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A NEW FRAMEWORK OF STUDYING THE COGNITIVE MODEL OF CREATIVE DESIGN

Ganyun Sun[1], Shengji Yao[1]
(1) University of New Brunswick

ABSTRACT

This paper proposes a new framework for studying the cognitive model of creative design. In this paper, first the general cognitive process of creativity is reviewed, and then current studies of the cognitive models in engineering design are introduced. Assuming design creativity is related to design performance and design workload, a new framework is introduced to study factors affecting design creativity and designer's behavior in the design process, the cognitive process and the physical/physiological process. Experimental approaches are discussed to validate the proposed framework and investigate the relation of design creativity to design performance and design workload in the future work. This framework is expected to efficiently accommodate designer's role in the design process, the cognitive process and the physical / physiological process. The expected results of this framework will provide suggestions for promoting design creativity and developing an efficient design method to integrate designer's cognitive activities in the design process.

Keywords: Cognitive model, creative design, conceptual design, workload

1 INTRODUCTION

Creativity is one of the most mysterious subjects in human cognition. "Cognitive" pertains to thinking or conscious mental processes. "Cognitive model" is usually used to describe a specific cognitive phenomenon or process (e.g., panic attacks, learning [1]), to find connection between two or more processes (e.g., information processing and decision making), or to analyze behaviors in a specific process or task (e.g., drug urges and drug-use behavior). To study the cognitive model of creative design, we first need to analyze the relations among design, human (designer), and creativity, as shown in Figure 1. The "model" put in the center is connected with three critical components: creativity, design, and human. The connection between "design" and "human" indicates that designers utilize design theories and methodologies to carry out design solutions during the design process. The connection between "design" and "creativity" implies creative design introduces something new in the design solution. The connection between "human" and "creativity" implies the cognitive process of designers in delivering the creative design solution. This connection has been studied to develop general cognitive model of creativity by psychologists and cognitive scientists. Horvath suggests that design cognition research comprises cognitive mechanisms and design thinking [2]. The former focuses on knowing, perceiving, and conceiving design knowledge, intuitions, and hypotheses, while the latter investigates the thought processes of designers, especially on logical, visual, spatial, and functional thinking. Therefore, the cognitive model of creative design, including all the three components, refers to the mechanisms in the cognitive activities of designers when creativity is generated during the design process.

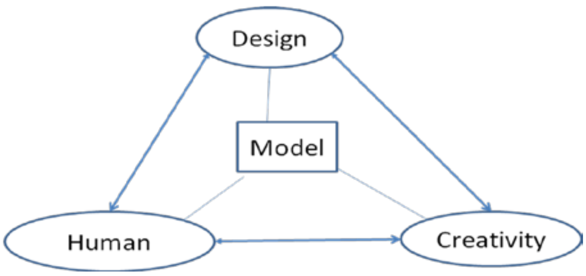

Figure 1. Cognitive model of creative design: essential components

Considering the three components in the cognitive model of creative design, the existing cognitive models relating to creative design can be classified into two levels. The first level is the general cognitive model of creativity. It aims to investigate cognitive activities relating to creativity rather than specifically relating to creative design. The second level is to describe cognitive activities in conceptual stages of the design process or in specific design methods. These models help us understand designer's thinking steps during the design process. However, the designer's cognitive model in the design process has not been studied systematically and this study lacks an efficient method. Based on the existing models, this paper proposes a new framework of the cognitive model of creative design. This framework would help us understand designer's thinking and reasoning process and explore how creative ideas are generated in engineering design. The rest of this paper is organized as follows. Section 2 examines the general cognitive process of creativity. Section 3 reviews existing cognitive models in engineering design. Based on the existing models, a new framework of cognitive model of creative design is proposed in Section 4. Finally the paper is summarized and future work is discussed in Section 5.

2 COGNITIVE PROCESS OF CREATIVITY

The cognitive process of creativity has been studied since 1826 [3]. One of the earliest contemporary models of creativity is Dewey's model, which describes the process of problem solving in five logical steps: (1) a difficulty is felt, (2) the difficulty is located and defined, (3) possible solutions are considered, (4) consequences of these solutions are weighed, and (5) one of the solutions is accepted [4]. Wallas went beyond Dewey's logical sequencing and generated a series of five steps of the creative process: preparation, incubation, intimation, illumination, and verification [5]. Guilford first proposed the concept of "divergent thinking" and separated the creative process into convergent and divergent forms of thinking [6]. Rhodes classified the theories and models of creativity into four areas: characteristics of creative people, creative process, creative product, and creative press [7]. Torrance divided the creativity into four logical stages: sensing problems, making hypothesis, evaluating, and communicating [8]. Sternberg edited some comprehensive creativity researches into the Handbook of Creativity [9].

These cognitive models of creativity have shed some lights for design researchers to understand the concepts of creativity and study how the cognitive process of creativity can be integrated into the design context. In engineering design, creativity is regarded as "breakthrough" [10] or "creative leap" [11]. Creativity in design is seen as a super-ordinate construct defined by three lower order constructs: (1) flexibility, originality, and fluency of cognitive processes, (2) freedom and originality of personal expression, and (3) autonomy of an axiological system [12]. Creativity has been elucidated as historical creativity, personal creativity, and situated creativity [13, 14]. Historical creativity (H-creativity) means this design has not been previously produced by any designers; personal or psychological creativity (P-creativity) occurs if the design is novel to this designer; situated creativity (S-creativity) means the design contains ideas that are not necessarily novel in any absolute sense or novel to the designer but that are novel in that particular design situation. Taura and Nagai pointed out the cognitive process of creativity is a concept-synthesizing process including combining, blending, and integrating [15]. Howard et al compared 19 creative process models, classified the process into four phases: analysis, generation, evaluation, and communication / implementation, and proposed a creative design process by integrating design process from engineering design and creativity process from cognitive psychology based on the function-behaviour-structure (FBS) framework [16].

Most of the research results of studying the general cognitive model of creativity by psychologists and cognitive scientists are mainly from the observations and analysis of the personal, social and cultural aspects of creativity. There is no general and unified theory that we can use to develop the designer's cognitive model of creative design. Next section we will review the studies of the cognitive models of creativity in engineering design.

3. COGNITIVE MODEL OF CREATIVITY IN ENGINEERING DESIGN

According to Encyclopedia Britannica, creativity is "the ability to make or otherwise bring into existence something new, whether a new solution to a problem, a new method or device, or a new artistic object or form". In engineering design, creativity means original / adaptive / variant ideas or concepts [16]. The definitions of creativity tell us one key characteristic of creativity is something new. How designers think and reason about a problem to generate new designs may decide the creativity of the design solution. Therefore, it is essential to study designers' cognitive activities during the design process in order to understand the factors leading to design creativity and develop more effective design methods.

Some researchers have studied what processes, strategies and problem-solving methods designers use to create designs based on empirical approaches. Roseman and Gero suggested four procedures by which creative design might occur: combination, mutation, analogy and first principles [17]. One other creative design procedure with similar potential has since been added to this list: emergence [18]. Using the design of microprogramming as an example, Dasgupta pointed out that inventing is a goal-directed yet opportunistic act; thus, the design agent's freedom and capacity to use his/her knowledge contribute significantly to the design creativity [19]. Akin and Akin studied creative problem-solving behavior and concluded: "Realizing a creative solution, by breaking out of a FR, depends on simultaneously specifying a new set of FRs that restructure the problem in such a way that the creative process is enhanced [20]. The new FRs must, at a minimum, specify an appropriate representational medium (permitting the explorations needed to go beyond those of the earlier FRs), a design goal (one that goes beyond those achievable within the earlier FRs), and a set of procedures consistent with the representation domain and the goals." After comparing three cases of creative design in three different domains, Cross concluded that there is a common "systems approach" to the design problem, but designers may frame their problems in a distinctive and sometimes rather personal manner, and "first principles" are the foundation of design problem solving [21]. Bonnardel has conducted two experimental studies in a creative professional area: non-routine design and suggested ways to facilitate creative acts from designers [22]. C-K theory defined creative design as the co-evolution of a space of concepts C and a space of knowledge K through four types of interdependent operators [23].

Protocol analysis is an important approach to studying designers' thinking processes and problem-solving behaviors in order to understand design creativity. The studies of protocol analysis in design have been growing increasingly since the 1980's in investigating the process of designing and in understanding how designers design. Two primary methods of protocol analysis are concurrent reports and retrospective reports. Dorst and Cross analyzed the protocol studies of nine experienced industrial designers and stated that "Our observations confirm that creative design involves a period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent bridge which identifies a problem-solution pairing" [24]. Jin and Chusilp used protocol analysis to validate the proposed cognitive activity model of conceptual design [25]. Sketches are languages for representing design ideas in engineering design. Sketching plays an important role in conceptual design and could be used to investigate how designer's cognitive activities evolve during the design process [26]. Goel proposed that lateral and vertical transformations occurring between designer's sketches are respectively related to divergent and convergent thinking [27]. These transformations can be used to help track designer's thinking mode which might increase the efficiency of the sketching activities [28]. The process of sketching and the final sketches could be used to evaluate design output, e.g. the quantity of novel ideas, the difference between two ideas, and the quality of an idea [29].

In addition to the empirical studies on design creativity, there are a few studies to explore the mechanism of design creativity theoretically. The theoretical approach attempts to establish a formal model to capture the mechanism of creative design so that the results can be easily adapted to support the development of design tools. Based on the logic of design [30], Zeng and Gu speculated that a chaotic motion is implied in design creativity [31]. Kryssanov et al. studied creative design using the notations of Algebraic Semiotics and clarified the nature of emergence in design: while emergent properties of a product may influence its creative value, emergence can simply be seen as a by-product of the creative process [32]. Zeng et al. argued that design creativity can be studied mathematically and proposed a formal mechanism of creative design based on design governing equation, which relates the design process to the chaotic motion [33].

Designers play an active and important role in guiding the design process to achieve design breakthroughs and innovation. To understand the designers' role in design creativity, it is important to study how designers know, perceive, make decisions, and construct behavior in the design process and investigate what factors could affect a creative design. From existing studies, we can see empirical approaches are the main methods to study designers' cognitive activities in the design process. Empirical studies including verbal protocol analysis, sketch study, virtual experiment and case studies have been used to study designers' cognitive activities, but design research based on empirical studies is limited and lacks an efficient method. There are no systematic and effective experimental approaches to studying designers' cognitive processes and verifying the mechanisms and observations behind the design activities. Next section will propose an experimental framework to studying the cognitive model of creative design.

4. FRAMEWORK

Based on the existing studies of the general cognitive model of creativity and the cognitive models of creativity in engineering design, a framework is proposed to study the cognitive model of creative design. In this framework the physical / physiological process is included. Although designers mainly conduct the cognitive activities of thinking and reasoning of solving a design problem, human is viewed as a complex and integrated system. During the design process, designers may have various postures, body movements, and some physiological reactions. The physical / physiological process and the cognitive process are related. Designer's cognitive process may be reflected in their physical/physiological measurements, such as brainwave activity, eye movement, gesture, and heart rate. To solve a design problem, designers are involved in three processes: design process, physical/physiological process and cognitive process, as shown in Figure 2.

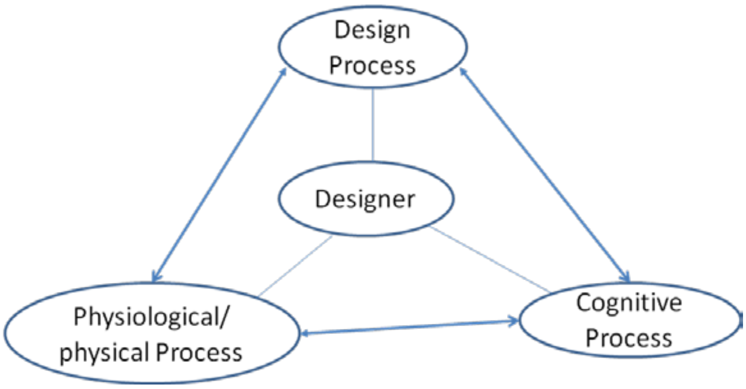

Figure 2. Three processes

During the design process, designers apply design strategies, theories and methodologies to accomplish design tasks. In this research, we focus on the conceptual design process, which includes concept generation and concept evaluation. The evolution of the design concepts is also a cognitive process of designer's problem-solving and decision-making. Visual thinking by sketches and talking aloud by verbal reports can be used to investigate the cognitive process of designers. The role of sketches in the conceptual design has been identified as an external memory, a provider of visual cues and a physical setting [34]. Verbal protocol is another widely used method in studying designer's cognitive activities. Sketches and verbal protocol analysis can help us understand designers' cognitive process. The physical / physiological process can be investigated through some measurements of brain activities, eye movement, heart rate, gestures, body temperature, etc. Designers play a central role in the three processes. With the understanding of the three processes, we will explain the structure of the framework in Section 4.1 and the experimental approaches to studying the cognitive model of creative design based on the framework in Section 4.2.

4.1 Structure of the Framework

To understand designer's behavior in the design process, cognitive process and physical/physiological process would help us develop the cognitive model of creative design. When a design task is given to designers, design workload can be formed in terms of task complexity and designer's capacity. With different design workload, designer's behavior in the three processes is different. Different designer's behavior can lead to different design outcome. The proposed framework of studying the cognitive model of creative design is shown in Figure 3. In this framework, design performance measures how successfully a designer accomplishes a design task. It consists of two parts: design outcome and designer's behaviour. Design outcome can be specifically quantified by four measures, namely, novelty, variety, quality, and quantity [29]. According to Shah's definition, novelty measures how unusual or unexpected an idea is compared to other ideas; variety measures the degree of differences between generated ideas; quality measures how feasibly an idea meets the design specification; and quantity measures the total numbers of ideas generated. Designer's behavior can be studied using structured information and unstructured information collected from designers during the design process. The structured information refers to the physical / physiological measures of the designers, such as brain activity, eye movement, and heart rate. The unstructured information refers to sketches and verbal protocols generated by the designers.

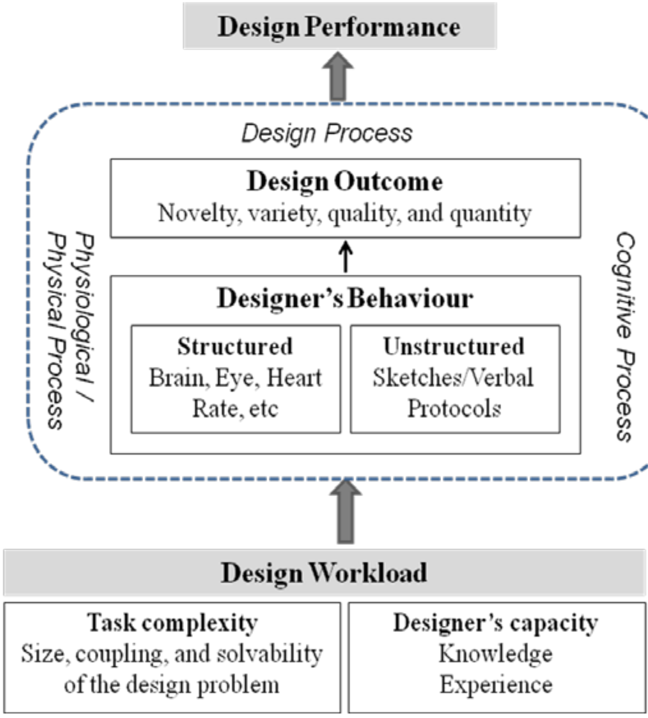

Figure 3. Structure of the framework

Design workload can affect designer's behavior and then affect design performance. Workload is not only task-specific but also person-specific [35]. It can be defined as the proportion of an individual's capacity that is allocated for a task demand [36]. Directly related to task demand is task complexity which describes the objective properties of the task. An individual's capacity is defined as the upper limit of processing capability [37]. Design workload can be specified in terms of task complexity and designer's capacity. In conceptual design, task complexity can be represented by the size, coupling, and solvability of a design problem [38]; and designer's capacity can be extended by designer's knowledge and experience in solving design problems. In this proposed framework, we need to evaluate the impact of design workload on design performance and design creativity. Stevens, et. al. studied skill acquisitions during the process of problem solving and found that workload increases with the degree of task difficulty but does not decrease as expected when skills are improved [39]. Stevensson, et. al. verified that an overly high workload decreases the operator's performance but performance may not decrease as workload increases if the operator acquires a strategy for handling task demands in the combat aircraft studies [40]. Some studies pointed out that poor performance and lower creativity may be a direct result of workload pressures [41]. Avoiding overload or underload is suggested to promote personal development [42].

In this framework, designers are involved in the physical/physiological process, the cognitive process, and the design process to deliver creative design outcomes. To consider the three processes together can help us understand designer's behavior thoroughly and further explore the effect of design workload and design performance in the cognitive model of creative design. We will employ experimental approaches to further study the relationships of design creativity, design performance and design workload in the three processes.

4.2 Experimental approaches

This section discusses and reviews experimental approaches to quantify design workload and design performance. In our future work, we will apply some experimental approaches to investigate the relationships of design workload, design performance and design creativity.

4.2.1 Design workload

As discussed in Section 4.1, design workload measurement is the specification of the amount of a designer’s capacity needed to accomplish a design task. A design task is characterized by creative thinking and a design process cannot be duplicated. The mechanism of how design workload affects design creativity is still unknown. One possible reason comes from the limitation of cognitive capacity. Research has found that as cognitive capacity declines, the brain’s ability to flexibly and creatively solve problems declines [43]. Meanwhile, increased levels of cognitive capacity may improve problem solving of novel tasks and comprehensive thinking; hence to this extent high levels of cognitive capacity may improve creative thinking and increase creative outcomes [44].

Workload measurement in creative design may provide some information about the relationships between workload and design creativity. The study of investigating the effect of design workload on design creativity seems not to have attracted sufficient attention yet in the design area except for some pilot studies on quantifying a designer's mental stress by EEG and eye gaze signals [45] and body movements [46]. This category of workload measures is based on the subject’s physical/physiological parameters. Different physiological measures have been found to be sensitive to different cognitive activities and to different stages in information processing [36]. The advantage of physiological responses is that most of the measures can be collected continuously and unobtrusively. The main disadvantage of physiological measures is that subjects’ physiological states may affect their performance [47]. The other two categories of workload measures are self-report measures and task performance measures [48]. Self-report measures are based on subjects’ individual judgments according to some standard questionnaires such as National Aeronautics and Space Administration Task Load Index (NASA-TLX) [49], Subjective Workload Assessment Technique (SWAT) [50], Multiple Resources Questionnaire (MRQ) [51], Workload Profile (WP), and Rating Scale Mental Effort (RSME) [52]. Task performance measures are applied to three levels of tasks, namely, primary tasks, secondary tasks, and reference tasks in ascending order of effort [48].

The measurements of workload introduced above have been employed for different tasks such as operation tasks [40], memory tasks [53], learning tasks [54], and problem solving tasks [39]. Most of these tasks can be repeated and subjects’ performance can be improved by training in a relatively short period. Since a design task is very different from these tasks, the first step is to check sensitivity of the workload measures, which describes the capability of detecting different levels of design workload. After that the relationships between the levels of design workload and design creativity can be identified. Finally, the effect of workload on design creativity can be investigated.

4.2.2 Design performance

Designer’s behaviour during the design process can be reflected in their sketching process, verbal protocol reports, body movements, facial expressions, brain activities, eye movement, etc. Different behaviour may lead to different design outcome. Then design performance can be specified based on design behaviour and design outcome. Studies in neuroscience have shown that reliable and valid measures of creative thinking become possible by directly measuring human brain activities, e.g. functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG) [55, 56]. It has been quantified that the dimensional complexity of the EEG is greater during divergent thinking than during convergent thinking [57]. Different thinking modes can be measured by brain activities probably because creativity requires a variety of classic cognitive abilities, e.g. working memory, sustained attention, cognitive flexibility, and judgment of propriety, and all these factors are typically ascribed to the prefrontal cortex, a structure of the brain [58]. It has also been pointed out that the human physical parameters, e.g. respiratory rate, blood pressure, pulse wave, and heart rate, are highly related to mental performance, e.g. mental stress, vigilance, fatigue, and attention [59].

The tasks in neuroscience studies used for measuring creative thinking, however, are relatively simple compared with a design task, such as, “thinking of unusual/original uses of conventional everyday objects” [56] or “thinking of things or situations in an incomplete picture” [57]. Accomplishing a design task involves understanding the design problem, generating and evaluating solutions to it, and deciding on the best solution [60]. Therefore, only when physical/physiological information is linked to specific design activities (e.g. understanding design problem, generating solutions, evaluating solutions, and deciding [60]), it can be significant for specifying designer's behavior in the design process. Empirical studies on sketches and verbal protocols have generated cognitive models of creative design based on observations (as discussed in Section 3). A combination of the physical/physiological information and the information from the sketching process and verbal protocol reports can establish a connection between design performance and design creativity.

4.2.3 Experimental validation in future work

In this proposed framework, design creativity is assumed to be related to design performance and design workload. Design performance is determined by design outcome and design behavior. Design workload is determined by task complexity and designer's capacity. To find out the relation of design creativity to design performance and design workload, we need to investigate designer's role in the design process, the physical/physiological process, and the cognitive process. In this framework, we will use sketches and verbal protocol reports to analyze designer's cognitive process. In the meantime, we will identify some significant physical/physiological parameters, such as EEG brainwaves, eyegaze movement, and heart rate to measure designers' cognitive activities during the design process. The results from the physical/physiological process will be used to validate the findings from the cognitive process. We will combine the physical/physiological studies with the verbal protocol reports and sketches to explore the relationships among design workload, design performance and design creativity and how creative solutions are generated during the design process. In this paper, the proposed framework is a preliminary study of developing the cognitive model of creative design. We are currently working on these experiments. Experimental data analysis and validation will be our future work.

5. SUMMARY

This paper first reviewed the general cognitive process of creativity and the existing cognitive models of creative design. Based on the existing models, a new framework for the cognitive model of creative design is proposed by emphasizing the role of the designer during the design process, the cognitive process and the physical/physiological process. This framework is expected to efficiently accommodate designer's role in the cognitive process and the physical / physiological process. Experimental approaches are also discussed to qualify workload and design performance. Our future work is to validate the proposed framework and investigate the relationships among design workload, design performance and design creativity. This proposed framework provides a preliminary study for understanding designer's role in design creativity and investigating factors affecting design creativity. In the near future, we will combine the sketches and verbal protocol reports of the designers and some significant physical/physiological parameters to understand designer's behavior in the design process. This research can be also used to evaluate existing design methods and design strategies.

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REFERENCES

[1] Grow, G.O., Teaching learners to be self-directed. *Adult Education Quarterly*, 1991, 41(3), pp.125-149.
[2] Horvath, I., A treatise on order in engineering design research. *Research in Engineering Design*, 2004, 15(3), pp.155-181.
[3] Helmholtz, H., *Vortrage and reden*. In Eysenck H., ed. *Genius* (Cambridge University Press, New York, 1826).
[4] Dewey, J., *How We Think*. (D.C. Heath & Company, Boston, 1910).
[5] Wallas, G., *The art of thought*. (Harcourt Brace, New York, 1926).
[6] Guilford, J.P., *A revised structure of intellect studies of aptitudes of high-level personnel*. (University of Southern California, California, 1957).
[7] Rhodes, M., An analysis of creativity. *Phi Delta Kappan*, 1961, 42, pp.305-310.

[8] Torrance, E.P., The nature of creativity as manifest in its testing. In Sternberg, R.J., ed. *The nature of creativity*, pp.43-75 (Cambridge University Press, New York, 1988).
[9] Sternberg, R.J., *Handbook of creativity*. (Cambridge University Press, New York, 1999).
[10] Madanshetty, S.I., Cognitive basis for conceptual design. *Research in Engineering Design-Theory Applications and Concurrent Engineering*, 1995, 7(4), pp2.32-240.
[11] Cross, N., Creativity in design: analyzing and modeling the creative leap. *Leonardo*, 1997, 30(4), pp.311-317.
[12] Strzalecki, A., Creativity in design - general model and its verification. *Technological Forecasting and Social Change*, 2000, 64(2-3), pp.241-260.
[13] Suwa, M., Gero, J.S. and Purcell, T., Unexpected discoveries and S-inventions of design requirements: important vehicles for a design process. *Design Studies*, 2000, 21(6), pp.539-567.
[14] Gero, J.S., Computational models of creative designing based on situated cognition. In *Creativity & Cognition 2002.* Loughborough, Leic, United Kingdom, October 14-16. pp.3-10 (ACM Press)
[15] Taura, T. and Nagai, Y., Primitives and principles of synthetic process for creative design. In *Computational and Cognitive Models of Creative Design VI.* Sydney, Australia. pp.177-194 (Key Centre of Design Computing and Cognition, University of Sydney)
[16] Howard, T.J., Culley, S.J. and Dekoninck, E., Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*, 2008, 29(2), pp.160-180.
[17] Rosenman , M.A. and Gero, J.S., Creativity in design using a design prototype approach. In Gero, J.S. and Maher, M.L., eds. *Modelling Creativity and Knowledge-based Creative Design* (Lawrence Erlbaum, Mahwah, U.S.A., 1993).
[18] Gero, J., Computational models of creative design processes. In Dartnall, T., ed. *Artificial Intelligence and Creativity* (Kluwer Academic, Dordrecht, 1994).
[19] Dasgupta, S., *Creativity in Invention and Design - Computational and Cognitive Explorations of Technological Originality*. (Cambridge University Press, New York, 1994).
[20] Akin, O. and Akin, C., Frames of reference in architectural design: analyzing the hyperacclamation (A-h-a-!). *Design Studies*, 1996, 17(4), pp.341-361.
[21] Cross, N., Descriptive models of creative design: application to an example. *Design Studies*, 1997, 18(4), pp.427-440.
[22] Bonnardel, N., Towards understanding and supporting creativity in design: analogies in a constrained cognitive environment. *Knowledge-Based Systems*, 2000, 13, pp.505-513.
[23] Hatchuel, A. and Weil, B., A new approach of innovative design: an introduction to C-K theory. In *International Conference on Engineering Design (ICED 03)* Stockholm, Sweden. pp.109-124 (The Design Society)
[24] Dorst, K. and Cross, N., Creativity in the design process: co-evolution of problem–solution *Design Studies*, 2001, 22(5), pp.425-437.
[25] Jin, Y. and Chusilp, P., Study of mental iteration in different design situations. *Design Studies*, 2006, 27(1), pp.25-55.
[26] Purcell, A.T. and Gero, J.S., Drawings and the design process: a review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, 1998, 19(4), pp.389-430.
[27] Goel, V., *Sketches of thought*. (MIT Press, Cambridge MA, 1995).
[28] Rodgers, P.A., Green, G. and McGown, A., Using concept sketches to track design progress. *Design Studies*, 2000, 21(5), pp.451-464.
[29] Shah, J.J., Smith, S.M. and Vargas-Hernandez, N., Metrics for measuring ideation effectiveness. *Design Studies*, 2003, 24(2), pp.111-134.
[30] Zeng, Y., On the logic of design. *Design Studies*, 1991, 12(3), pp.137-141.
[31] Zeng, Y. and Gu, P., A science-based approach to product design theory - Part I: formulation and formalization of design process. *Robotics and Computer-Integrated Manufacturing*, 1999, 15(4), pp.331-339.
[32] Kryssanov, V.V., Tamaki, H. and Kitamura, S., Understanding design fundamentals: how synthesis and analysis drive creativity, resulting in emergence. In. pp.329-342
[33] Zeng, Y., Yan, B., Chen, B. and Yao, S., *A theoretical and experimental study on design creativity*. (McGill University, Montreal, Quebec, 2004).

[34] Suwa, M., Gero, J.S. and Purcell, T.A., The roles of sketches in early conceptual design processes. In Gernsbacher, M.A. and Derry, S.J., eds. *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society*, pp.1043-1048.
[35] Rouse, W.B., Edwards, S.L. and Hammer, J.M., Modeling the dynamics of mental workload and human performance in complex systems. *IEEE Transactions on Systems, Man and Cybernetics*, 1993, 23(6), pp.1662-1671.
[36] De Waard, D., The measurement of drivers' mental workload. Thesis (Ph.D Dissertation). Traffic Research Centre, University of Groningen 1996.
[37] Miller, G.A., The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, 1956, 63, pp.81-97.
[38] Summers, J.D. and Shah, J.J., Mechanical engineering design complexity metrics: size, coupling, and solvability. *Journal of Mechanical Design*, 2010, 132(2), pp.021004-1~11.
[39] Stevens, R., Galloway, T., and Berka, C., EEG-related changes in cognitive workload, engagement and distraction as students acquire problem solving skills. *Lecture Notes in Computer Science*, 2007, UM 2007 LNAI 4511, pp.187-196.
[40] Svensson, E., Angelborg-Thanderz, M., Sjoberg, L. and Olsson, S., Information complexity - Mental workload and performance in combat aircraft. *Ergonomics*, 1997, 40(3), pp.362-380.
[41] Elsbach, K.D. and Hargadon, A.B., Enhancing creativity through "mindless" work: a framework of workday design. *Organization Science*, 2006, 17(4), pp.470-483.
[42] Nachreiner, F., Standards for ergonomics principles relating to the design of work systems and to mental workload. *Applied Ergonomics*, 1995, 26(4), pp.259-263.
[43] Hallowell, E.M., Overloaded circuits: why smart people underperform. *Harvard Business Review*, 2005, 83(1), pp.54-62.
[44] Van Merrienboer, J.J.G. and Sweller, J., Cognitive load theory and complex learning: recent developments and future directions. *Educational Psychology Review*, 2005, 17(2), pp.147-177.
[45] Petkar, H., Dande, S., Yadav, R., Zeng, Y. and Nguyen, T.A., A pilot study to assess designer's mental stress using eye gaze system and electroencephalogram. In *ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE2009)* San Diego, California, U.S.A., August 30-September 2. pp.899-909.
[46] Tang, Y. and Zeng, Y., Quantifying designer's mental stress in the conceptual design process using kinesics study. In Norell Bergendahl, M., Grimheden, M., Leifer, L., Skogstad, P. and Lindemann, U., eds. *Proceedings of the 17th International Conference on Engineering Design (ICED'09)*, pp.211-220.
[47] Kramer, A.F., Physiological metrics of mental workload: a review of recent progress. In Damos, D.L., ed. *Multiple-task Performance* (Taylor & Francis Ltd, London, 1991).
[48] O'Donnell, R.D. and Eggemeier, F.T., Workload assessment methodology. In Boff, K.R., Kaufman, L. and Thomas, J.P., eds. *Handbook of perception and human performance, Vol. II: Cognitive processes and performance*, pp.42/41-42/49 (Wiley, New York, 1986).
[49] Hart, S.G. and Staveland, L.E., Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In Hancock, P.A., and Meshkati, N., eds. *Human Mental Workload*, pp.139-183 (Elsevier Science Publishers, Amsterdam, Netherlands, 1988).
[50] Reid, G.B. and Nygren, T.E., The subjective workload assessment technique: A scaling procedure for measuring mental workload. In Hancock, P.A., and Meshkati, N., eds. *Human Mental Workload* (Elsevier Science Publishers, Amsterdam, Netherlands, 1988).
[51] Boles, D.B., Bursk, J.H., Phillips, J.B. and Perdelwitz, J.R., Predicting dual-task performance with the Multiple Resources Questionnaire (MRQ). *Human Factors*, 2007, 49(1), pp.32-45.
[52] Zijlstra, F.R.H. and Doorn, L.v., The construction of a scale to measure subjective effort. (Delft University of Technology, Department of Philosophy and Social Sciences., 1985).
[53] Van Orden, K.F., Limbert, W., Makeig, S. and Jung, T.P., Eye activity correlates of workload during a visuospatial memory task. *Human Factors*, 2001, 43(1), pp.111-121.
[54] Wiebe, E.N., Roberts, E. and Behrend, T.S., An examination of two mental workload measurement approaches to understanding multimedia learning. *Computers in Human Behaviour*, 2010, 26(3), pp.474-481.

[55] Fink, A., Benedek, M., Grabner, R.H., Staudt, B. and Neubauer, A.C., Creativity meets neuroscience: experimental tasks for the neuroscientific study of creative thinking. *Methods*, 2007, 42(1), pp.68-76.
[56] Fink, A., Grabner, R.H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper, C., Ebner, F. and Neubauer, A.C., The creative brain: investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping*, 2009, 30(3), pp.734-748.
[57] Molle, M., Marshall, L., Wolf, B., Fehm, H.L. and Born, J., EEG complexity and performance measures of creative thinking. *Psychophysiology*, 1999, 36(1), pp.95-104.
[58] Dietrich, A., The cognitive neuroscience of creativity. *Psychonomic Bulletin & Review*, 2004, 11(6), pp.1011-1026.
[59] Lin, Y., Leng, H., Yang, G. and Cai, H., An intelligent noninvasive sensor for driver pulse wave measurement. *IEEE Sensors Journal*, 2007, 7(5-6), pp.790-799.
[60] Ullman, D.G., *The Mechanical Design Process*. (McGraw-Hill Higher Education, New York, 2009).

Contact: Shengji Yao
University of New Brunswick
Department of Mechanical Engineering
15 Dineen Dr
E3B 5A3, Fredericton
Canada
Phone: 506-453-4687
Fax: 506-453-5025
E-mail: syao@unb.ca
URL: http://www.unb.ca/ME

Shengji Yao is an Assistant Professor of the Department of Mechanical Engineering at the University of New Brunswick, Canada. She received her PhD degree in Mechanical Engineering from Concordia University in 2008. Her research interests include Design Creativity and Innovation, Human Centered Design, Human Performance Analysis, and Artificial Intelligence in Design.