ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

DISTRIBUTION OF MENTAL STRESSES DURING CONCEPTUAL DESIGN ACTIVITIES

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ABSTRACT

In this paper, we study how different mental stress levels are distributed in a conceptual design process. Firstly, we reviewed a Stroop Test experiment conducted earlier in our lab to confirm the use of heart rate variability (HRV) as a reliable index of mental stress. Secondly, we reported our experiment on seven designers; HRV data and body movements were recorded along with design processes. Design data was segmented and HRV parameter as indicator of mental stress was computed for each segment. Then the mental stresses were classified into seven levels. The result showed that most of the activities in a design process were performed at low levels of mental stress. The design activities reduce as the level of mental stress increases. No correlation was found between types of design activities and mental stress.

Keywords: mental stress, heart rate variability (HRV), design activity, LF/HF ratio

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1 INTRODUCTION

In recent years, increasing research efforts have been reported in understanding design creativity (Nagai and Gero, 2012). Gero (2010) categorized design creativity research into three main focuses: design process, cognitive behaviors, and interaction between designers and environments. Research methodology adopted ranges from construction of computational models to input-output experiments and protocol studies (Gero, 2010). In an attempt to contribute to this important topic, we aim to develop a formal model of creative design. In our previous work, we postulated that design creativity is related to designer's mental stress through an inverse U shaped curve as shown in Figure 1 (Nguyen and Zeng, 2012). Design creativity happens when designer's mental stress is at a medium level. As a result, if mental stress can be quantified, it is possible to develop a formal model for creative design. Among many approaches to measuring mental stress, heart rate variability (HRV) is viewed as one of the most sensitive (Hjortskov et al., 2004; Karthikeyan, Murugappan and Yaacob, 2011). In this paper, we present our experimental results on the quantification of designer's mental stress using HRV.

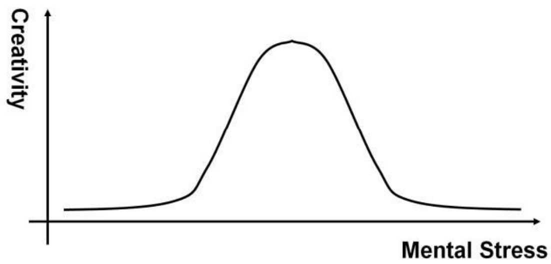


Figure 1. Relationship between creativity and mental stress (Nguyen and Zeng, 2012)

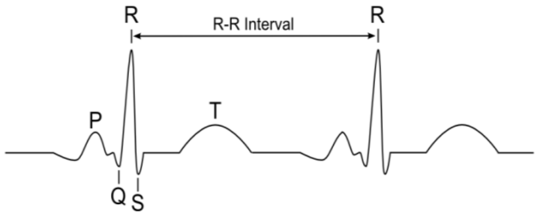


Figure 2. R-R interval

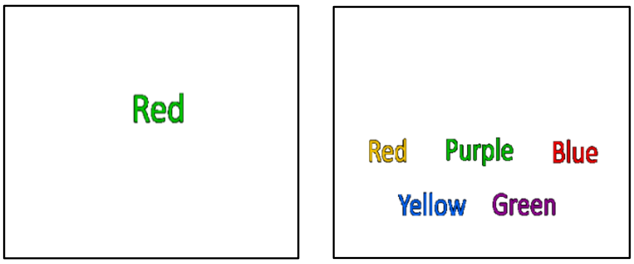
HRV is the fluctuation in heart beat intervals, as shown in Figure 2. HRV is mainly controlled through the sinoatrial (SA) and atrioventricular (AV) nodes. Both SA and AV nodes are influenced by the parasympathetic and sympathetic nervous systems (Schwab et al., 2003). Under stress, the increased activity of sympathetic system and/or decreased activity of parasympathetic system increase the firing rate of SA node and AV node, leading to variation in heart rate or HRV. The HRV frequency components are divided into: Ultra low frequency (ULF) from 0 to 0.003Hz, Very Low Frequency (VLF) band from 0.003 to 0.04 Hz, Low Frequency (LF) band from 0.04 to 0.15 Hz, and High Frequency (HF) band from 0.15 to 0.4 Hz (Camm et al., 1996). Researchers have been associating HF with parasympathetic activity and LF with both sympathetic and parasympathetic activities. The ratio LF/HF has long been considered as an index of sympathetic and parasympathetic activities (or sympathovagal balance) (Karim, Hasan and Ali, 2011). Thus, LF/HF ratio can be considered as an index of mental stress.

On the one hand, research found that LF/HF rises significantly during stressful task (Hjortskov et al., 2004), exam period (Lucini et al., 2002), earthquake encounter (Lin et al., 2001). On the other hand, researchers reported that there are no significant differences in LF, HF, LF/HF between exam and holiday periods (Tharion, Parthasarathy and Neelakantan, 2009), no significant difference in LF/HF between control and stressful task (Stroop task in this case) (Hoshikawa and Yamamoto, 1997), and no correlation between LF/HF and stress (Sloan et al., 1996). Because of these conflicting results, we performed an experiment to validate the use of HRV parameters as indicators of mental stress. We adopted Stroop Color Word Test as stressor because according to (Karthikeyan, Murugappan and Yaacob, 2011), it is one of the efficient stimuli to induce mental stress. From this experiment, we found that LF/HF was the best index of mental stress. The result is reviewed in Section 2. In Section 3, using LF/HF to quantify designer's mental stress in a conceptual design process, we found that as mental stress increases, design activities reduce.

2 CONFIRMATION OF HRV AS A MEASUREMENT OF MENTAL STRESS

This section reviews an experiment that was previously conducted in our research group (Petkar, 2011). The objective of the experiment was to choose an HRV parameter that best represents mental stress. Stroop color word test, introduced by J.R. Stroop (1935), was used as a stressor.

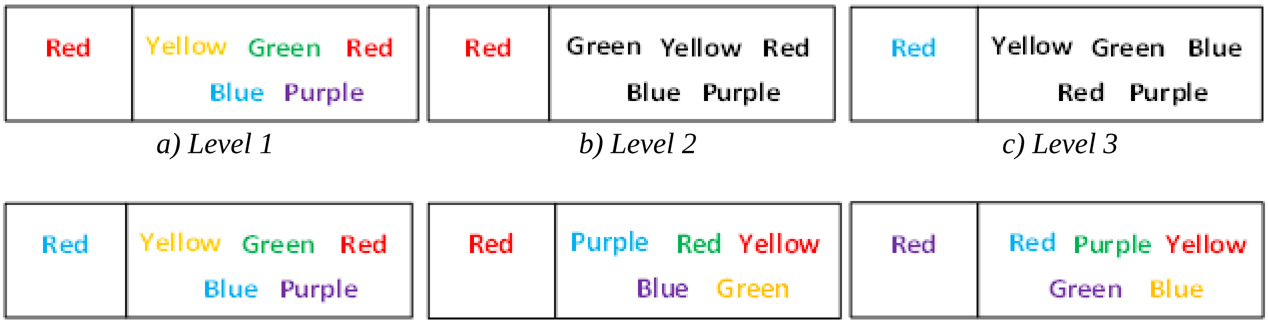
The Stroop test is a psychological experiment, which aims to demonstrate the impact of interference on subjects' reaction time. When the name of a color is displayed in a color not denoted by the name (e.g., the word "yellow" displayed in red font instead of yellow font), it takes longer and is more error-prone for a subject to name the color of the word than when the name of a color is displayed in the same color denoted by the name (e.g., the word "yellow" displayed in yellow font) (Stroop, 1935).
In the experiment (Petkar, 2011), a stimulus word is displayed for 500 miliseconds. Then an answer list is displayed and subjects have to choose the right answer within 1500 miliseconds (1.5 seconds). A blank screen is displayed for 1000 miliseconds (1 second) between two Stroop tasks.



a) Stimulus word *b) Answer list*

Figure 3. A Stroop task.

Six difficulty levels, as shown in Figure 4, were designed based on different combinations of color and color name in both stimulus word and the answer list. Those difficulty levels were arranged into two sets: High interference (i.e. very high difficulty level follows very low difficulty level) and Low interference (i.e. difficulty levels increase gradually). Twenty subjects (21-30 years old) volunteered to participate in the experiment. Further details can be found in (Petkar, 2011).



a) Level 1 *b) Level 2* *c) Level 3*

d) Level 4 *e) Level 5* *f) Level 6*

Figure 4. Six difficult levels.

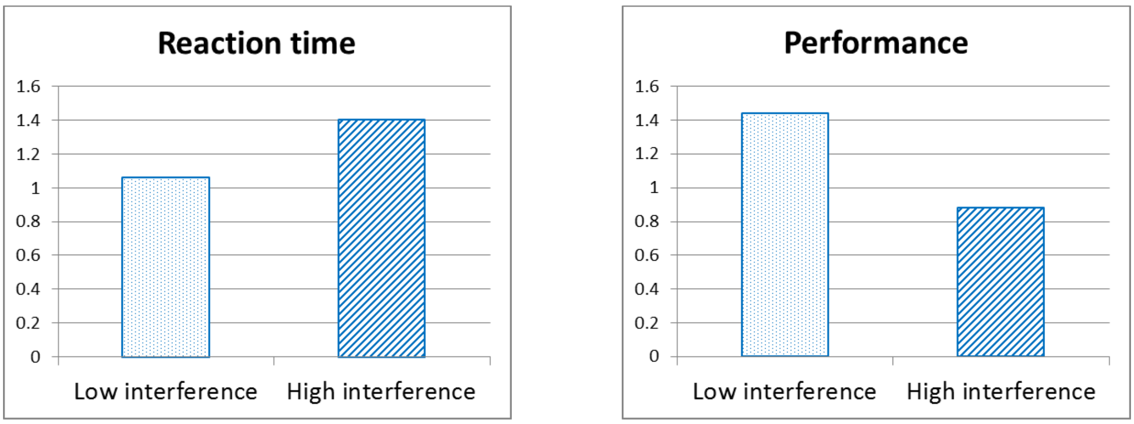


Figure 5. Reaction time and performance of Low and High interference (Petkar, 2011).

In this experiment, HRV data was analyzed using the software developed by Niskanen et al. (2004). HRV variables such as mean heart beat intervals (mRR), mean heart rate - number of heart beat per minutes (mHR), standard deviation of heart rate per minute (STD), low frequency of HRV in normalized unit (LF(n.u.)), high frequency of HRV in normalized unit (HF(n.u.)) and ratio of (LF/HF) during High Stroop interference and Low Stroop interference segments were studied. LF(n.u.) is defined as LF(n.u.)= LF/(LF + HF) and HF(n.u.) is defined similarly.

The performance and response time of all subjects in the Stroop test were also calculated, presented in Figure 5. The significant differences ($p<.05$) found between Low and High Stroop interference tests indicate that Low and High Stroop interference clearly have different load effects on subjects.

Two-sided t-test was conducted between Stroop tests and relaxing state at 0.05 significant level, significant results are indicated by '*'. Table 1 shows that significant changes in HRV features are only observed in High Stroop interference, not in Low Stroop interference. LF, HF and LF/HF ratio have larger ratio changes than mRR and mHR. The study confirms that HRV indices such as LF, HF and LF/HF ratio are sensitive indicators of mental stress (Hjortskov et al., 2004; Taelman et al., 2009). Among all the HRV features, LF/HF ratio has the largest ratio changes; therefore, we use LF/HF to evaluate mental stress in design experiment.

Table 1. Results of t-test, comparing Stroop test with relaxing state (Petkar, 2011)

HRV Features	**Low Stroop Interference & Relax**		**High Stroop Interference & Relax**	
	t-test	**Ratio change**	**t-test**	**Ratio change**
Mean RR (s)	t(38) = 0.67, p = 0.5	0.02	*t(38) = 2.31, p = 0.03	0.07
Mean HR (1/min)	t(38) = 0.86, p = 0.39	0.03	*t(38) = 2.80, p = 0.01	0.08
STD (1/min)	t(38) = 1.47, p = 0.15	0.16	t(38) = 1.59, p = 0.12	0.17
LF (n.u.)	t(38) = 0.16, p = 0.87	0.01	*t(38) = 2.60, p = 0.01	0.22
HF (n.u.)	t(38) = 0.16, p = 0.87	0.02	*t(38) = 2.60, p = 0.01	0.24
LF/HF	t(38) = 0.23, p = 0.79	0.01	*t(38) = 1.97, p = 0.05	0.56

3 DESIGNER'S MENTAL STRESS DURING DESIGN ACTIVITIES

The purpose of this experiment is to study the relation of mental stress and design activities. Eleven subjects volunteered to join the experiment. All the subjects are graduate students with engineering background in the age range of 25 to 35 years old.

The experiment protocol is approved by Human Research Ethics and Compliance, Concordia University. Three devices, which are HRV (Heart rate variability), Electroencephalogram (EEG), and cameras, were used in this experiment to record the subject's physiological responses and design activities. In this article, we analyze only HRV. Result from EEG measurement is reported in a separate paper (Nguyen and Zeng, 2013).

3.1 Experiment setup

Each subject was required to perform one of the following design tasks chosen by the experimenter:

1. Design a vehicle that can transport an object between any two locations on earth within a few seconds.
2. Design a desk that helps a messy university student to keep things organized and tidy.
3. Design a house that can easily fly from one place to another place.

The experiments were conducted following the procedures below:

1. Ask the subject to relax for 3 minutes with eyes open.
2. Ask the subject to relax for 3 minutes with eyes closed.
3. Show the subject the design problem to solve. No time limit is set.
4. After the subject finishes the design:
   a. Ask the subject to relax for 3 minutes with eyes closed.
   b. Interview the subject.

All the subjects used tablet to design. On average, each designer took 45 minutes to complete the design.

3.2 Data collection and processing

Heart rate variability is recorded by Polar RS800G3. Cameras record body movement and tablet monitor (design activities). Figure 6 shows a subject's design activities and HRV data.

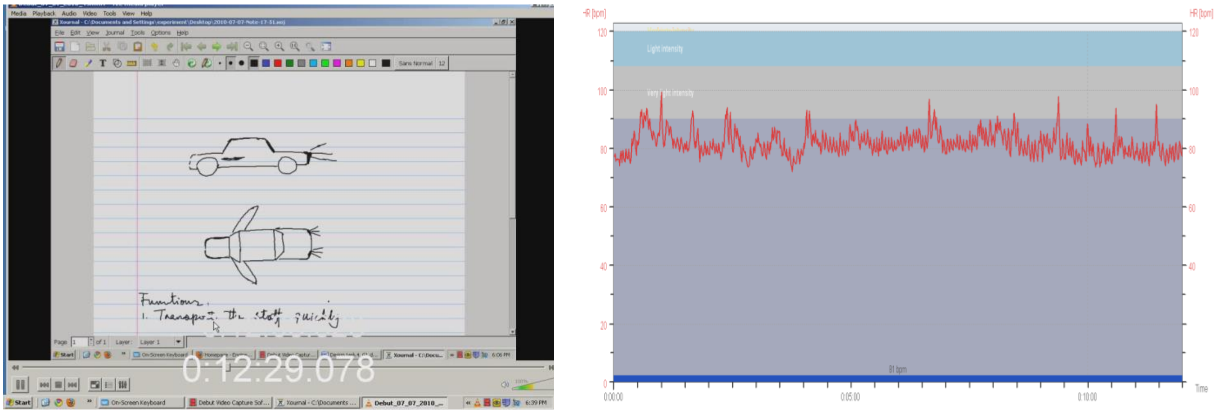


Figure 6. Video and HRV data

3.2 Data analysis

HRV data is analyzed by HRVAS (Ramshur, 2010). The interface of the software is shown in Figure 7. The input is R-R intervals in the unit of seconds.

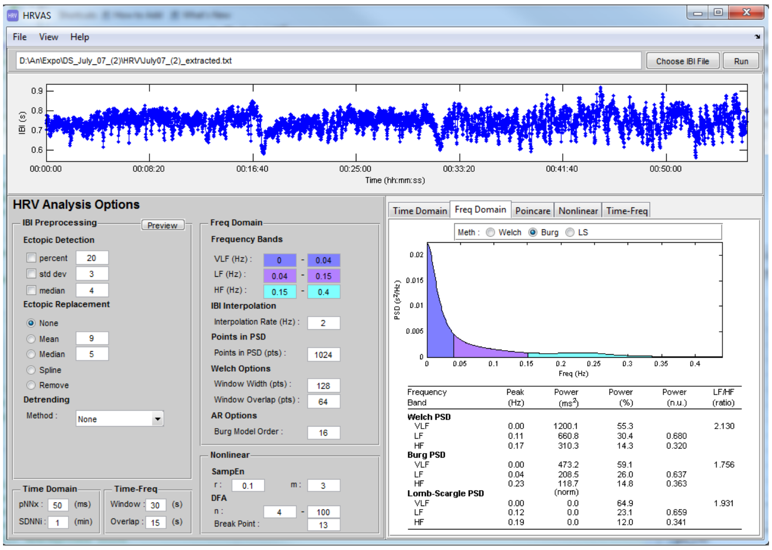


Figure 7. Interface of HRVAS

In this analysis, LF/HF ratio was computed for each 0.5 second interval. For each subject, the data analysis was conducted in three steps:

– Step 1: The design process was segmented based on designer's activities observable from the tablet screen. An example is shown in Table 2. Table 2 shows four actions observed from the tablet: write, pause, write, and pause. These actions result in four segments: 120, 121, 122 and 123.
– Step 2: The LF/HF ratio was then calculated for each segment as shown in Eq. (1).

$$R_A = \frac{\sum_{i=1}^{n}(t_i \times r_i)}{\sum_{i=1}^{n} t_i} \qquad (1)$$

where R_A is the LF/HF ratio for segment A, r_i is LF/HF ratio for duration t_i and n is the number of 0.5-second LF/HF components in segment A. For instance, the LF/HF ratio of segment X in Figure 8 is:

$$R_X = \frac{0.5r_1 + 0.5r_2 + 0.5r_3 + 0.02r_4}{1.52}$$

Table 2. An example of four segments

Segment No.	Start	End time	Behaviors observed from the video	Description
…				
120	00:52:41.583	00:53:02.803	Write	Write solutions
121	00:53:02.803	00:53:15.13	Pause	Lift pen Scrub eyes
122	00:53:15.13	00:53:35.160	Write	Write solutions
123	00:53:35.160	00:53:41.760	Pause	Check if there is enough space to write
…				

– Step 3: Finally, all the LF/HF computed in Step 2 were clustered into seven levels by k-means. K-means was applied twice the number of segments. The calculation was done in Matlab R2011b.

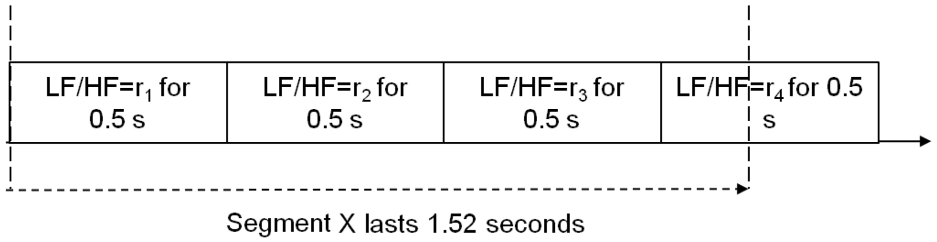


Figure 8. LF/HF ratio was computed for each 0.5 seconds

3.3 Result

Out of eleven subjects, only seven subjects are chosen for the analysis due to problem with EEG signals (even though we do not analyze EEG signal in this article). The number of segments at each mental stress level for all seven subjects was calculated. The results are shown in Table 3 and are plotted in Figure 10.

Due to the small number of subjects, the Friedman test was used to check if there are differences between mental stress levels. The result of Friedman test is shown in Figure 9.

Table 3. Number of segments at different mental stress levels

STRESS	SUBJECT 1	SUBJECT 2	SUBJECT 3	SUBJECT 4	SUBJECT 5	SUBJECT 6	SUBJECT 7
LEVEL 1	72	91	95	295	12	51	27
LEVEL 2	30	73	53	204	14	70	34
LEVEL 3	19	41	37	114	11	47	21
LEVEL 4	8	22	15	31	7	21	25
LEVEL 5	5	3	6	24	3	15	13
LEVEL 6	4	2	6	6	1	2	16
LEVEL 7	1	1	2	2	1	1	4

Table 4. Percentage of segments at different mental stress levels

STRESS	SUBJECT 1	SUBJECT 2	SUBJECT 3	SUBJECT 4	SUBJECT 5	SUBJECT 6	SUBJECT 7
LEVEL 1	0.518	0.391	0.444	0.436	0.245	0.246	0.193
LEVEL 2	0.216	0.313	0.248	0.302	0.286	0.338	0.243
LEVEL 3	0.137	0.176	0.173	0.169	0.224	0.227	0.150
LEVEL 4	0.058	0.094	0.070	0.046	0.143	0.101	0.179
LEVEL 5	0.036	0.013	0.028	0.036	0.061	0.072	0.093
LEVEL 6	0.029	0.009	0.028	0.009	0.020	0.010	0.114
LEVEL 7	0.007	0.004	0.009	0.003	0.020	0.005	0.029

Friedman's ANOVA Table

Source	SS	df	MS	Chi-sq	Prob>Chi-sq
Columns	187.357	6	31.2262	40.35	3.88094e-007
Error	7.643	36	0.2123		
Total	195	48			

Figure 9. Friedman's ANOVA Table

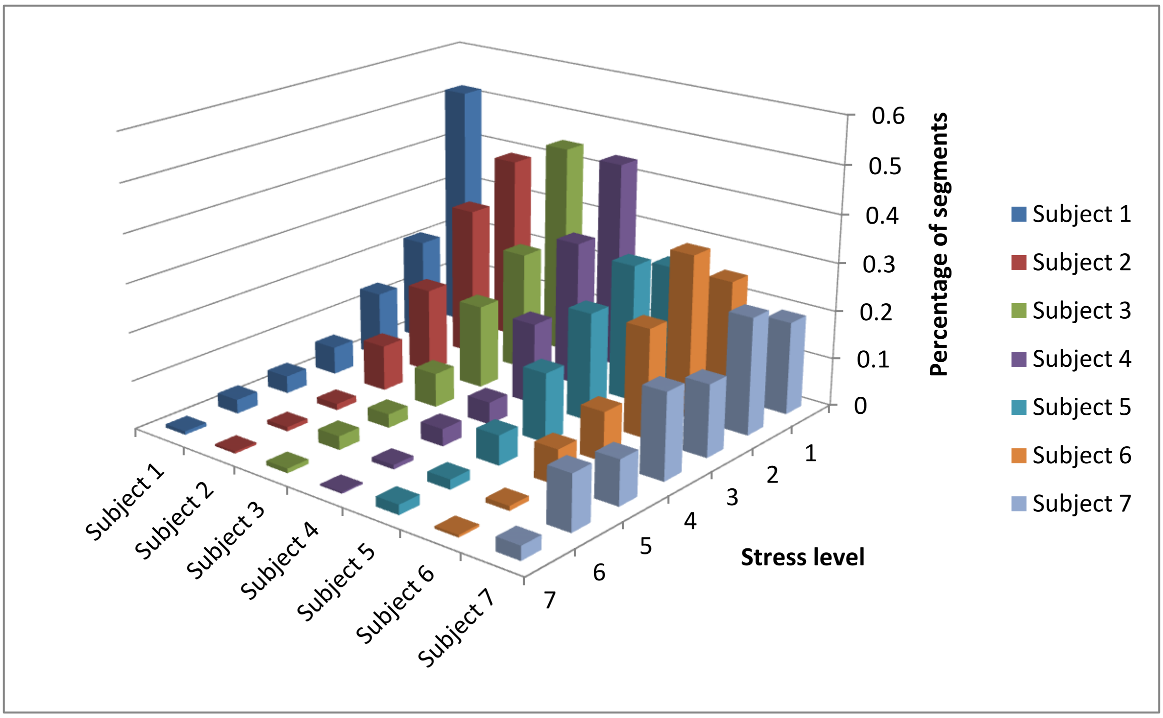


Figure 10. Percentage of segments associated with stress levels

From Friedman test, we conclude that there are significant differences in number of segments associated with mental stress levels ($p < .05$). The follow up test is the one sided Wilcoxon signed rank test. This test is to check if the number of segments at low stress level is greater than the number of segments at high stress level. The result of Wilcoxon-test is shown in Table 5.

Table 5. Result of Wilcoxon signed rank test

BETWEEN LEVELS	TEST STATISTICS	BETWEEN LEVEL	TEST STATISTICS
1,2 (n.s)	21	3,4	26.5
1,3	28	3,5	28
1,4	28	3,6	28
1,5	28	3,7	28
1,6	28	4,5	28
1,7	28	4,6	28
2,3	28	4,7	28
2,4	28	5,6 (n.s)	17(n=6)
2,5	28	5,7	28
2,6	28	6,7	21(n=6)
2,7	28		
(n.s): non-significant			

Table 6. Activities during high level mental stress

	Simplified description	Level		Simplified description	Level
Subject 1	Pause	6	Subject5	Write	6
	Erase	6		Try to delete a word	7
	Modify sentences	6	Subject 6	Pause	6
	Pause	7		Scrub nose	6
	Fix a grammar mistake	6		Go back to the design solution, move slightly	7
Subject 2	Pause	6	Subject 7	Draw	6
	Erase	6		Move slightly	6
	Pause	7		Write	6
Subject 3	Draw	6		Move slightly	7
	Pause	6		Move slightly	7
	Pause	6		Write	7
	Fix a grammar mistake	6		Write	6
	Browse the internet	6		Move slightly	6
	Close an application	6		Move slightly	6
	Browse the internet	7		Write	6
	Choose an online article and read	7		Erase	6
Subject 4	Pause	6		Erase, scroll up	6
	Open a new page	6		Pause	6
	Try to erase the figure quickly	7		Scroll down	6
	Erase	6		Write	6
	Go to the "side view" page	6		Write	6
	Erase	6		Draw	6
	Go back to the question	7		Pause, move slightly	6
	Go back to the design page	6		Scroll down	6
				Draw	7

In Table 5, most of the number of samples is seven except for stress level 5, 6 and 6, 7 because one sample is deleted in those two samples due to calculation in Wilcoxon test. The critical value for $n = 7$ and $\alpha = 0.05$ is 25, and for $n = 6$, the critical value is 19. As a result, most stress levels are different between each other except for level 1and 2, and 5 and 6.
An example of design activities at stress levels 6 and 7 is displayed in Table 6.

3.4 Discussions

According to Figure 9 and Table 5, we conclude that there exist significant differences in number of segments associated with mental stress levels. The number of design activities generally decreased with the increase of stress levels. This may imply that the higher mental stress is, the fewer design activities are performed. As seen in Table 6, we do not find any correlation between types of design activities and high mental stress levels.

4 SUMMARY AND FUTURE WORK

In this paper, we reviewed the Stroop Test previously conducted in our lab to confirm the use of LF/HF ratio derived from HRV as a valid indicator of mental stress. In our cognitive experiment on design activities, designers' HRV data was recorded along with design data. The design data was then segmented based on designer's activities. For each segment, LF/HF ratio was computed and then clustered into seven levels using k-means. According to the results, it was found that most of the activities in a design process were performed under low levels of mental stress. The design activities reduce as the level of mental stress increases. However, we found no correlation between types of design activities and levels of mental stress.

The research presented in this paper only focused on quantifying mental stress using HRV. However, electroencephalogram (EEG), eye gaze and some other approaches can also be applied into mental stress and performance quantification. In the future, we will increase the number of subjects.

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