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A Theoretical Model of Design Creativity: Nonlinear Design Dynamics and Mental Stress-Creativity Relation

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Abstract Creativity is an important topic in design research. Attempts have been made to develop methods and tools that can help designers become more creative. Yet how and why creativity occurs is still unknown to researchers. In this paper, we propose a theoretical model for creative design. This theoretical model builds on two postulates: 1) design reasoning follows a nonlinear dynamics, which may become chaotic; and 2) there is an inverse U shaped relationship between designer's mental stress and design creativity. In the first postulate, the nonlinear dynamics assumes the form of design governing equation and can be solved by Environment Based Design (EBD). The first postulate implies that design reasoning is sensitive to initial conditions, which are defined by the combination of design problem, design solutions, design knowledge, and other design related information. Since the major components in initial conditions may evolve simultaneously and are subject to continuous change during the design process, the design process is highly unpredictable. Some of the unpredictable solutions, which could be of high quality and useful, can be deemed creative. From this first postulate, three paths to creative design are derived, which specify how the initial conditions can be changed. The second postulate states that design creativity occurs when a designer is under a medium mental stress. Mental stresses are positively related to the workload associated with a design problem and negatively related to the designer's mental capacity. The workload is related to the complexity of the design problem and the amount of work in the design process whereas the mental capacity is related to the knowledge and skills required by the design process and to the designer's affect when dealing with the stresses arising from uncertainties and unpredictability of the design dynamics. To show how this theoretical model can be used to study design phenomena, an interpretation of the roles of sketching in design is presented.

Keywords: design creativity, mathematical model, Environment Based Design (EBD), design governing equation, nonlinear dynamics, chaotic dynamics, mental stress

1. Introduction

Creativity, the ability to generate something new and useful either historically or psychologically (Boden, 1990), is a universal phenomenon. The concept of creativity has changed over time. To the ancient Greeks, creativity is an act of divine forces and is beyond human control (Sawyer, 2006; Weiner,

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2000) (Blake, 2008). Thus, little can be done to enable creative acts. In contrast, the contemporary view attributes creativity to one's ability or talent. Therefore, efforts have been dedicated to studying the mechanism of creativity. In psychology, the most well-known model of creativity is proposed by Wallas, which includes four stages: preparation, incubation, illumination, and verification (Wallas, 1931). However, this stage – based model has been criticized by many researchers as it does not reflect the concurrent, integrated and recursive manner of creativity (Eindhoven & Vinacke, 1952). In cognitive science, while creativity is widely known to be associated with the right hemisphere of the brain (Roco, 1994), some researchers report connections between creativity and left cerebral hemisphere (Mihov *et al.*, 2010) and other researchers believe that creative thinking is more likely the result of communication and coordination between two hemispheres (Hoppe & Kyle, 1990). For a complete review on models of creativity process, readers can refer to (Lubart, 2001).

In engineering design, supporting creative design is believed to be one of the most important features of the next generation of CAD system (Goel *et al.*, 2012). Studies of creativity have attracted increasing attentions from research community (Nagai & Gero, 2012). Several models of creative design have been proposed. For instance, Akin and Akin (Akin & Akin, 1996; Akin & Akin, 1998) proposed a computational model of creativity. The model is based on the observation that by formulating a design problem differently, designers can find creative solution. Howard et al (Howard *et al.*, 2006) described the creative design process by combining models of creative process from cognitive psychology and models of engineering design process using function-behavior-structure framework (Howard *et al.*, 2008). Benami and Jin presented cognitive model of conceptual design that considers the relationships between design entities, cognitive processes and design operations. The model includes three steps: stimulation, production of internal design, and production of external design (Benami & Jin, 2002). Pahl presented a generic model of creativity for engineering design (Pahl et al., 2007). Kryssanov used semiosis to study creative design (Kryssanov et al., 2001). Goldschmidth proposed a model of design creativity that emphasizes the interactions between designer, memory and stimuli (Goldschmidt, 2011). Different types of stimuli have different impacts on creativity by evoking different memory locations, which affects the chance of retrieving information necessary for solution generation. Designers, who are more sensitive to the presence of stimuli, have more chance to be creative. Hatchuel and Weil developed C-K design theory in an attempt to capture creative activity through the interaction and expansion of C and K (Hatchuel & Weil, 2003). Effort was also made to use this theory to analyze other creativity methods (Reich *et al.*, 2010). Gero considered a design process creative when new variables are introduced into the design space (Gero, 1994; Gero & Kumar, 1993). Such introduction of new variables signifies changes in design space and leads to concept evolution (Gero, 1996). Altshuller proposed theory of inventive problem solving (TRIZ) which includes 40 inventive principles and concept of level of invention (LOI) (Altshuller, 1984). These 40 principles provide directions on how the contradictions in inventive problems can be solved effectively. Based on TRIZ and LOI, a software prototype (Becattini *et al.*, 2012) and an automatic classification of patent (Li *et al.*, 2012) were developed to guide designers in the beginning stage of the design process. Stressing the importance of rational and scientific approach to designing, Suh proposed the Axiomatic Design theory (Suh, 1984; Suh, 1990). The theory enhances creativity by identifying and removing bad ideas in the early phases of design (Suh, 2001).

Although "important steps have been taken towards modeling creativity in the computer, paving the way for formal models concerning creativity" (Akin & Akin, 1996), it is a challenging task to develop a theoretical model that can reason about design creativity and can derive interpretations of phenomena related to design creativity. Such a theoretical model of design creativity must be able to answer the following two fundamental questions (Zeng & Cheng, 1991b; Zeng & Jin, 1993):

(1) How to integrate design problem, design solutions, design knowledge, design process, and particularly designers into a design theory in a coherent manner?

(2) How can it be possible to investigate phenomena of design creativity, which is believed to be nondeterministic, ill-structured, and unpredictable, in a formal, structured and deterministic framework?

The objective of this paper is to introduce such a theoretical model. It must be noted, however, that this theoretical model does not necessarily automate the creative design process, but rather identifies the factors affecting the creative design. Fig. 1 gives the underlying research methodology adopted in this paper. In contrast to the approaches widely used in design research where retrospection, experiments, and case studies are used to develop theories, we will present a design theory that can logically derive interpretations to design phenomena.

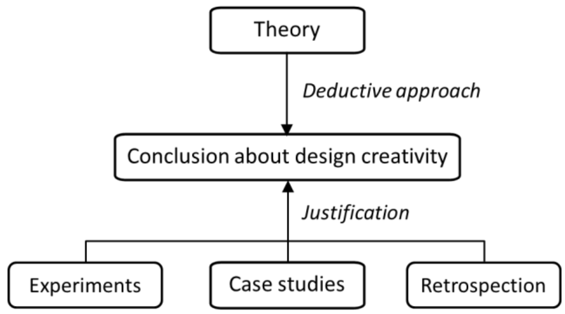


Fig. 1. Research methodology.

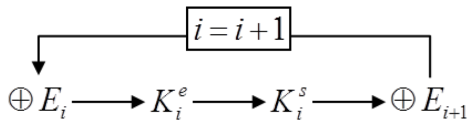
The rest of this paper is organized as follows: Section 2 describes the mathematical foundation including recursive logic (Section 2.1), axiomatic theory of design modeling (ATDM) (Section 2.2), and design governing equation (Section 2.3). Section 3 presents the model of design creativity, which consists of two parts: nonlinear design dynamics and relations between mental stress and creativity. Section 4 interprets the role of sketching in design using the proposed model. Finally, conclusions are given in Section 5.

2. Mathematical Foundation

2.1. Recursive logic

It is widely accepted among design researchers that design is not a linear process. Design is looping and jumping among design problem, design knowledge, and design solutions. This iteration is attributed to the inherent ill-structured property of design problem. Never does a design problem contain all the necessary information. For this reason, from the original design problem, a designer generates tentative solutions; the tentative solutions help the designer understand the problem better. Based on the new understanding, the designer reformulates the problem and then adjusts the solutions to fit the newly redefined problem. The adjustment, in turn, triggers new problems. The process continues until the designer decides that a solution is satisfactory. This recursive nature of design requires different mode of reasoning rather than deduction, abduction and induction. Zeng and Cheng named this mode of design reasoning recursion (Zeng & Cheng, 1991b) and Roozenburg named it innovative abduction (Roozenburg, 1993).

Fig. 2 illustrates the recursive logic. A design problem in a design state ($\oplus E_i$) will determine the design knowledge (K_i^s, K_i^e) required to solve the present problem. The design solution generated from the design knowledge (K_i^s, K_i^e), together with the current design state, defines a new design state ($\oplus E_{i+1}$), which, in turn, determines a new set of design knowledge. Therefore, design problem, design knowledge, and design solutions evolve interdependently throughout the design process. This is the recursive logic of design.



$\oplus E_i$ design state i
K_i^e evaluation knowledge at design state i
K_i^s synthesis knowledge at design state i
$\oplus E_{i+1}$ design state $i+1$

Fig. 2. Recursive interdependence between design problem, design solutions and design knowledge.

2.2. Axiomatic theory of design modeling (ATDM)

In an effort to formalize the recursive logic of design, Zeng developed the axiomatic theory of design modeling (ATDM) (Zeng, 2002). This theory provides a mathematical reasoning and representation tool for studying design. It includes two groups of axioms addressing both the representation of objects and the nature of human thought process. In addition to the common operations such as equality, union, and intersection, a major operation in ATDM is structure operation, denoted by ⊕, which is defined as the union (∪) of an object and the relation (⊗) of the object with itself:

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

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

Structure operation provides a means to represent the structure of an artefact being designed during the design process. It puts the known and the unknown into the same representation framework.

Due to the capacity of human cognition and the scope of an application, a group of primitive objects can always be defined as objects that cannot or need not be further decomposed (Zeng, 2002; Zeng, 2008):

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

where O_i^a is a primitive object and n is the number of primitive objects.

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

Following this theory, a formal model of design could be derived to represent the syntactic structure of hierarchical design objects evolving along with the dynamic design process.

2.3. Design governing equation

Let K_i^e be the evaluation operator for identifying the conflicts between the current and desired states of design; let E_i be the design state i (or design environment at state i). The design problem at the state i is defined as:

$$P_i^d = K_i^e(\oplus E_i). \quad (3)$$

The environment structure $\oplus E_i$ includes the description of the design solution at design stage i, the design requirements for the design stage $(i+1)$, the relevant design knowledge, and other design information (Zeng, 2004).

A new design state $(i+1)$ is the result of a synthesis operator K_i^s on the design problem P_i^d:

$$\oplus E_{i+1} = K_i^s\left(P_i^d\right). \quad (4)$$

From Eq.(3) and Eq.(4), we have:

$$\oplus E_{i+1} = K_i^s\left(K_i^e(\oplus E_i)\right). \quad (5)$$

Eq.(5) models the recursive logic of design and is called the design governing equation (Zeng, 2004; Zeng & Gu, 1999; Zeng & Jin, 1993; Zeng *et al.*, 2004b). The equation describes design as a recursive process in which the current design state E_{i+1} is determined by its previous design state E_i through synthesis and evaluation. Furthermore, the synthesis and evaluation operations are constantly updated, as shown in Eq.(8). Fig. 2 shows a graphical presentation of Eq.(5).

3. Theoretic Model of Design Creativity

3.1. Relations between design states: Nonlinear design dynamics

The French mathematician Poincaré argued that certain dynamical systems whose time evolution is governed by deterministic law may display chaotic motion, which is of the characteristics of randomness and uncertainty (Poincaré, 1921).

Crutchfield *et al* argued that “innate creativity may have an underlying chaotic process that selectively amplifies small fluctuations and models them into macroscopic coherent mental states that are experienced as thoughts. In some cases the thoughts may be decisions, or what are perceived to be the exercise of will. In this light, chaos provides a mechanism that allows for free will within a world governed by deterministic laws” (Crutchfield *et al.*, 1986). In an effort to understand design creativity, Lansdown (Lansdown, 1987) modeled the creative act with the catastrophe theory by combining the routine and creative design into a united schema. Inspired by those speculations, Zeng and Cheng associated design with chaotic dynamics (Zeng & Cheng, 1991a).

Zeng and Cheng’s speculation has also been confirmed independently by other researchers working in the area of general design. For example, chaotic dynamics has been applied to understand software development process (Raccoon, 1995) and to solve critical problems in software engineering (Xiong, 2011), both of which are a kind of design problems in general. In another context, some characteristics of creative process were shown to resemble those of chaotic dynamics (Schuldberg, 1999).

3.1.1. Nonlinear chaotic design dynamics

A dynamical system consists of two parts: a state and a dynamic (Crutchfield, *et al.*, 1986). A state includes the essential information about the system - its components and corresponding relations. A dynamic is a rule used to find how a system evolves from a given initial state with time.

Any dynamical system that is converged to a stable motion with the passage of time can be characterized by an attractor in its state space. Chaos is an attractor that corresponds to unpredictable motions and has a complicated geometric form. The most fundamental characteristic of chaos is its sensitive dependence on the initial conditions. A small fluctuation can be amplified in its time evolution, which may change the system under consideration significantly. The chaotic motion can be illustrated by a mapping $f: x_{n+1} = f(x_n)$, where an initial difference ε between two x's is amplified to the separation $\varepsilon e^{n\lambda(x_0)}$, as is shown in Fig. 3. A dynamical system can have several attractors, which may evolve to different attractors under different initial conditions.

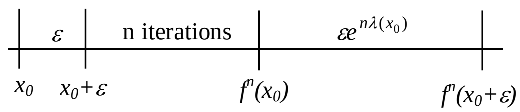


Fig. 3. Chaotic motion.

However, not all nonlinear dynamical equations will generate the chaotic motion. An important element in chaotic dynamics is the existence of a simple stretching and folding operation in the state space. The stretching operation makes an orbit in state space diverge exponentially whereas the folding operation makes the orbit pass close to one another. The orbits on a chaotic attractor are shuffled by these two operators. The randomness of the chaotic orbits is the result of the shuffling process.

As is stated in the theory of dynamical systems, the dynamic to control the state transition of a system is indispensable for studying the system. As can be seen in Eq.(3)-(5), each new state of design will be redefined by a new design solution, new design knowledge related to the solution, and a refined design problem formulation. This leads us to further formulate Eq.(5) as

$$\oplus E_{i+1} = K_i^s\left(K_i^e(\oplus E_i)\right) = D^i(\oplus E_i). \tag{6}$$

Eq.(6) means that design problem solving is a process looking for fixed points of the function D^i. The fixed points for Eq.(6) are the interaction points between $y = \oplus E_i$ and $y = D^i(\oplus E_i)$. A fixed point is usually found through an iterative method. Starting from an initial design state $\oplus E_0$, $\oplus E_1$ can be found through Eq.(6), which updates the design state as well as the function D^i. As a result, D^0, D^1, …, and D^n are generated for each stage of the design process. They redefine knowledge required to generate design solutions. Based on Eq.(6), the relation between the final design state $\oplus E_s$ and the initial design state $\oplus E_0$ can be represented as:

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

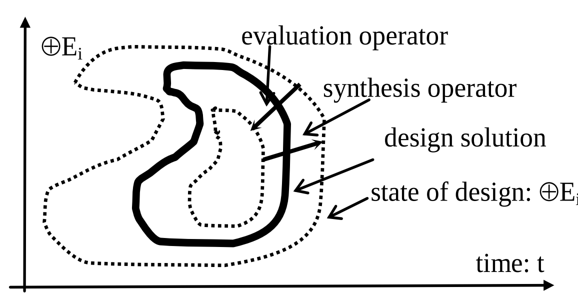


Fig. 4. State space of design under synthesis and evaluation operators (Zeng, 2004).

The design process above is indeed consistent with the recursive logic of design (Zeng & Cheng, 1991b).

In Eq.(6), the evaluation operator K_i^s is defined in terms of the design solutions generated by the evaluation operator K_i^e at each step of the design process. This fact means that the two operators K_i^e and

K_i^s are interdependent and they interact with each other. Hence, function D^i is nonlinear. As a result, there may exist multiple fixed points for the same design problem. The convergence depends on the initial design state. Furthermore, the synthesis process K_i^s, responsible for proposing a set of candidate design solutions based on the design problem, acts like the stretching operator in chaotic dynamics to expand the state space of design. The evaluation process K_i^e, used to screen candidate solutions against the requirements in the design problem through the identification of undesired conflicts and acts like the folding operator in chaotic dynamics to shrink and adjust the state space of design. The interaction of both operators gives rise to the final balanced design solutions as shown in Fig. 4.

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

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

It is noted that this postulate implies necessary conditions for creative design. The chaotic design dynamics is represented by the design governing equation, which generates creative design solutions under certain initial conditions that are continuously reformulated by the designing itself.

The relationships between recursive logic, axiomatic theory of design modelling, design governing equation and nonlinear design dynamics are depicted in Fig. 5. The design governing equation is developed based on the recursive logic and the ATDM and implies a nonlinear design dynamics.

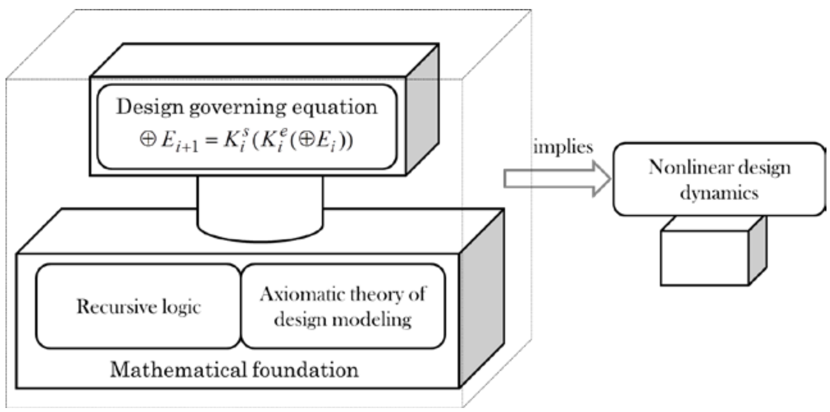


Fig. 5. Nonlinear dynamics underlying design activities.

3.1.2. Sensitive dependence on initial conditions: routes to creative design

Since design may imply a nonlinear chaotic process, multiple design solutions exist for the same design problem. Furthermore, because of its nonlinearity, different initial conditions may lead to different design solutions, some of which might be creative. In practical applications, these initial conditions may be manifested as different designers or as the same designer designing in different times. Mathematically, these initial conditions are included in the state of design.

Let n_e be the number of environment components in design environment E_i and let E_{ij} be an environment component, then Eq.(4) and Eq.(5) can be further expressed as:

$$\oplus E_{i+1} = K_i^s(P_i^d) = K_i^s(K_i^e(\oplus E_i)) = K_i^s\left(K_i^e\left(\oplus\left(\cup_{j=1}^{n_e} E_{ij}\right)\right)\right),$$
$$K_i^e \subset \{K_1^e, K_2^e, \dots, K_n^e\}, \exists K_i^e: K_i^s \subset \{K_1^s, K_2^s, \dots, K_m^s\}. \quad (8)$$

Eq.(8) means that a design problem can be decomposed into subproblems and for each design problem there are different approaches (K_i^e) to evaluating the problem and for each identified problem, there are different approaches (K_i^s) to generating solutions. It can be seen from Eq.(8) that three possibilities, which may lead to different design states, can be derived.

The first possibility is to define a design problem differently in the original design state or during the design process. The initial difference in problem formulation will be amplified in the design process because each design stage will redefine the design problem. The idea is shown in Fig. 6. It coincides with a common sense that changing the perspective of seeing a problem may lead to a creative solution.

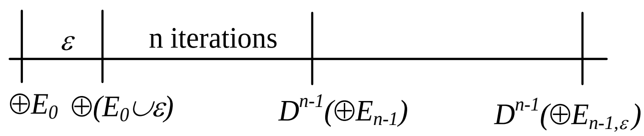


Fig. 6. Nonlinearity of design process: a small difference in the design problem is amplified.

The second possibility is to extend design knowledge. The extended knowledge provides the possibility for the selection of different K_i^e and K_i^s, which results in different intermediate design state $\oplus E_{i+1}$. As a result, the final design solutions could be significantly different, as depicted in Fig. 7.

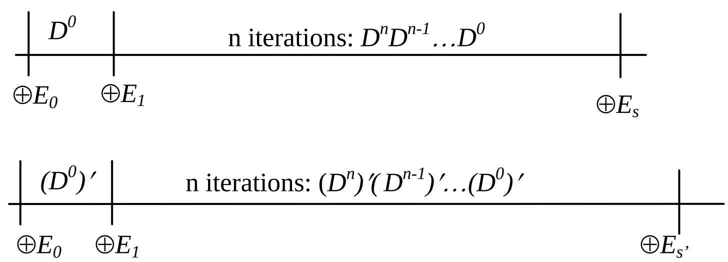


Fig. 7. Nonlinearity of design process: the same design problem with different design solutions.

The last possibility is to choose a different strategy to decompose a complex problem.

Therefore, three routes leading to different design solutions are identified. They describe how the initial conditions of a design process can be changed, which in turn can lead to dramatic changes in the final design solutions. They are given as follows:

(1) Formulating a design problem differently: Formulating a design problem differently (i.e. different choice of K_i^e) will result in different initial design states.

(2) Extending design knowledge: In Eq.(6), the design state $\oplus E_i$ is updated through K^s and K^e. If the design knowledge is extended (i.e. extend the set $\{K_1^e, K_2^e, \ldots, K_n^e\}$ and/or $\{K_1^s, K_2^s, \ldots, K_n^s\}$), the updated design state $\oplus E_{i+1}$ will be different.

(3) Changing the environment decomposition: This is the strategy related to how to decompose the environment (i.e. $\oplus(\cup_{j=1}^{n_e} E_{ij})$). A different approach to decomposing the environment results in different components E_{ij}, which leads to different problem formulation.

3.2. Relations between design states and designer: Mental stress and creativity

In this section, we will identify factors that affect the three routes mentioned in the previous section. First, we will use a descriptive model of design (EBD) derived from the recursive logic (Zeng, 2002;

Zeng, 2011). From EBD, we will identify what factors in the design process may contribute to changes in initial conditions. Then the role of human designer in this process will be considered through the inverse U shaped relationship between mental stress and design creativity.

3.2.1. Descriptive design model: EBD

Following the ATDM, the EBD methodology is derived to solve the design governing equation (Zeng, 2002), which includes three activities – environment analysis, conflict identification, and solution generation as follows (Zeng & Yao, 2009):

- Environment analysis: define the current environment system $\oplus E_i$:

$$\oplus E_i = \oplus \left(\bigcup_{j=1}^{n_e} E_{ij} \right), \tag{9}$$

$$\oplus E_i = \left(\bigcup_{j=1}^{n_e} (\oplus E_{ij}) \right) \cup \left(\bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e} \left(E_{ij_1} \otimes E_{ij_2} \right) \right), \tag{10}$$

  where n_e is the number of components included in the environment E_i in the i^{th} design state; E_{ij} is an environment component j in the same design state. It should be noted that decisions on how many (n_e) and on what environment components (E_{ij}) are included in E_i depend on designer's experience and other factors relevant to the concerned design problem. A roadmap is provided to facilitate this process in (Chen & Zeng, 2006).
- Conflict identification: identify undesired conflicts C_i between environment relationships by using evaluation operator K_i^e:

$$C_i \subset K_i^e \left(\bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e} \left(E_{ij_1} \otimes E_{ij_2} \right) \right). \tag{11}$$

- Solution generation: generate a design solution S_i by resolving a group of chosen conflicts through a synthesis operator K_i^s. The generated solution becomes a part of the new product environment for the succeeding design:

$$\exists C_{ik} \subset C_i, K_i^s : C_{ik} \rightarrow S_i, \oplus E_{i+1} = \oplus \left(E_i \cup S_i \right). \tag{12}$$

The three activities work together to update the design environment and its internal relationships to solve a design problem. The design process continues with new environment analysis until no more undesired conflicts exist. The EBD is illustrated in Fig. 8.

Table 1. Environment Based Design: Process

Activity	Algorithm	Description
1	$r_i^{ad} \in R_{i-1}^d \cap R_a^d$;	Identify a critical requirement r_i^{ad}, which is also a member of primitive requirements R_a^d, from a list of requirements R_{i-1}^d to start the design
2	$\forall r_i^{ad}, \exists K_a^s(K_a^s: r_i^{ad} \to S_a^i)$;	Search for the right synthesis knowledge K_a^s based on the identified requirement r_i^{ad} to generate tentative primitive design solution S_a^i
3	$\forall S_a^i, \exists (r_i^{ad})', (r_i^{ad})^+ = (r_i^{ad}) \cup (r_i^{ad})'$;	Search for new design requirements $(r_i^{ad})'$ associated with the primitive design solution S_a^i to update design requirements to $(r_i^{ad})^+$
4	$\forall S_a^i[P_a], \exists K_a^p: S_a^i \to P_a, \left(K_a^p = [S_a^i \cup [P_a], L]_\approx\right)$;	Search, from knowledge L, for the evaluation knowledge K_a^p relevant to both the design solution S_a^i and design requirements $[P_a]$
5	$\exists S^{[s]} \in S_a^i, \exists P^{[p]} \in P_a,\ K_a^e\left(S^{[s]}\right) \wedge K_a^e\left(P^{[p]}\right)$, $if\ S^{[s]} = \emptyset \vee P^{[p]} = \emptyset, then\ go\ to\ 2$;	Verify if the primitive solution $S^{[s]}$, generated from structural requirements, meets structural and performance requirements
6	$\forall P^{[p]}, \exists S^{[p]} \in S_a^i, \left(K_a^p: S^{[p]} \to P^{[p]}\right)$, $if\ S^{[p]} = \emptyset, then\ go\ to\ 2$	Verify if knowledge exists to evaluate the performance of the primitive solution $S^{[p]}$ generated from performance requirements
7	$S' = S^{[s]} \cap S^{[p]}\ if\ S' = \emptyset, then\ go\ to\ 2$;	Identify a common solution S' based on those from performance and structural requirements
8	$S_p^i = \xi(S', S_p^{i-1})$;	Add the newly generated primitive solution S' to already completed intermediate solution S_p^{i-1}.
9	$X_a^i = K_a^p(S_a^i); X_p^i = K_a^p(S_p^i)$;	Analyze the performance X_a^i of the newly generated primitive design solution S_a^i and the performance X_p^i of the partial design solution S_p^i using the right performance knowledge K_a^p
10	$R' = X_a^i \updownarrow X_p^i$;	Search for the conflicts R' between the performances $X_a^i\ and\ X_p^i$
11	$R_i^d = (R_i^d / \{r_i^{ad}\}) \cup R'$;	Redefine the design requirements
12	$if\ R_i^d \neq \emptyset, then\ go\ to\ 1$;	Stopping condition
13	$S = S_p^i$;	Output the design solution.

Corresponding to EBD, a formal model of design process is explained in Table 1, of which the details can be found in (Zeng & Gu, 1999). This model, which is an earlier and algorithmic version of EBD, formalizes the design process by using the conventional terminology adopted in the design community. The new version of EBD (Zeng, 2011) can handle earlier stages before requirements are developed rather than starting with a set of requirements as shown in Table 1. The relationships between EBD and activities in Table 1 are: Activity 3-4, Activity 6-9 and Activity 11 corresponding to *environment analysis*, Activity 5 and Activity 10 corresponding to *conflict identification*, and Activity 1-2 corresponding to *solution generation*.

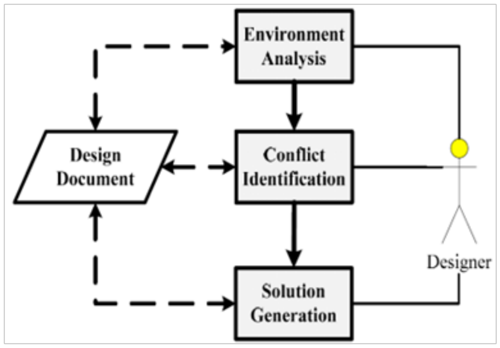


Fig. 8. EBD: process model (Zeng, 2011).

3.2.2. Initial conditions in EBD

Listed in Table 2 are possible design activities that a designer should conduct. Some of those activities will contribute to the change of initial conditions of design. Table 3 shows the connections between activities in Table 2 and three paths possibly leading to creative design described in Section 3.1.2. It must be noted that searching and identifying knowledge also includes learning and discovery processes.

Table 2. Summary of information and skills required by design

	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 1 shows an ideal design process for human designers[1], which implies basic design activities that could lead to changes in the initial conditions for a design. In practice, designers may not be able to perform all the necessary activities as required by Table 1 due to their experiences, current cognitive state and available cognitive resources. Such a lack or downgrade of design activities will affect the initial design conditions and thus the final design outcome. In the next section, we will focus on factors that affect designer's performance regarding these necessary design activities.

[1] The ideal design process for human designers is different from the ideal design defined by Yoshikawa (Yoshikawa, 1981), Braha and Maimon (Braha & Maimon, 1998) and TRIZ (Altshuller *et al.*, 1996; Altshuller, 1984) where the ideality is the situation in which no resource is needed for the design.

Table 3. How initial conditions may change

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

3.2.3. Designer's contribution to the initial conditions through mental capacity

Up to now, we have discussed what a complete design "algorithm" should include in order to accomplish a design task. However, it is how a designer actually designs that determines the quality of the design. This subsection aims to develop the bridge to integrate designer into this nonlinear design dynamics through the second postulate.

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

This postulate, depicted in Fig. 9, was built up on research findings in psychology. Researchers found that relation between performance and arousal follows an inverted U shape (Wilke *et al.*, 1985; Yerkes & Dodson, 1908). For a review of relationship between stressors and creativity, readers can refer to (Byron *et al.*, 2010).

We hypothesize that the level of mental stress is positively related to workload and negatively related to mental capacity (Tang & Zeng, 2009). Workload can be defined as an external load assigned to a person whereas mental capacity is the person's ability to handle the external load. The amount of external workload is the most direct source of mental stress. A greater workload may trigger a greater mental stress. This workload can be associated with the complexity of the problem. Moreover, it is not uncommon that the same workload may trigger different mental stresses on different individuals and the same workload may trigger different mental stresses for the same individual under different circumstances.

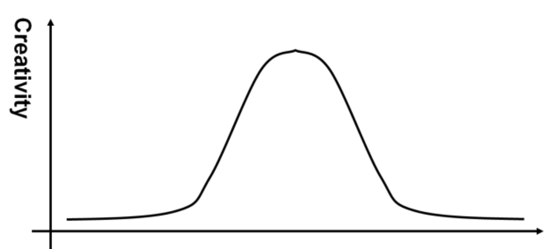


Fig. 9. Relationship between creativity and mental stress.

A designer's mental capacity can be defined by his/her knowledge and skills (listed in Table 2) necessary for accomplishing a design task. The lack of skills and knowledge for the current design problem may increase mental stress. Furthermore, uncertainty and unpredictability exist in completing a design task due to the recursive nature of design. This uncertainty may be transformed to different levels of mental stress in the form of emotion based on the designer's ability to take on the unpredictability and uncertainty. Thus, the uncertainty may trigger negative feelings such as frustration, sense of being lost, and fear of failure, which will increase mental stress on designers. Obviously, designers' affect will determine how well their knowledge and skills will be used in the design process. This explains the designers' impact on the initial design conditions, which places designers into the nonlinear design dynamics.

Therefore, it can be assumed that three main factors would affect mental capacity: knowledge, skills and affect.

Knowledge is influenced by: 1) the structure of knowledge: this depends on how the knowledge is structured and organized for efficient storage and retrieval; for instance, experts are often found to process a large chunk of knowledge that is highly structured; 2) the availability of cognitive resources: according to information processing theory, past knowledge is believed to be retrieved from long term memory and to be held in working memory for use (Atkinson & Shiffrin, 1968). Any factor that affects the availability of working memory, therefore, will affect knowledge activation.

Skills refer to the thinking styles, thinking strategy or reasoning methods. Table 2 shows essential design skills for design activities. With skills, knowledge can be expanded and the right knowledge can be identified to solve a problem.

Affect refers to emotion, and any mental state associated with feeling such as tiredness (Salovey & Sluyter, 1997). Affect is also determined by personality, attitude, belief, motive and stress. Affect will determine how much of one's knowledge and skills can be effectively used in solving a problem.

Some of these proposed factors have also been discussed by other researchers such as Chakrabarti (Chakrabarti, 2006), McKim 1980 (McKim, 1980), Perkins (Perkins, 1988), and Torrance (Torrance, 1965) although not in the same manner and not in a theoretical framework. They consider motivation, knowledge and flexibility in thinking as the most influential factors in creativity.

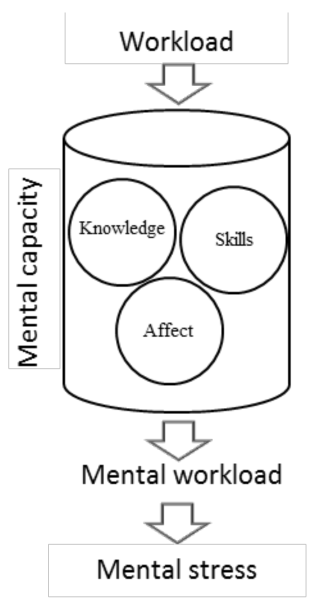


Fig. 10. Factors affecting mental capacity: mental stress is positively related to workload and negatively related to mental capacity.

Fig. 10 shows the relationship between workload, mental capacity and mental stress. Depending on the mental capacity, the mental workload which is the workload perceived by an individual can be higher or smaller than the actual workload. The mental workload will then determine the mental stress. The level of mental stress, in turn, affects designer's creativity performance.

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

(1) Mental capacity cannot be viewed in separation of workload. Facing different design problem, a designer could exhibit different mental capacity. This is because designer can be very knowledgeable in one design problem but may lack knowledge in another one.
(2) Affect determines how well knowledge and skills can be used in the design process.
(3) When a designer recognizes the complexity and the uncertainty of the problem which is beyond the designer's mental capacity, the designer's mental stress will be high. In contrast, when the complexity and/or the uncertainty in the problem perceived by a designer are well below the designer's capacity, the designer's mental stress will be low.

In summary, the governing factors affecting design creative process, through the nonlinear design dynamics, are manifested in designers by

- Formulating design problem through his/her knowledge and skills such as information search and understanding
- Extending design knowledge through effective information acquisition, knowledge learning, and scientific discovery
- Decomposing the design problem through skills such as conflict identification and problem generalization, and
- Coping with stresses arising from uncertainties, unpredictability, and complexities implied in the design problem.

The quality and effectiveness of these activities are dependent on designer's mental capacity which includes knowledge, skills, and affect. The skill and information set required by a design process are listed in Table 2. Designer's mental capacity determines his/her mental stress. Following the Yerkes–Dodson law, both high and low mental stresses will have negative impact on creativity.

4. Example: Interpreting the Role of Sketch in Creative Design

In previous sections, we propose two postulates. The first states that creative design process is a nonlinear dynamics in which the final outcomes are sensitively dependent on the initial conditions. Creativity may occur when a small difference in initial conditions leads to completely unpredictable and unanticipated outcomes. The second postulate adopts Yerkes–Dodson law to relate designer's mental stress to creativity. Both very high and very low mental stresses jeopardize creative performance. The first postulate is used to interpret design phenomena that are independent of designer's performance whereas the second postulate is used to interpret design phenomena that are related to design performance.

In this section, we use the proposed theory to study design activities, following four steps:

(1) Step 1 – statement of the phenomenon
(2) Step 2 – extraction of research questions
(3) Step 3 – derivation of a theoretical model to answer the research question
(4) Step 4 – interpretation of existing research findings and/or experimentation to verify the theoretical model.

The study is focused on the interpretation of the effect of sketches on design creativity. Details of each step are given below:

Step 1 - Statement of the phenomenon

Research indicates that sketches play the following main roles in a design process:

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

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

It is noted that in team/collaborative design, sketches also serve as a medium to facilitate communication between designers. When communication helps activate the knowledge necessary for design, the role of sketches is similar to (2).

Researchers in design found several phenomena, among others, associated with sketches and sketching activities as follows:

Phenomenon 1: The ambiguity in sketches triggers various alternative forms by reminding designer of relevant knowledge or realizing new shapes; and therefore helps designer to generate different design ideas (Ellen Yi-luen & Mark, 1996; Goel, 1995; Schön, 1983; Yang, 2009).

Phenomenon 2: There are no differences in design solutions between expert architects who are allowed to sketch and those who are not allowed to sketch (Bilda & Gero, 2006).

Step 2 - Extraction of research question

By generalizing the sketching phenomena in design, the research question can be formulated as: how do sketches and sketching influence design performance?

Step 3 - Theoretical model - roles of sketches and sketching

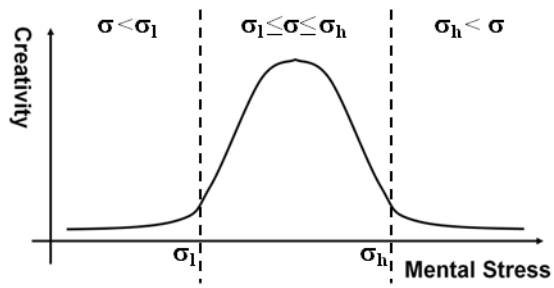


Fig. 11. Level of mental stress.

It can be assumed that the mental stress, denoted by σ, can be divided into three levels: low, medium and high as shown in Fig. 11:

$$\sigma < \sigma_l,\ \sigma_l \leq \sigma \leq \sigma_h,\ \sigma > \sigma_h. \quad (13)$$

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

As mentioned in Step 1, sketch can play the role of a memory aid (let mental stress in this case be denoted by σ_u^m) or serve as a stimulus to provoke synthesis knowledge (mental stress denoted by σ_u^s) or can provoke evaluation knowledge (mental stress denoted by σ_u^e). Assume that information being processed is stored in the working memory. Let $f^{size}(C_o)$ and $f^{size}(C_u)$ be the number of conflicts before and after sketching, $f^{level}(C_o)$ and $f^{level}(C_u)$ are the level of difficulty of the problem before and after sketching; g is a function that transforms f^{level} and f^{size} into a workload. In the case of sketching activity, the following rules can be observed:

When sketch is a memory aid, cognitive load is released and mental stress decreases:

$$\sigma_u^m < \sigma_o, \forall \sigma_o. \quad (14)$$

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

$$\sigma_u^s \leq \sigma_o, \forall \sigma_o < \sigma_h. \quad (15)$$

When sketch activates evaluation knowledge that makes the complexity of the problem increase substantially, mental stress increases. (The complexity of a problem can be characterized by the number of conflicts and/or the difficulty of solving the conflicts):

$$\frac{g\left(f^{size}(C_u), f^{level}(C_u)\right)}{g\left(f^{size}(C_o), f^{level}(C_o)\right)} > \delta \rightarrow \sigma_u^e > \sigma_o, \forall \sigma_o < \sigma_h, \quad (16)$$

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

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

$$\frac{g\left(f^{size}(C_u), f^{level}(C_u)\right)}{g\left(f^{size}(C_o), f^{level}(C_o)\right)} \leq \delta \rightarrow \sigma_u^e \leq \sigma_o, \forall \sigma_o < \sigma_h. \quad (17)$$

When the mental stress is high, we believe that sketching only helps to release memory. Because all cognitive resources are heavily overloaded, no working memory can be allocated to support the stimulus function of sketch. Therefore, except Eq.(14), other equations (i.e. Eq.(15), Eq.(16) and Eq.(17)) requires the stress input to be in the low or in the optimal level.

Because sketch can serve as different roles simultaneously and also for the sake of simplicity, the output mental stress σ_u can be treated as the sum of σ_u^m, σ_u^s and σ_u^e:

$$\sigma_u = \sigma_u^m + \sigma_u^s + \sigma_u^e. \quad (18)$$

It should be noted that designer's performance is determined by the mental stress σ_o. For instance, if mental stress σ_o is at high and tend to reduce, the reduction in mental stress can help increase performance because mental stress moves towards the optimal level, as illustrated in Fig. 12. Designer's mental stress can be high, after sketching mental stress may decrease to medium level (Fig. 12). The sketch, then, can activate relevant knowledge that help designer to generate some possible solutions. Mental stress, therefore, further decreases (Fig. 13). However, if σ_o is at the low level, reduction in mental stress does not enhance performance as illustrated in Fig. 14. Sketch can play several roles in one design state: as memory aid and as stimulus

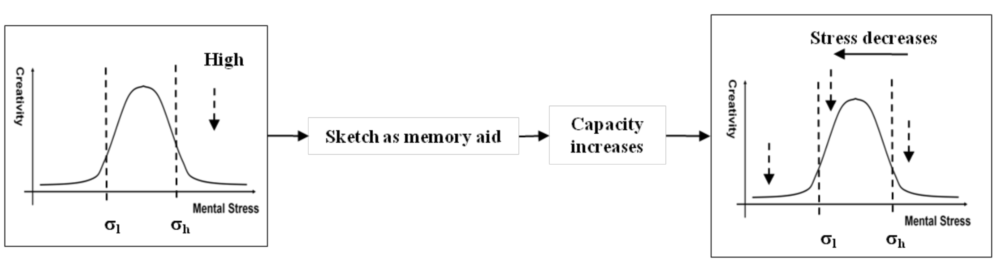


Fig. 12. Effect of sketching on creative performance when mental stress is high.

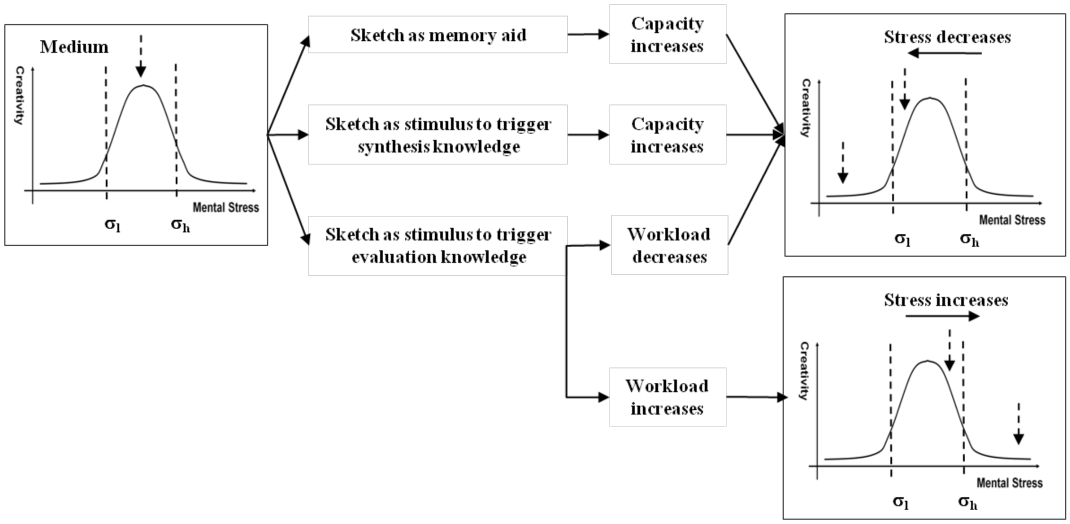


Fig. 13. Effect of sketching on creative performance when mental stress is medium.

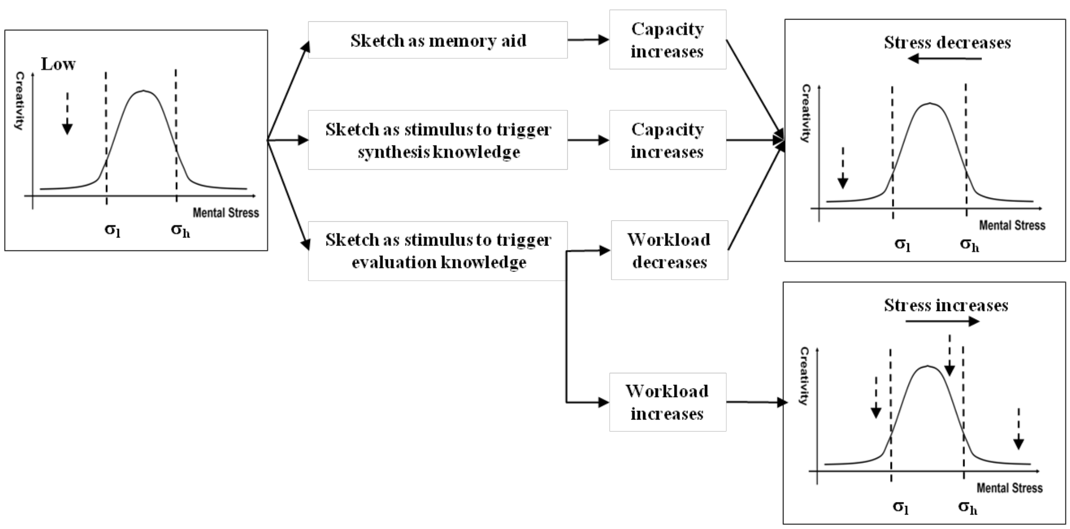


Fig. 14. Effect of sketching on creative performance when mental stress is low.

Step 4 - Interpretation/Verification

***Phenomenon 1*:** The ambiguity in sketches reminds a designer of relevant knowledge or helps designers realize new shapes, which will assist the designers to generate different design ideas.

[Interpretation] Let an ambiguous sketch be denoted by S_0. Because S_0 is ambiguous, it can be assumed that it has m substances in the designer's mind: $S_{0k}(k = 1,2,\ldots,m)$. According to the ATDM,

$$S_0 = \oplus \left(\bigcup_{k=1}^{m} S_{0k}\right) = \left(\bigcup_{k=1}^{m}(\oplus S_{0k})\right) \cup \left(\bigcup_{k=1}^{m} \bigcup_{\substack{l=1 \\ l\neq k}}^{m} (S_{0k} \otimes S_{0l})\right). \tag{19}$$

Obviously,

$$S_{0k} \subset S_0, \forall k. \tag{20}$$

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

$$\oplus E_{i+1} = \oplus (E_i \cup S_0) = (\oplus E_i) \cup (\oplus S_0) \cup (E_i \otimes S_0) \cup (S_0 \otimes E_i). \tag{21}$$

As is defined in Eq.(5), Eq.(21) determines what is going to happen in the next step of design. Considering Eq.(8), different design knowledge can be used based on the environment components m to move forward the design process. The m components included in S_0, which is represented in Eq.(19), implies many possibilities for the next move. Needless to say, the more substances the ambiguous sketch can stimulate (i.e., m is greater), the more possibilities there will be. This in turn triggers the three approaches leading to different design solutions as given in Postulate 1. Therefore, different design ideas can be resulted from the ambiguity in sketch.

***Phenomenon 2*:** There are no differences in design solutions between expert architects who are allowed to sketch and those who are not allowed to sketch.

[Interpretation] Assume that expert architect 1 (EA1) is allowed to sketch whereas expert architect 2 (EA2) is not allowed to sketch. Let σ_{o_sk} and σ_{u_sk} be mental stresses for EA1 before and after sketching. Let σ_{o_nsk} and σ_{u_nsk} be those mental stresses for EA2.

Assume that both architects have similar mental capacity. Because the problem is the same, the workload is the same for both architects. That is to say,

$$\sigma_{o\_sk} = \sigma_{o\_nsk} = \sigma_o \tag{22}$$

Since no differences were found between their design solutions, ~~t~~the final workload remains the same for them. Hence, we have

$$\sigma_{u\_sk} = \sigma_{u\_nsk} = \sigma_u \tag{23}$$

According to Eq. (14), with sketching

$$\sigma^m_{u\_sk} < \sigma_u \tag{24}$$

So, without sketching

$$\sigma^m_{u\_nsk} \geq \sigma_u \tag{25}$$

Hence

$$\sigma^m_{u\_nsk} \geq \sigma^m_{u\_sk} \tag{26}$$

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

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

$$\sigma_{u\_nsk} = \sigma^m_{u\_nsk} + \sigma^s_{u\_nsk} + \sigma^e_{u\_nsk} \tag{27}$$

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

$$\sigma_{u\_sk} = \sigma^m_{u\_sk} + \sigma^s_{u\_sk} + \sigma^e_{u\_sk} \tag{28}$$

Because $\sigma_{u\_nsk} = \sigma_{u\_sk}$, we have

$$(\sigma_{u\_nsk}^{m} - \sigma_{u\_sk}^{m}) + (\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) + (\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) = 0 \quad (29)$$

Hence

$$\varepsilon + (\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) + (\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) = 0 \quad (30)$$

There are four possibilities for Eq.(30) to be true:

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

- $\varepsilon \approx 0$: The extra stress caused by non-sketching activity is very small.
- $\sigma_{u\_nsk}^{s} \approx \sigma_{u\_sk}^{s}$, $\sigma_{u\_nsk}^{e} \approx \sigma_{u\_sk}^{e}$: sketch and mental image trigger similar synthesis and evaluation knowledge.
  This is the case where the problem is relatively easy for the architects.

(2) **Possibility 2**: $\varepsilon \approx 0$ and $(\sigma_{\mathrm{u\_nsk}}^{s} - \sigma_{\mathrm{u\_sk}}^{s}) + (\sigma_{\mathrm{u\_nsk}}^{e} - \sigma_{\mathrm{u\_sk}}^{e}) \approx 0$.

- $\varepsilon \approx 0$: The extra stress caused by non-sketching activity is very small, which means the problem is not difficult for the architects.
- $\sigma_{u\_nsk}^{s} + \sigma_{u\_nsk}^{e} \approx \sigma_{u\_sk}^{s} + \sigma_{u\_sk}^{e}$
  $\Rightarrow \begin{cases} \sigma_{u\_nsk}^{s} > \sigma_{u\_sk}^{s} \\ \sigma_{u\_nsk}^{e} < \sigma_{u\_sk}^{e} \end{cases}$ (Case 1) or $\begin{cases} \sigma_{u\_nsk}^{s} < \sigma_{u\_sk}^{s} \\ \sigma_{u\_nsk}^{e} > \sigma_{u\_sk}^{e} \end{cases}$ (Case 2)

  Case 1:
  - $\sigma_{u\_nsk}^{s} > \sigma_{u\_sk}^{s}$: Sketch is more effective in activating synthesis knowledge than mental image or sketch can trigger more relevant knowledge to solve the problem.
  - $\sigma_{u\_nsk}^{e} < \sigma_{u\_sk}^{e}$: Sketch activates evaluation knowledge that make problem more complex than the problem identified by the evaluation knowledge triggered by mental image. In other words, sketch causes designers to identify more problems than mental image.

  Case 2:
  - $\sigma_{u\_nsk}^{s} < \sigma_{u\_sk}^{s}$: Mental image is more effective in activating synthesis knowledge than sketch.
  - $\sigma_{u\_nsk}^{e} > \sigma_{u\_sk}^{e}$: Mental image activates evaluation knowledge that make problem more complex than the problem identified by the evaluation knowledge triggered by sketch.

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

- $\varepsilon + \left(\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}\right) \approx 0$
  Hence, we have $\begin{cases} \sigma_{u\_nsk}^{s} < \sigma_{u\_sk}^{s} \\ \varepsilon = \sigma_{u\_sk}^{s} - \sigma_{u\_nsk}^{s} \end{cases}$
  Mental image activates more synthesis knowledge than sketch does. The difference between $\sigma_{u\_nsk}^{s}$ and $\sigma_{u\_sk}^{s}$ is equal to ε.
- $(\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}) \approx 0$: Sketch and mental image trigger similar evaluation knowledge.

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

- $\varepsilon + \left(\sigma_{u\_nsk}^{e} - \sigma_{u\_sk}^{e}\right) \approx 0$
  Hence, we have $\begin{cases} \sigma_{u\_nsk}^{e} < \sigma_{u\_sk}^{e} \\ \varepsilon = \sigma_{u\_sk}^{e} - \sigma_{u\_nsk}^{e} \end{cases}$
  Sketch activates evaluation knowledge that make problem more complex than the problem identified by the evaluation knowledge triggered by mental image. The difference between $\sigma_{u\_nsk}^{e}$ and $\sigma_{u\_sk}^{e}$ is equal to ε.
- $(\sigma_{u\_nsk}^{s} - \sigma_{u\_sk}^{s}) \approx 0$: Sketch and mental image trigger similar synthesis knowledge.

From the analysis of the experiment in (Bilda & Gero, 2006), one significant difference between sketching and non-sketching sessions is that more information was recalled in the non-sketching session. Therefore, it is more likely that possibility 2 (case 2) or possibility 3 happened.

In summary, the reasons that there are no differences in design solutions between expert architects who are allowed to sketch and who are not allowed to sketch are:

(1) The design problem was not challenging enough for designers, mental stress is very low. Therefore, whether designers are allowed to sketch or not to sketch does not affect the result.

(2) Mental stresses in both cases are the same due to two possibilities:

- Without sketching, designers were able to retrieve more synthesis knowledge to solve the problem; mental stress in non-sketching case is lower than the mental stress in sketching case (possibility 2, case 2). However, without sketching the evaluation knowledge makes the problem more complex, mental stress in non-sketching case is higher than the mental stress in sketching case (possibility 2, case 2). Therefore, the final mental stress in both cases can be equal.
- Without sketching, designers experience an increase in mental workload, mental stress increases; however, designers were able to retrieve more synthesis knowledge to solve the problem (possibility 3), mental stress reduces. This reduction offsets the increase (possibility 3). Therefore, mental stress of designers in non-sketching case remains equals to that of designers in the sketching case.

It can be seen that our model helps provide a systematic way to derive interpretation for the phenomenon.

Summary

In this section, we showed that the nonlinear design dynamics model and mental stress-creativity relation model can be used to interpret phenomena in design creativity, which have been experimentally studied by other researchers. In particular, we use postulate 1 to explain why the ambiguity in sketch can help designers generate different design solutions and we use postulate 2 to explain why it is possible that there were no differences in design solutions when sketching was allowed and when sketching was not allowed.

5. Conclusions

Two approaches are usually used to validate a hypothesis in research: inductive and deductive. Inductive approach largely depends on experimentation, observation, and retrospection whereas deductive approach aims to reason about the hypothesis following first principles and logical inference. In this paper, we propose a new theoretic model of design creativity following the deductive approach, which takes the axiomatic theory of design modeling as its formal reasoning tool and two postulates as its first principles.

As the formal reasoning tool, the axiomatic theory of design modeling (ATDM) is employed to represent all of the information appearing throughout the design process, mainly with the structure operation ($\oplus$). The structure of an object is the union of the object and the relation from the object to itself. The two postulates address the relation between evolving design states and between designers and design states, respectively. They are summarized as follows:

Postulate 1: *Design reasoning follows a nonlinear dynamics, which may become chaotic.*

Postulate 2: *Design creativity is related to designer's mental stress through an inverse U shaped curve.*

The first postulate describes design as a nonlinear dynamical process, of which the outcome is sensitive to initial conditions. This postulate depicts the nondeterministic and unpredictable nature of design creativity and is implied by the design governing equation. The design governing equation is logically derived from the recursive logic of design by using the ATDM. The recursive logic of design captures the recursive interdependence between design problem, design solutions, and design knowledge, all of which evolve simultaneously in the design process. Based on the first postulate, three routes leading to design creativity are derived: formulating design problem differently, extending design knowledge, and changing the environment decomposition. A small change in the initial design state may lead to diverging states of design outcomes where design creativity is likely to occur. The continuous change of initial conditions is deeply rooted in the design activity due to the presence of the recursive logic of design.

The second postulate describes the inverse U shaped relationship between designer's mental stress and design creativity. By taking into account designers in the process, a question is raised: how is a designer's design action related to the initial conditions of design and the dynamical design process? The answer lies in a descriptive model of design – EBD and Yerkes-Dodson law. The EBD describes what activities are indispensable in the (conceptual) design process, which determines the workload of design problem. The Yerkes-Dodson law addresses the relation between designer's mental stress and performance. Both high and low mental stresses have negative impact on creativity. Designer's mental stress is assumed to be positively related to workload and negatively related to the designer's mental capacity. Major factors affecting mental capacity, and thus indirectly affecting mental stress, are identified: knowledge, skills and affect. As such, the role of designers is seamlessly integrated into the proposed theoretical model.

As a validation of the proposed model, the roles of sketching in design are interpreted following four steps: statement of a phenomenon, formulation of research questions, derivation of models and interpretation of the results in the context of the concerned phenomenon. This validation shows the feasibility of the proposed theory to logically interpret design phenomena.

Naturally, the proposed theory has moved forward in answering the two critical questions for design research:

(1) How to integrate design problem, design knowledge, design process, and particularly designers into a design theory in a coherent manner?

(2) How can it be possible to investigate phenomena of design creativity, which is believed to be nondeterministic, ill-structured, and unpredictable, in a formal, structured and deterministic framework?

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