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A physiological study of relationship between designer's mental effort and mental stress during conceptual design

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HIGHLIGHTS

- We propose a new approach to process EEG and HRV signals for design activities.
- We assume that an inverse U curve relationship exists between mental effort and mental stress.
- We found that designers' mental effort is the lowest at the highest mental stress.
- There is no significant difference in mental effort at low and medium stress levels.

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ABSTRACT

In the development of the next generation computer-aided design (CAD) systems, it is important to consider systematically the interactions between designers and design tools. As one of the first steps in quantifying such relations, we propose a method to investigate the relation between a designer's mental stress and mental effort. We hypothesize that mental effort is low at low and high stress levels but high at a medium stress level. To test the hypothesis, we conducted experiments on seven subjects. Design activities, body movements, brain signals and heart rate were recorded during a design process. Mental stress was quantified by LF/HF ratio and mental effort was quantified by EEG energy. The statistical analysis shows that mental effort is the lowest at high stress level and there is no significant difference in mental effort between medium stress level and low stress level.

1. Introduction

1.1. Theoretical model of design activities

In the development of the next generation CAD systems, it is important to consider systematically the interactions between a designer and design tools [1]. This hangs on the designer's cognitive model [2]. Such a model should account for both creative design and routine design processes. It is not unusual to observe that sometimes designers may produce creative solutions even when they did not intend to and sometimes designers may not be able to produce creative solutions even when they tried very hard. One implication of this observation is that a good design process model should imply a creative design process and a creative design process model should imply a routine design process. There should be no difference between a design process model and a design creativity model. Therefore, a good design process model should have two major components: a general design process model and the conditions under which the general design process model may lead to creative solutions.

In our previous work, we proposed a theoretical model of design creativity which includes the Environment-Based Design [3,4] as a general design process model and the following two postulates defining conditions for creative design [5]:

- Postulate 1: Design reasoning follows a nonlinear dynamics, which may become chaotic.
- Postulate 2: Design creativity is related to a designer's mental stress through an inverse U shaped curve.

The first postulate addresses the relation between evolving design states. Designing is formulated as an environment evolution process where an earlier design solution becomes a part of the environment for the current design stage. This environment evolution implies a nonlinear chaotic dynamics, in which design problem, design solution, and design knowledge will change in a recursive and interdependent manner [6,7]. A great uncertainty is thus inherent in this nonlinear recursive design process, which may lead to mental stress on designers. The second postulate then relates a designer's mental stresses to creativity through an inverse U shaped curve (Fig. 1), which is adopted from the well-known Yerks–Dodson law [8].

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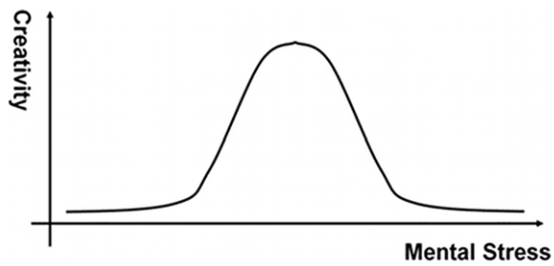

Fig. 1. Inverse U curve relation between mental stress and design creativity [5].

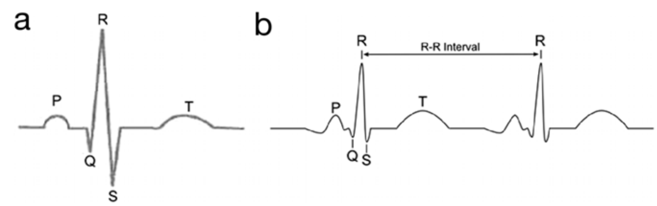

Fig. 2. (a) A normal heartbeat; (b) Interval between two heartbeats.

The present paper is one of the first steps in quantifying the second postulate: the inverse U shaped curve relation between a designer's mental stresses and design creativity.

1.2. Mental stress, creativity, and mental effort

It is widely known that mental stress can be measured from physiological responses such as respiration rate, heart rate, pupil diameter, skin temperature, and galvanic skin response. However, when it comes to the assessment of creativity throughout a design process (that is to say, creativity has to be assessed at any particular moment), to the best of our knowledge, no effective method has been reported in the literature. Therefore, mental effort is adopted as an indirect assessment of creativity in this paper.

Mental effort can be defined as the total use of cognitive resources [9]. Sun and Yao found that mental effort is positively related to design novelty and quantity [10]. Therefore, in design, we assume that high mental effort is associated with high creative ability while low mental effort is associated with low creative ability.

2. Background: measurement of mental stress and mental effort

2.1. Heart Rate Variability (HRV) and mental stress

Heart rate variability (HRV) is the variation in time intervals between consecutive heartbeats. A heartbeat is composed of five waveforms denoted by P, Q, R, S, and T as shown in Fig. 2(a). The time interval between two heartbeats is the time between two R and R components as shown in Fig. 2(b). The HRV spectrum is classified into four bands: ultra-low frequency less than 0.003 Hz (ULF), very low frequency from 0.003 Hz to 0.04 Hz (VLF), low frequency from 0.04 Hz to 0.15 Hz (LF), and high frequency from 0.15 Hz to 0.4 Hz (HF) [11].

Mental stress is the body's response to an uncomfortable or a threatened event which can be internal or external. The stress mechanism is closely related to the autonomic nervous system, which consists of the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). The SNS stimulates organs, dilates pupils, activate sweat glands, elevates blood pressure and increases heart rate [12] whereas the PNS does the opposite. Under stressful situations, SNS becomes dominant, causing physiological, biological and psychological changes to adapt the body to the situation.

The measurement of mental stress using HRV frequency components dated back to 1981. From a study of HRV in dogs, Akselrod et al. found the contribution of PNS activity to the high frequency component (HF) of the HRV spectrum and the contribution of both PNS and SNS activity to the low frequency (LF) component [13]. To answer the question if a similar association can be observed in humans, Pomeranz et al. conducted a similar study on humans and concluded that LF power of human HRV also reflects both PNS and SNS while HF power is mediated by only PNS activity [14]. Since then, there are a large number of studies using HRV power spectral components as an index of psychosocial stress. For instance, psychosocial stress is found to be associated with rising LF, increasing LF/HF ratio [15] and/or decreasing HF [16]. Nesvold et al. found that meditation reduces stress through increasing HF and decreasing LF/HF during the practice [17]. In a study of mental stress induced by demanding computer work and an unfriendly environment, Hjortskov et al. observed lower HF and higher LF/HF in a stress session than in a control session [18]. Kristiansen et al. compared between resting and working conditions and concluded that the group shows higher LF/HF ratio, lower HF and higher LF when working [19]. Studying 32 subjects during a arithmetic task, Colombo et al. found significant increase in LF and significant decrease in HF [20]. Comparing among HRV measures, Boonnithi and Phongsuphap claimed the LF/HF ratio to be the most accurate indicator of mental stress in the frequency domain [21]. The sensitivity of LF/HF to mental stress is also supported by several other studies [22–24].

Even though the number of studies above seem to confirm the use of HRV components (LF, HF, and LF/HF) as reliable indices of mental stress, another group of studies failed to show the relation between HRV components and stress [25]. For instance, Jokkel et al. showed that blockage of SNS does not reduce LF while blockage of PNS significantly reduces both LF and HF [26]. Therefore, the authors argued that mental stress might not be associated with increase in LF or LF/HF as widely believed. Similarly, Muth et al. reported no correlation between LF and cold stressors [27]; Sloan et al. found neither correlation between LF and norepinephrine (a type of hormone secreted during stress) nor correlation between LF/HF and norepinephrine [28].

Due to these inconsistent results, a member in our group conducted experiments to test the sensitivity of different HRV parameters [29]. It was found that LF/HF was the most sensitive variable. Based on that test, we use the LF/HF ratio to quantify mental stress in our experiments.

2.2. Electroencephalography (EEG) and mental effort

Electroencephalography (EEG) is a method to record electrical signals emitted from the brain. The EEG signals are usually divided into four bands based on frequency: delta (from 1 Hz up to 4 Hz), theta (from 4 Hz up to 8 Hz), alpha (from 8 Hz up to 13 Hz) and beta (from 13 Hz up to 30 Hz).

Mental effort is believed to be reflected to some degree by various physiological parameters such as facial muscle activity [30], eye blink frequency [31], pupil diameter [32], eye movement (saccade) [32,33], eye fixation [32,34], HRV [35,34], skin conductivity [33], and EEG [33,36,37]. Among these, EEG is the most sensitive to changes to cortical activation [38].

Under the assumption that a high cognitive task demand usually requires additional mental effort, researchers have studied how EEG changes at different levels of task difficulty. In particular, researchers have reported an increase in the theta band and a decrease in the alpha band as task difficulty increases [39–42]. During video game play, mental effort is reflected in an increase