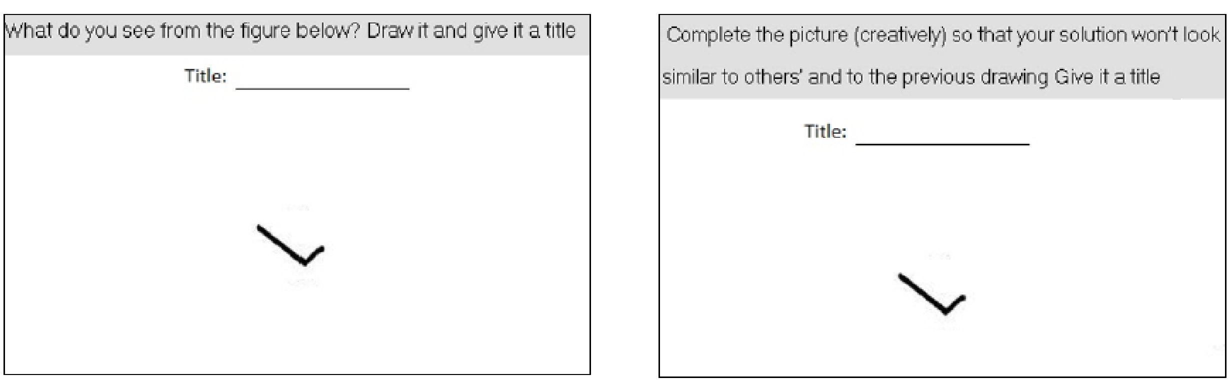


Figure 3-6: Experiment procedure

The experiment consists two chief tasks such as non-creative design task and creative design task. Two similar sketches were presented in both the tasks as shown in figure 3.7. In non-creative design task, the participants were instructed to indicate what they observe intuitively from the given sketch by adding title to the sketch. They were allowed to provide additional information if it is necessary to describe the sketches.



(a) (b)

Figure 3-7: (a) Non-creative design task, (b) creative design task (Nguyen & Zeng, 2014b)

In the creative design task, the participants were asked to think creatively and generate concept which could be different from what they originally perceive from the given sketch. The time limit to complete the task is three minutes. The test was developed with some modification to the Torrance Test of Creative Thinking (TTCT) (Torrance, 1966). We used visual TTCT because it is widely used for behavioral measures, and very useful in assessing individual differences on very specific items (T. M. Amabile & Pillemer, 2012; Nguyen & Zeng, 2012b). The participants were required to rate their experience after finishing the second task (i.e. creative task).

The participants were required to repeat an experiment three times for three different sketches provided to them as shown in figure 3.8. The similar order of sequence was used to present sketches to participants as listed in figure.

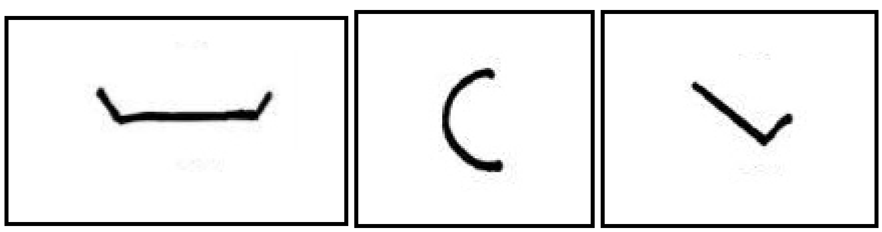


Figure 3-8: Sketches used for experiment (Nguyen & Zeng, 2014b)

3.4.3 Data collection

The physiological signals were recorded by EEG cap, Skin Conductance (SC) finger strap, ECG belt, and respiration rate belt. To capture, facial expressions, hand gestures, and body movements, camera were placed at different angles. The skin conductance recorded at 32 Hz with two sensors which were wrapped around subject's ring finger and little finger of non-dominant hand. EEG signal was recorded for 64 channels at 500 Hz frequency through electrode placement using the 10-10 system. Electrode impedances were retained below 5 $k\Omega$. Besa software was used to remove artifacts and EEG signals were filtered between 0.1 Hz and 100 Hz. The sensor chest map was used to collect ECG signal at 256 Hz. The Cz channel was used as reference for recordings. Abdominal belt was used for collecting respiration rate.

3.4.4 Data analysis

For data analysis, we perform three major tasks: Power spectral analysis, aggregate electrode positions for cortical areas, and statistical analysis as shown in data analysis flow chart.

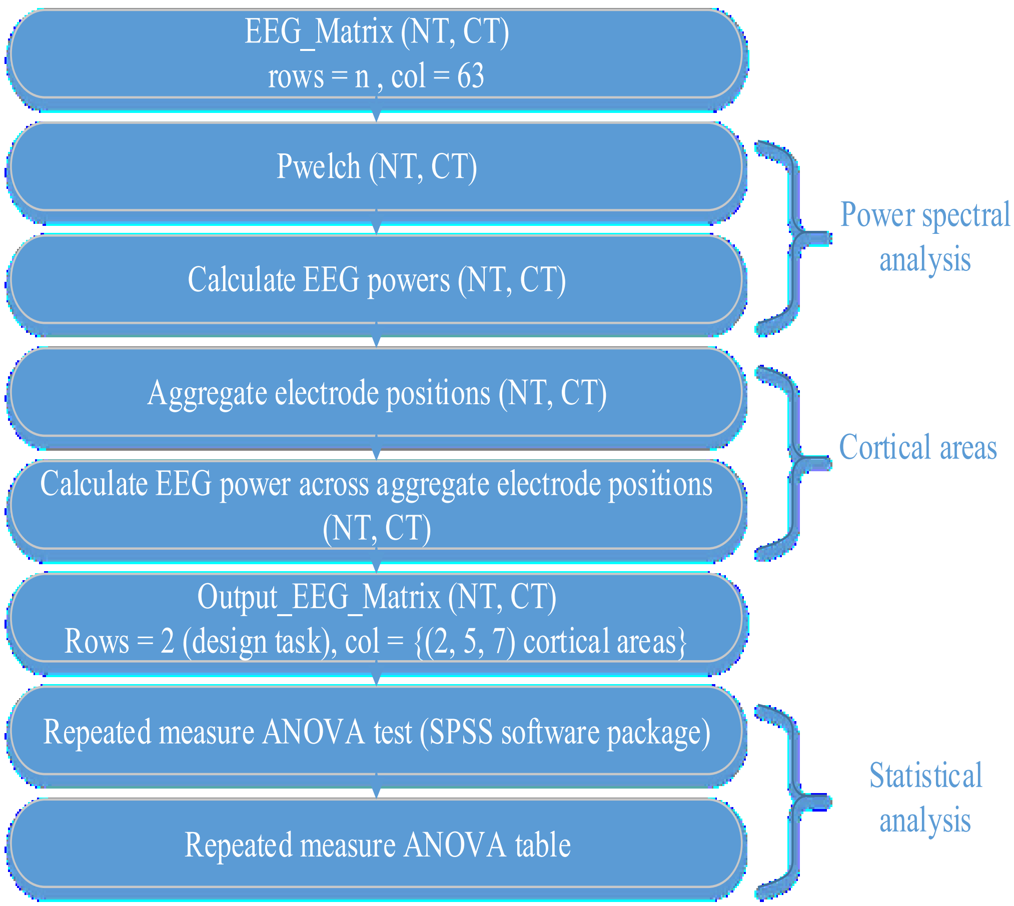


Figure 3-9: Data analysis flow chart

Firstly, we estimate the spectrum of EEG signal using welch method. This is a non-parametric technique to estimate Power Spectral Density (PSD). PSD is used to determine the distribution of EEG power of signal over frequencies. The welch method allow to use any window which aids to control the amount of smoothing. We use hamming window with 50% overlapping which improves resolution by reducing energy leakage from excessive side-lobes. After estimating the spectrum of EEG signals, we calculated EEG power for non-creative design task and creative design task. We analyze the data for sixteen subjects (i.e. based on their performance during design task observed from video analysis) at 63 channels with all frequency bands: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-50 Hz).

Secondly for statistical analysis we aggregated electrode positions for three different possibilities of cortical areas:

I. Fronto-central:

FP1,FZ,F3,F4,FT9,FC5,FC1,FT10,FC6,FC2,F4,F8,FP2,AF7,AF3,AFz,F1,F5,FT7,FC3,FCz,FC4,FT8,F6,F2,AF4,AF8,C3,CP5,CP1,CP6,CP2,C4,C1,C5,CP3,CPz,CP4,C6,C2

Temporal, Occipital, and Parietal (TOP):

T7,TP9,TP10,T8,TP7,TP8,O1,OZ,O2,PZ,P3,P7,P4,P8,P1,P5,PO7,PO3,POZ,PO4,PO8,P6,P2.

II. Frontal:

FP1,FZ,F3,F4,FT9,FC5,FC1,FT10,FC6,FC2,F4,F8,FP2,AF7,AF3,AFz,F1,F5,FT7,FC3,FCz, FC4, FT8, F6, F2, AF4, AF8.

Central: C3,CP5,CP1,CP6,CP2,C4,C1,C5,CP3,CPz,CP4,C6,C2.

Temporal: T7, TP9, TP10, T8, TP7, TP8.

Occipital: O1, OZ, O2.

Parietal: PZ,P3,P7,P4,P8,P1,P5,PO7,PO3,POZ,PO4,PO8,P6,P2.

III. Pre-frontal: FP1, FP2, AF7, AFz, AF4, AF8.

Frontal: Fz, F3, F7, FC1, FC2, F4, F8, FC3, FCz, FC4, F5, F1, F2, F6.

Central: C3, C4, C1, C2.

Left-temporal: FT9, FC5, T7, CP5, TP9, FT7, C5, TP7.

Right-temporal: TP10, T8, FT10, FC6, CP6, FT8, TP8, C6

Occipital: O1, Oz, O2, PO7, PO3, POz, PO4, PO8.

Parietal: PZ, P3, P7, P4, P8, CP1, CP2, CP3, CPz, CP4, P5, P1, P6, P2, P8

Then we applied the repeated measure ANOVA considering the within-subject factors TASK (i.e. creative and non-creative design task) and AREA (i.e. we use three different possibilities of area as given above). The sphericity assumption violation is protected using Greenhouse-Geisser procedure and the probability of Type I error is maintained at 0.05. Sphericity is an important assumption for repeated measure ANOVA which refer to the condition where variance of differences between all the treatments of within subject factors are equal. Type I error is referred as incorrect rejection of null hypothesis. The likelihood of type I error rises with large sample size and p-value relies on sample size whereas significance level (i.e. alpha) is fixed. The p-value represents the probability of occurrence of given event which is used as an alternative to rejection points in order to render the lowest level of significance where null hypothesis would be rejected. The cut-off for significance is used at alpha equal to 0.05.

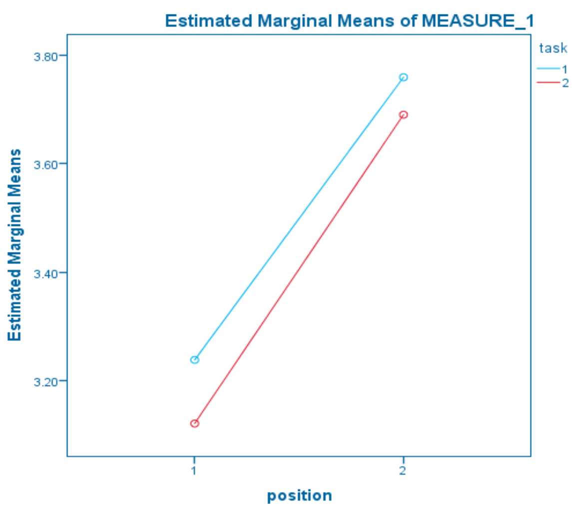
3.5 Results

The repeated measure ANOVA yielded non-significant interaction effect between TASK*AREA for all the EEG power with three different possible combinations of electrode positions, as shown in table 3.3, 3.4, and 3.5. The cortical area is defined by different combination of electrode positions. For two cortical areas (i.e. fronto-central, TOP), the interaction effect TASK*AREA of EEG delta, alpha, beta, and gamma is given as $(F[1.000,15.000] = 5.994, p > 0.05, \eta_p^2 = 0.286)$, $(F[1.000,15.000] = 1.064, p > 0.05, \eta_p^2 = 0.066)$, $(F[1.000,15.000] = 0.007, p > 0.05, \eta_p^2 = 0.000)$, $(F[1.000,15.000] = .482, p > 0.05, \eta_p^2 = 0.031)$ respectively. However, p value for EEG theta is under 0.05, so ($F[1.000,15.000] = 4.792, p < 0.05, \eta_p^2 = 0.242$) but it has non-significant main effects. As we can see in figure 3.10 (b) that both the independent variables interact with each other but because their main effects are non-significant, as a result we cannot get a special synergistic effect (i.e. interaction of two factors that can produce combined effect greater than the sum of their separate effects). The results of EEG theta can also be seen in figure 3.10 (f) which reflects that the distribution of theta power in cortical areas (i.e. fronto-central, TOP) is same in creative and non-creative design task. That is, EEG theta power is not sensitive to changes in tasks.

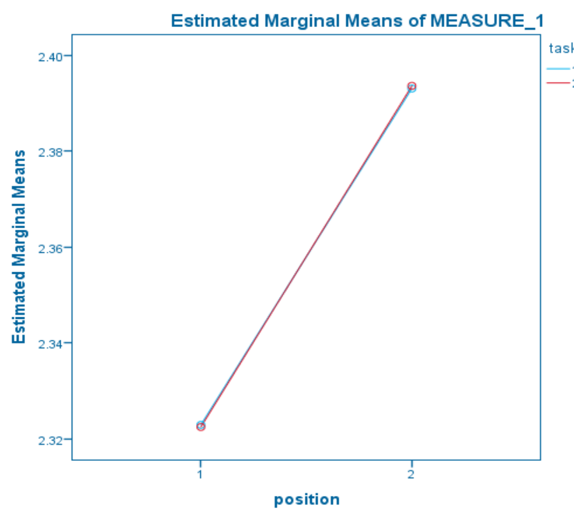
Table 3-3: Repeated measure ANOVA for cortical areas (fronto-central, TOP)

Absolute EEG power	Variables	Degrees of freedom	F-value	Sig.	Partial Eta Squared	Observed Power
Delta	TASK	1.000,15.000	5.994	.27	.286	.629
	POSITION	1.000,15.000	133.178	.000	.899	1.000
	TASK*POSITION	1.000,15.000	1.953	.183	.115	.258
Theta	TASK	1.000,15.000	1.816	.198	.108	.243
	POSITION	1.000,15.000	2.580	.129	.147	.324
	TASK*POSITION	1.000,15.000	4.792	.045	.242	.535
Alpha	TASK	1.000,15.000	12.258	.003	.450	.905
	POSITION	1.000,15.000	910.263	.000	.984	1.000
	TASK*POSITION	1.000,15.000	1.064	.319	.066	.162
Beta	TASK	1.000,15.000	4.398	.053	.227	.501
	POSITION	1.000,15.000	321.018	.000	.955	1.000
	TASK*POSITION	1.000,15.000	.007	.932	.000	.051
Gamma	TASK	1.000,15.000	.498	.491	.032	.101
	POSITION	1.000,15.000	98.099	.000	.867	1.000
	TASK*POSITION	1.000,15.000	.482	.498	.031	.100

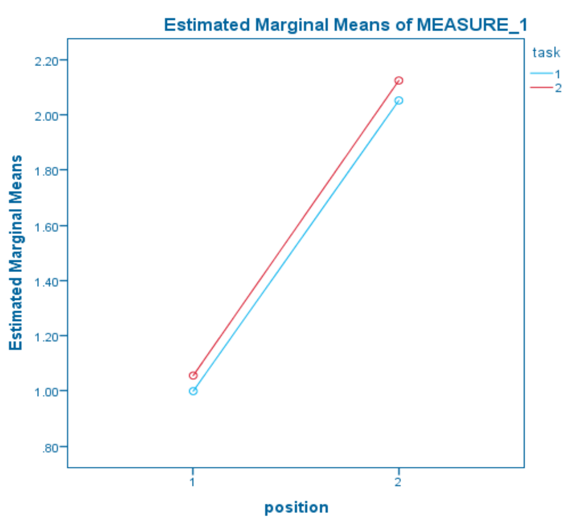
For an independent variable area, all EEG powers except theta are sensitive to area changes. Distribution of EEG powers is higher in TOP and lower in fronto-central. However for an independent variable task, only alpha has significant main effect which reflects that alpha power is sensitive to task changes but the interaction effect of alpha power is non-significant. Therefore, with these cortical areas, no EEG power is sensitive to the interaction of these two within factors, so we cannot compare EEG power between two tasks. The distribution of EEG power is not significantly different in both tasks at different cortical areas.



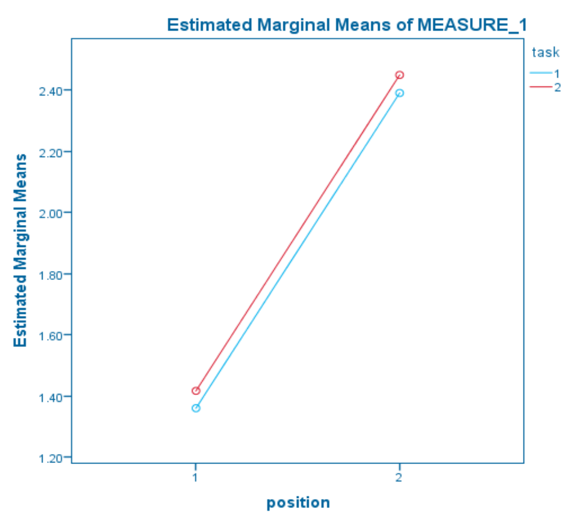
(a)



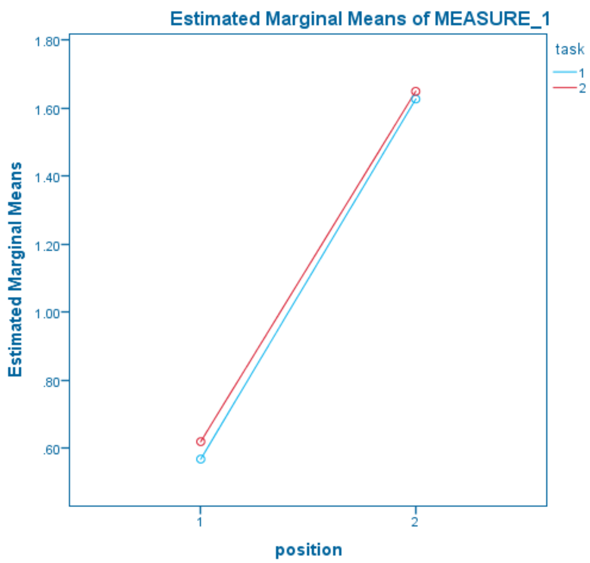
(b)



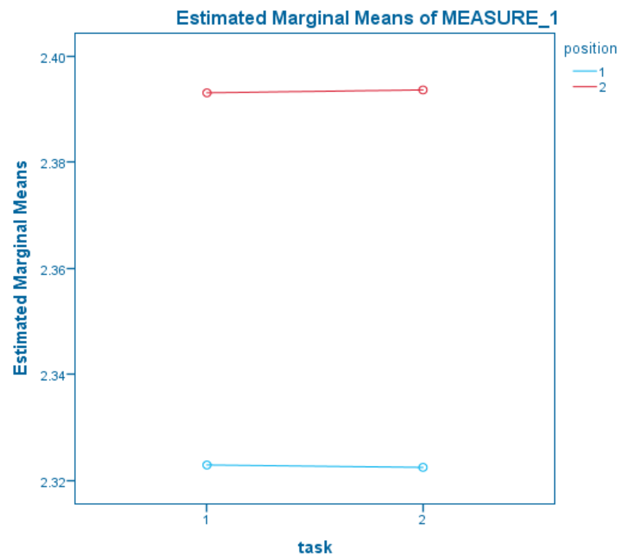
(c)



(d)



(e)



(f)

Figure 3-10: Interaction effect results for two cortical areas of EEG (a) delta (b) theta (c) alpha (d) beta (e) gamma (f) theta with independent variables at opposite axis

We can observe from the figure 3.10 that there is not significant interaction between the two independent variables for all the EEG powers except theta. The mean response for each factor is calculated by repeated measure ANOVA and presented as estimated marginal means.

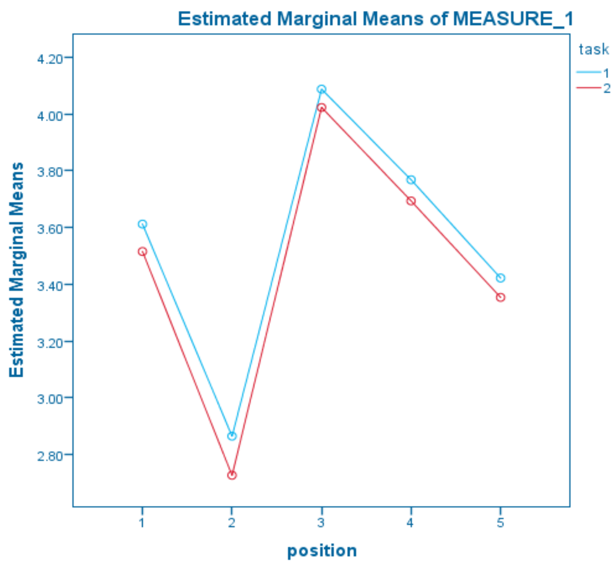
For five cortical areas (i.e. frontal, central, temporal, occipital, and parietal), repeated measure ANOVA yielded non-significant interaction effect TASK*AREA for all the EEG powers as shown in table 3.4.

Table 3-4: Repeated measure ANOVA for cortical areas (frontal, central, temporal, occipital, and parietal)

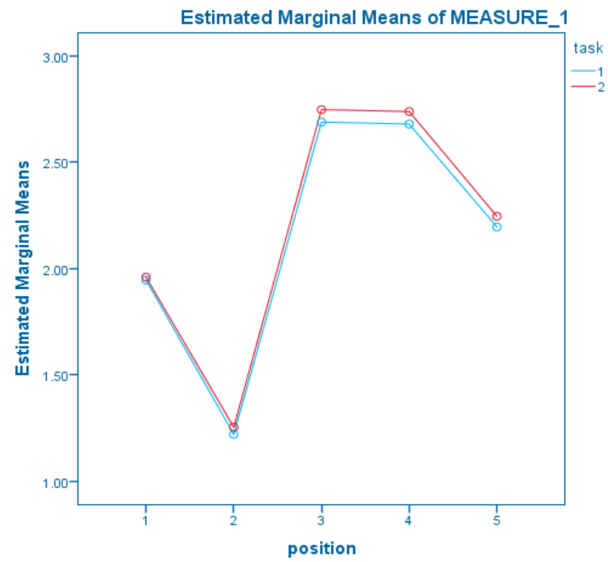
Absolute EEG power	Variables	Degrees of freedom	F-value	Sig.	Partial Eta Squared	Observed Power
Delta	TASK	1.000,15.000	5.143	.039	.255	.564
	POSITION	1.823,1.823	46.461	.000	.756	1.000

	TASK*POSITION	2.669,40.036	.918	.432	.058	.222
Theta	TASK	1.000,15.000	4.354	.054	.225	.497
	POSITION	2.382,35.725	213.250	.000	.934	1.000
	TASK*POSITION	2.654,39.809	1.744	.179	.104	.395
Alpha	TASK	1.000,15.000	12.009	.003	.445	.899
	POSITION	2.057,30.859	193.711	.000	.928	1.000
	TASK*POSITION	2.597,38.956	1.276	.295	.078	.185
Beta	TASK	1.000,15.000	4.678	.047	.238	.525
	POSITION	2.769,41.540	106.112	.000	.876	1.000
	TASK*POSITION	2.313,34.691	2.504	.089	.413	.503
Gamma	TASK	1.000,15.000	.460	.508	.30	.097
	POSITION	2.403,36.043	54.271	.000	.783	1.000
	TASK*POSITION	1.766,26.490	2.705	.091	.153	.461

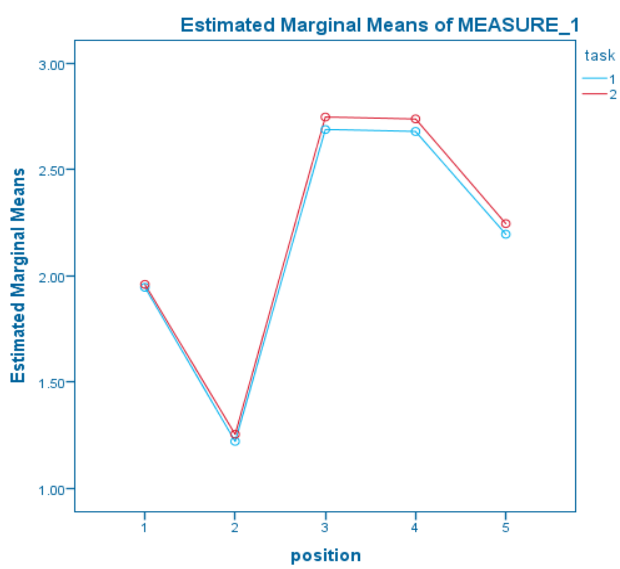
The interaction effect results for EEG powers delta, theta, alpha, beta, and gamma are given as $(F[2.669,40.036] = 0.918, p > 0.05, \eta_p^2 = 0.058)$, $(F[2.654,39.809] = 1.744, p > 0.05, \eta_p^2 = 0.104)$, $(F[2.597,38.956] = 1.276, p > 0.05, \eta_p^2 = 0.078)$, $(F[2.313,34.691] = 2.504, p > 0.05, \eta_p^2 = 0.413)$, $(F[1.766,26.490] = 2.705, p > 0.05, \eta_p^2 = 0.153)$ respectively. Figure 3.11 depicts these results which reflects there is not significant interaction between two independent variables. There is significant main effect for within subject factor position for all the EEG power. That is, the distribution of all EEG powers is sensitive to position. Mean of EEG power is significantly different at different cortical regions. However for within subject factor task, Alpha power is most sensitive to task changes. But the interaction effect between two within-subject factors is non-significant. Therefore, it is not possible to find the significant mean difference of EEG powers in context of design tasks and cortical areas. Distribution of EEG delta, beta, and gamma is higher in temporal, theta and alpha is higher in temporal and occipital.


Estimated Marginal Means of MEASURE_1
task
1
2
4.20
4.00
3.80
3.60
3.40
3.20
3.00
2.80
Estimated Marginal Means
1
2
3
4
5
position

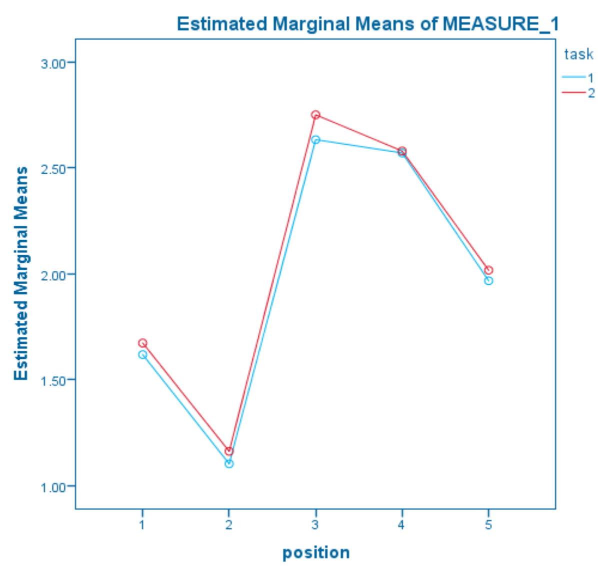
(a)


Estimated Marginal Means of MEASURE_1
task
1
2
3.00
2.50
2.00
1.50
1.00
Estimated Marginal Means
1
2
3
4
5
position

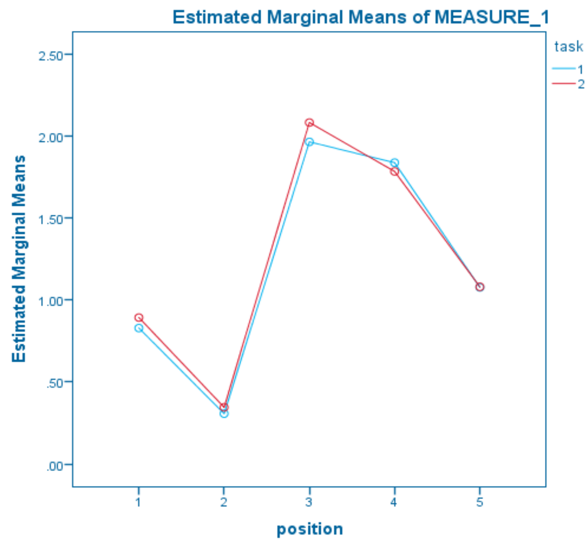
(b)


Estimated Marginal Means of MEASURE_1
task
1
2
3.00
2.50
2.00
1.50
1.00
Estimated Marginal Means
1
2
3
4
5
position

(c)


Estimated Marginal Means of MEASURE_1
task
1
2
3.00
2.50
2.00
1.50
1.00
Estimated Marginal Means
1
2
3
4
5
position

(d)



(e)

Figure 3-11: Interaction effect results for five cortical areas of EEG (a) delta (b) theta (c) alpha (d) beta (e) gamma

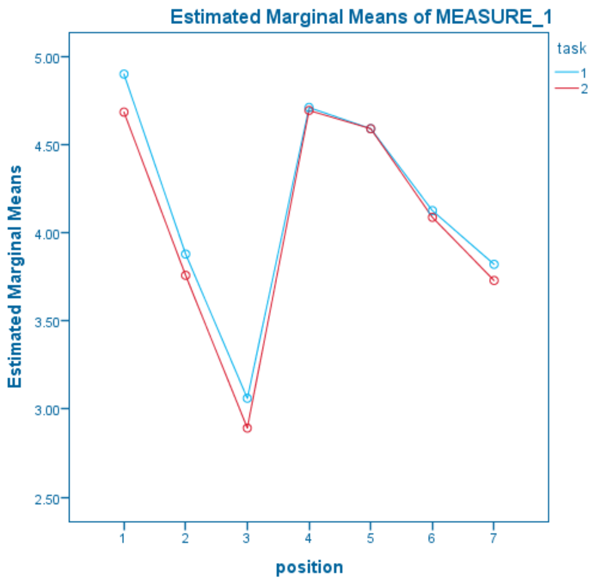
For seven cortical areas (i.e. pre-frontal, frontal, central, left-temporal, right-temporal, occipital, and parietal), repeated measure ANOVA yielded non-significant interaction effect TASK*AREA for all the EEG powers as shown in table 3.5.

Table 3-5: Repeated measure ANOVA for cortical areas (. pre-frontal, frontal, central, left-temporal, right-temporal, occipital, and parietal)

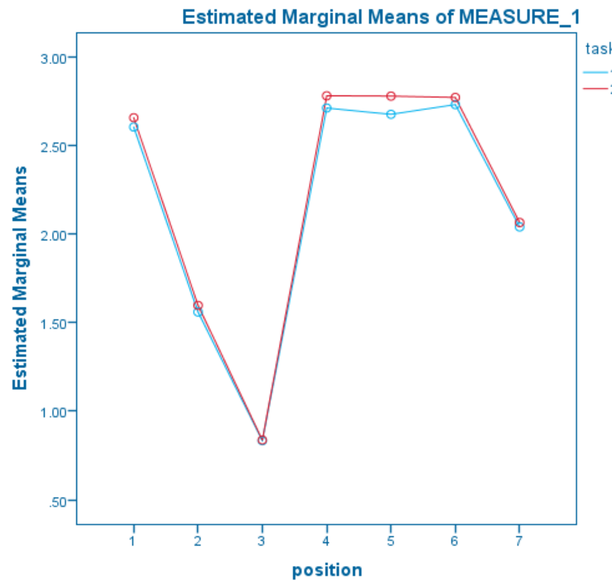
Absolute EEG power	Variables	Degrees of freedom	F-value	Sig.	Partial Eta Squared	Observed Power
Delta	TASK	1.000,15.000	.343	.567	.022	.085
	POSITION	2.903,43.548	27.376	.000	.646	1.000
	TASK*POSITION	1.858,27.877	.686	.502	.044	.150
Theta	TASK	1.000,15.000	2.031	.175	.119	.266
	POSITION	3.173,47.601	96.304	.000	.865	1.000
	TASK*POSITION	1.872,28.086	.463	.622	.030	.116

Alpha	TASK	1.000,15.000	8.119	.012	.351	.759
	POSITION	3.556,53.336	120.669	.000	.889	1.000
	TASK*POSITION	2.231,33.463	.544	.604	.35	.137
Beta	TASK	1.000,15.000	3.879	.068	.205	.454
	POSITION	3.480,52.196	82.019	.000	.845	1.000
	TASK*POSITION	2.738,41.077	.706	.542	.045	.180
Gamma	TASK	1.000,15.000	1.886	.190	.112	.251
	POSITION	3.102,46.527	49.144	.000	.766	1.000
	TASK*POSITION	2.562,38.428	1.594	.211	.096	.357

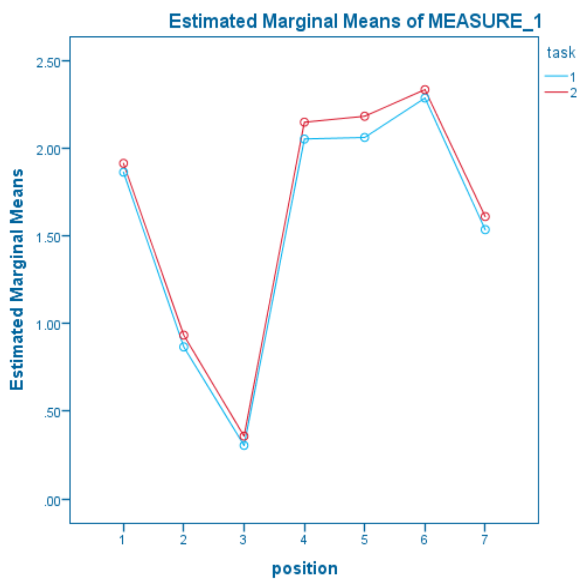
The interaction effect results for EEG powers delta, theta, alpha, beta, and gamma are given as ($F[1.858,27.877] = 0.686, p > 0.05, \eta_p^2 = 0.044$), ($F[1.872,28.086] = .463, p > 0.05, \eta_p^2 = 0.030$), ($F[2.231,33.463] = .544, p > 0.05, \eta_p^2 = 0.35$), ($F[2.738,41.077] = .706, p > 0.05, \eta_p^2 = 0.045$), ($F[2.562,38.428] = 1.594, p > 0.05, \eta_p^2 = 0.096$) respectively. Figure 3.12 depicts these results which reflects there is not significant interaction between two independent variables. We found significant main effect for variable position for all EEG powers which reflect that EEG power distribution is sensitive to cortical areas. However, we did not find significant main effect for task except alpha. The mean distribution of EEG power is similar in both tasks at different cortical regions that we can see form two lines which represents two tasks are almost parallel at each cortical area. Therefore, it is not possible to compare EEG in these two task based on cortical area to area approach.


Estimated Marginal Means of MEASURE_1
Estimated Marginal Means
position
task
1
2
5.00
4.50
4.00
3.50
3.00
2.50
1 2 3 4 5 6 7

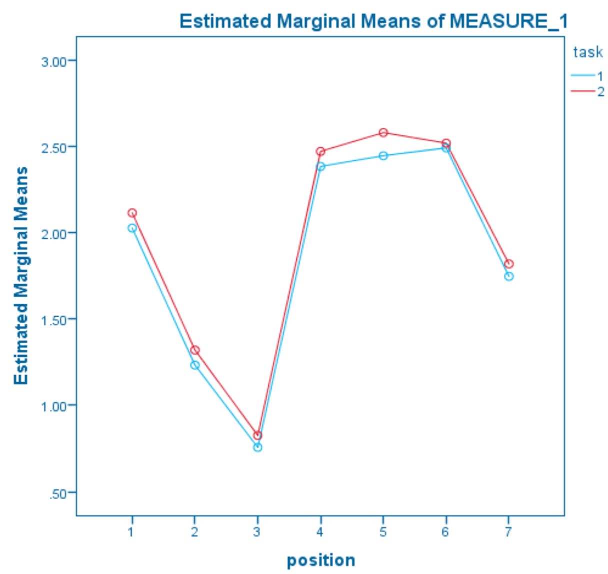
(a)


Estimated Marginal Means of MEASURE_1
Estimated Marginal Means
position
task
1
2
3.00
2.50
2.00
1.50
1.00
.50
1 2 3 4 5 6 7

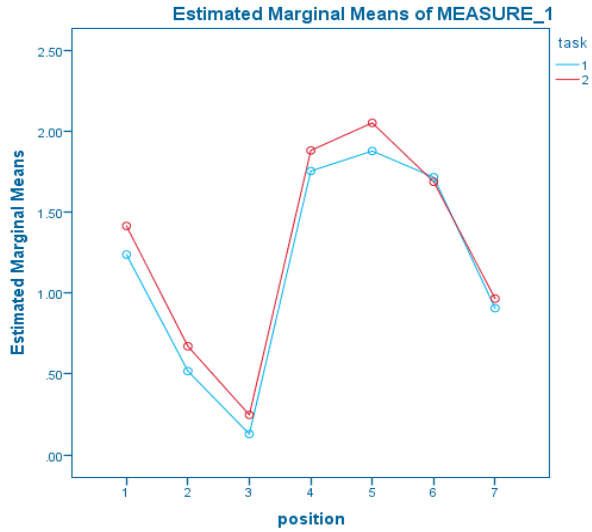
(b)


Estimated Marginal Means of MEASURE_1
Estimated Marginal Means
position
task
1
2
2.50
2.00
1.50
1.00
.50
.00
1 2 3 4 5 6 7

(c)


Estimated Marginal Means of MEASURE_1
Estimated Marginal Means
position
task
1
2
3.00
2.50
2.00
1.50
1.00
.50
1 2 3 4 5 6 7

(d)



(e)

Figure 3-12: Interaction effect results for seven cortical areas of EEG (a) delta (b) theta (c) alpha (d) beta (e) gamma

From all the above figures and tables presented for repeated measure ANOVA depicts that the interaction effect between TASK*AREA is not significant. It means that the independent variables are not combined in such a way that can give a different specific effect to dependent variable (i.e. EEG power). We can see in all the figures that two tasks (i.e. creative and non-creative design task) are parallel for all the EEG powers at all levels of cortical area (i.e. electrode positions), it means that the level of one independent variable (i.e. tasks) are changing constantly across the level of other independent variable (i.e. cortical area). Therefore, there is not significant mean difference of EEG powers distribution in two design tasks with respect to different cortical areas. That is, it is not possible to compare EEG between creative and non-creative design task with (cortical) area to area approach. However, we found significant main effect for independent variable position for all EEG powers and all cortical areas except theta power for two cortical areas. That is, EEG power is sensitive to all the positions as we can see in figure 3.10, 3.11, and 3.12.

However, if we would have found significant interaction effect between TASK*AREA, then we may determine where (i.e. in cortical area) EEG power is differed between creative and non-creative design task by Bonferroni post hoc test which allow us to do pairwise comparison between independent variables to discover which specific mean differed at different position.

Chapter 4. Conclusion and future work

4.1 Conclusion and contribution to the thesis

The chief objective of current thesis was “To investigate power of brain activity using EEG comparison between creative and non-creative design task”. The focus was to identify areas of brain which are activated during creative and non-creative design task based on changes in task difficulty. EEG power was used to reflect these changes because EEG is most sensitive to changes to the cortical activation. To achieve this objective we use data which was collected from the experiment designed by (Nguyen & Zeng, 2014b). In this experiment, participants performed creative and non-creative design task. Task difficulty in these tasks was different. We analyzed the EEG data for sixteen subjects who performed visual TTCT test used for creative and non- creative design task. In first step, we perform power spectral analysis to determine the distribution of EEG power of signal over frequencies. Then we aggregated EEG electrode position for three different combinations of cortical areas of brain. Further, we calculated the distribution of EEG powers among aggregated cortical regions when participants performed creative and non-creative design task. In the next step, we performed repeated measure ANOVA for within subject factor (i.e. design task, cortical area) to find the interaction effect between design task and cortical areas, since we wanted to compare EEG between two tasks using cortical area to area approach. It was concluded that:

- Repeated measure ANOVA yielded not-significant interaction effect between TASK*AREA for all cases except theta in two cortical area.
- An independent variable ‘AREA’ has significant main effect for all the EEG powers. That is, EEG is sensitive to cortical area changes.

- An independent variable ‘TASK’ has not-significant main effect for majority of cases. That is, EEG is not sensitive to task changes.
- It is not possible to find the significant mean difference of EEG power in two tasks by comparing EEG between creative and non-creative design task with (cortical) area to area approach. Hence, we achieved the objective of present thesis.

It may be possible that because in the current experiment, the cognitive process is continuous in two tasks, therefore it is not possible to extract task related power changes in both tasks with respect to rest state.

4.2 Future work

In future, we can compare cognitive state with rest state. We can also try to apply other methods to classify homogeneous design activities in these two design tasks. Therefore, it may be possible to compare the percentage of EEG power occurred during creative design task with those occurred in non-creative design task. Moreover, if we may differentiate creative design activities and non-creative design activities, then it may be possible to investigate following studies:

1. Cognitive behavior analysis for several subjects.
2. Approaches adopted by different designers to solve design problem.
3. If designers in creative design activities follow non-linear design dynamics.
4. Creativity assessment based on an appropriate creativity measurement index.

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