EFFECTS OF WORKING MEMORY DEMAND ON PERFORMANCE AND MENTAL STRESS DURING THE STROOP TASK

Harshad Chandrakant Petkar

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By: HarshadChandrakantPetkar

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Signed by the final examining committee:

Dr. Z. Tian ____________________ Chair

Dr. G. J. Gouw ____________________ Examiner

Dr. C. Wang ____________________ Examiner

Dr. Y. Zeng ____________________ Supervisor

Approved by ____

Director

Concordia Institute for Information Systems Engineering

__________ 20 _______ ____

Dr. R.A.L. Drew, Dean

Faculty of Engineering and Computer Science

Abstract

EFFECTS OF WORKING MEMORY DEMAND ON PERFORMANCE AND MENTAL STRESS DURING THE STROOP TASK

Harshad Chandrakant Petkar

Demands on working memory are associated with mental stress, but little is known about the underlying connection between the two. The primary purpose of this study was to quantify individual mental stress, and to monitor heart rate variability (HRV) during high and low working memory (WM) demands influenced by Stroop interference. Another aim was to quantify the performance and response time during the Stroop task and observe their trends during high and low (WM) demands. Finally, the third goal of this thesis was to predict the relationship between mental stress and performance. To this end heart rate was recorded both at rest and while performing the Stroop task. High and low WM demands were obtained by increasing the level of Stroop interference. The response time and performance were calculated for each difficulty level of the Stroop task, as well as during high and low WM demand. The power spectral components HF, LF, LF/HF and the time domain Mean R-R (S), Mean HR (1/min), were used as the components of HRV in the analysis. The results indicated that all the components of HRV examined were sensitive to WM demands. The HF and Mean R-R (S) components decreased with an increase in WM demands from the baseline values. The Mean HR (1/min), LF and the LF/HF ratio increased with increase in demands. Overall, the results indicated a reduction in HRV when higher order cognitive tasks were performed. The response time increased with WM demands. The performance in the Stroop task was decreased with an increase in WM demands. The results also indicated that an increase in WM demand correlates with an increase in an individual's stress level, and a decrease in performance level.

The present thesis contributes to the ongoing analysis of human computer interaction in the laboratory environment, and its effects on the autonomic nervous system. It is recommended that future research be conducted at the workplace to better understand the relationship between human computer interaction and mental stress levels.

Acknowledgements

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Dedicated To

My Father

and

My Family

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1. Introduction

Stress due to human computer interaction is associated with an increased risk of physiological arousal, somatic complaints, especially of the musculoskeletal system, and mood disturbances particularly anxiety, fear and anger [1]. Mental stress is induced by an imbalance between external demands and an individual's ability to meet them [2]. Due to high workload, high work pressure, diminished job control tasks that are monotonous, and poor supervisory relationships, many stressors of human computer interaction are developed [1]. Long term exposure to adverse mental stress affects the nervous system and may severely affect the performance of an individual at work. The demand/control model of job strain suggests that jobs with high demand, low control, and low social support are stressful [3]. Shift work, human factors, and ergonomics are also closely associated with mental stress. There is substantial evidence that heart disease is associated with excessive work demand, therefore assessing heart rate activity can assist in assessing occupational risks [4].

Unreasonable job demand with tight deadlines, lack of social support, lack of participation in decision making are some common stressors among working professionals [5]. Long working hours and monotonous work are also associated with the mental stress. The influence of mental stress on various physiological functions like blood pressure, heart rate, and catecholamine and cortisol secretion are well documented [6]. However, these physiological responses serve not only as indicators of stress, but may also be a possible link between psychosocial stress and performance of an individual when demands on working memory are increased [7]. Considerable amount of changes in physiological parameters were observed when demand on Working Memory (WM) was increased while performing cognitive tasks [7].

Quantification of stress has important applications in medicine and psychophysiology. Since stress levels cannot be measured directly, stressful events were generated as part of the study in order to annotate and relate their response to the physiological signals. A stressful event is generated by applying a stress stimulus in the interaction environment of the subject under observation. The physiological signals monitored over the subject displayed strong correlation with the changes in his or her emotional behavior. The physiological signals monitored included HRV (heart rate variability), galvanic skin response, eye related activity, brain activity, blood pressure, and other variables. It is difficult to assess an individual's mental capacity in order to determine his/her level of competency. A comprehensive assessment of an individual's wide range of cognitive abilities and specific knowledge skills was assessed in the study using the neuropsychological model [8]. Mental capacity was assessed using several tests and interview techniques with a purpose of stimulating contribution in various mental tasks. Working Memory Capacity (WMC) is the ability to actively hold information in the mind needed to do complex tasks such as reasoning, comprehension and learning. It has been observed that individuals with low WMC committed more errors than individuals with high WMC, while performing high-order cognition mental tasks, such as the Stroop test [9].

1.1 Purpose and Motivation

The study of mental/emotional stress is of great importance in human-computer interaction. Computerized jobs require little physical exertion, and involve more cognitive processing and mental attention [1]. If the production demands are high with constant work pressure and little opportunities for decision making, this leads to mental stress [1]. Earlier studies demonstrated that excess use of computers was correlated with greater job dissatisfaction and distress [10, 11]. The design of computerized work systems influences job design, organizational policies, management practices and career opportunities, all of which can be determining factors in psychological distress [12, 13]. As discussed earlier high mental stress affects the nervous system and may severely affect the performance of an individual at work. To reduce mental stress of computer technology several techniques were used for example proper ergonomic conditions, increased organization support, improved job content, proper workload etc. The quantification of mental stress plays an important role in modeling the relationship between mental stress and performance.

According to the Yerkes-Dodson law, shown in Figure 1, an inverted U-shaped curve correlation exists between an individual's performance and mental stress. It was observed that an optimal level of arousal led to the best performance on a given task, and an extreme level of arousal (i.e. either too high or too low) led to a decrease in performance [9]. Performance of an individual also depends on WMC, domain knowledge, and the age of an individual [8, 9, 14].

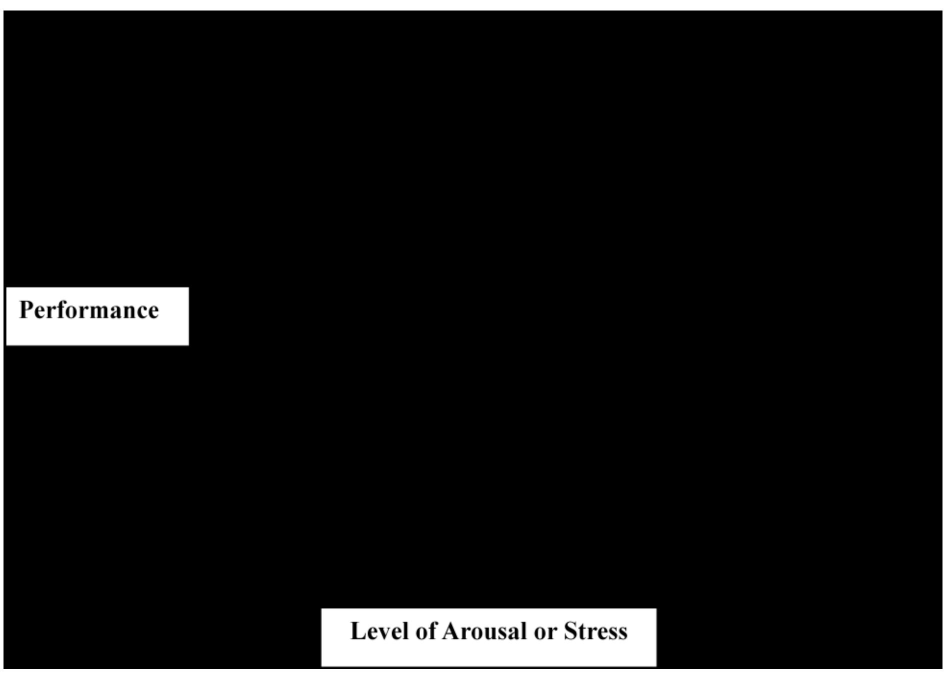

Figure 1: Stress vs. Performance, according to the Yerkes-Dodson law[15]

The purpose of this study was to quantify individual mental stress and to monitor heart rate variability (HRV) during high and low working memory (WM) demands during the Stroop task (a cognitive task). Another aim was to quantify the performance and response time during the Stroop task and observe its trends during high and low working memory (WM) demands. The third purpose was to predict the relationship between mental stress and the Stroop performance.

As mentioned earlier, a person's mental stress depends on his/her level of competence and experience related to the problem, as well as many other cognitive parameters. Different individuals will have different mental/emotional stress responses to the same problem. If a HRV activity is used to assess or quantify mental stress (which is the hypothesis for the present thesis), then different mental/emotional stresses will result in different HRV activities, leading to different Electro Cardio Gram (ECG) patterns. The ultimate aim of this thesis is to quantify the mental stress of an individual, while performing a mental task involving human computer interaction, using the HRV data.

The first step in achieving this long-term objective is to characterize the HRV data and to use it in the development of a methodology to quantify a subject's mental stress. The present research also focuses on the measurement of a given physiological variable, its characteristics, and WM. The experimental task in this research is human computer interaction task and applies to most other human cognitive activities. The physiological variable under study is the HRV (heart rate variability). The response time and performance in a mental task is also calculated. To achieve this goal the mental task used in this study was the Stroop test. The Stroop test was invented by psychologist John Ridley Stroop in 1935 [16], and has been widely used to study human psycho-physiological responses to mental stress.

1.2 Objectives and Scope

Motivated by:

(i) The variation in mental/emotional stress results in variation in the electrical activity of the heart, which in turn exhibits a variation in the ECG wave pattern.

(ii) The variation in demands on WM is correlated to task difficulty.

(iii) The Yerkes-Dodson law which states that correlation exists between mental stress to an individual's performance.

Objectives:

(i) Quantification of mental stress using HRV data.

(ii) Quantification of Performance during High and Low demands on WM.

(iii)Monitor HRV parameters during High and Low demands on WM.

Keeping in mind the long-term target of quantifying mental stress, using HRV data to monitor HRV during High and Low WM demand and qualitatively demonstrating a relationship between an individual's mental stress and his or her performance during the Stroop test, the specific tasks and scope of the project are as follows:

1. Develop a Questionnaire which evaluates the physical and psychological condition of an individual.
2. Develop a Stroop test with a methodology to calculate response time and performance.

3. Develop an experimental protocol to record heart signals during the Stroop test.
4. Design a Stroop test for Low Stroop interference and High Stroop interference segments using difficulty levels.
5. Record the HRV with a heart rate monitor for the entire experiment, i.e., Rest-Stroop test-Rest.
6. Develop an algorithm to filter raw HRV data, to segment it, and to analyze the mean value of HRV during the Rest-Stroop test-Rest phase of the experiment.
7. Analyze HRV data to calculate the average power ratio of LF/HF at standard frequency of HRV activity during high Stroop interference and low Stroop interference.
8. Develop a methodology to calculate the subject's performance and response time with the Stroop test, for each difficulty level of a Stroop task, as well as during high Stroop interference and low Stroop interference.
9. Study changes in different powers of HRV data during high Stroop interference, low Stroop interference and rest, and identify the dominant power ratio of LF/HF during various range stages.
10. Study the changes in mean values of response time, as well as performance during high Stroop interference, low Stroop interference.
11. Observe the trend in the variation of different powers, performances and response times simultaneously during high Stroop interference, low Stroop interference, rest and identify, and if possible, determine the qualitative correlation between them.

1.3 Thesis Outline

Chapter 1 summarizes the scope of the research including the importance of quantification of mental stress, specific objectives, purpose, and motivation.

Chapter 2 presents the background for analyzing the RR interval time series, importance of working memory, HRV, Stroop test and mental stress.

Chapter 3 presents the literature review which includes (i) a summary of the key findings in the field of analysis HRV during mental stress, (ii) a detailed summary of background knowledge and the relationship between the Stroop test, WM, HRV, mental stress and performance.

Chapter 4 presents a description of the HRV data analysis, experimental setup and procedure, data processing, collection and segmentation.

Chapter 5 includes the results and discussion.

Chapter 6 presents the conclusion and future work.

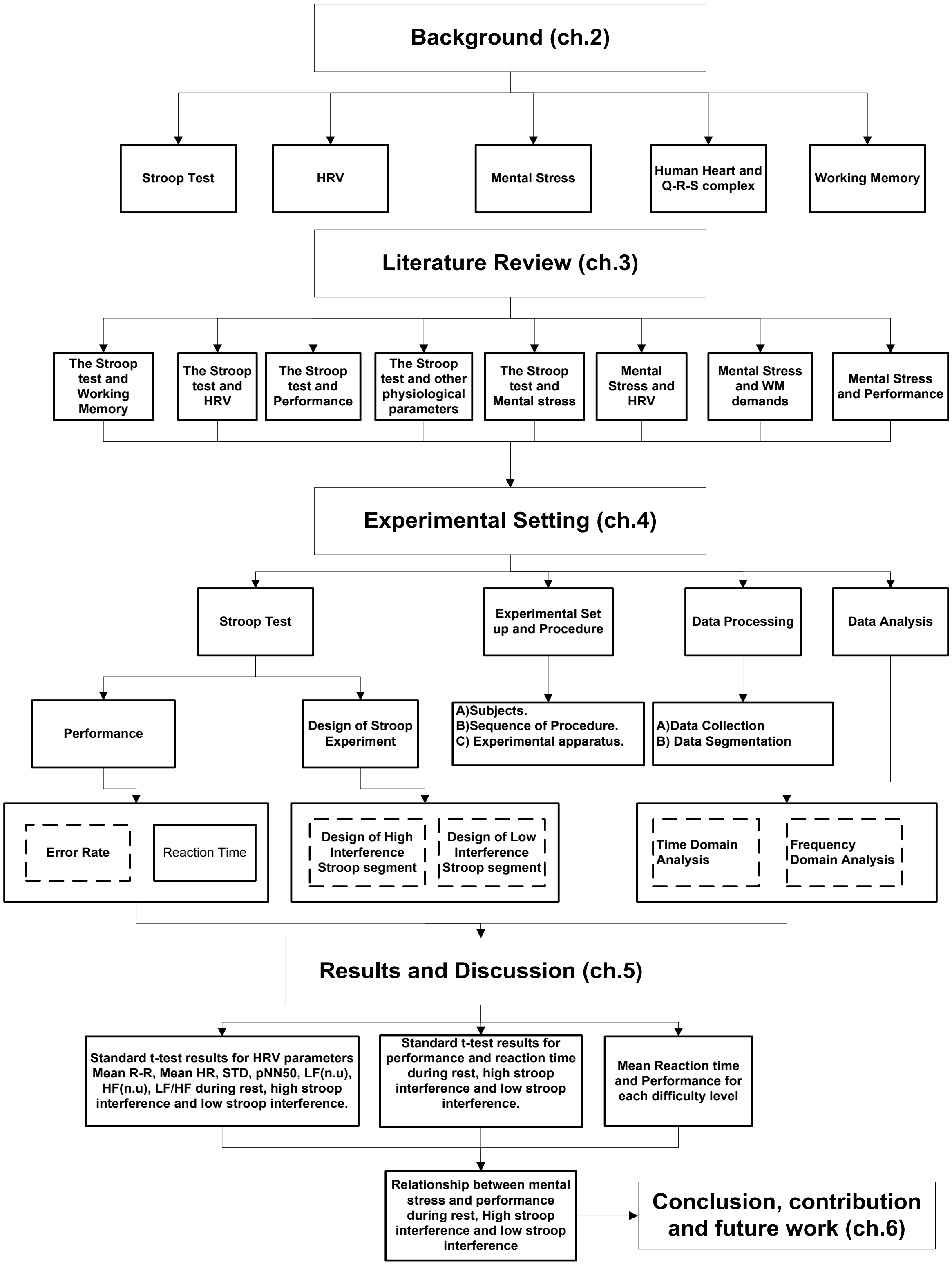

Figure 2: Thesis Overview and Organization

2. Background

A detailed survey of heart rate components, and factors affecting the HRV power spectrum was conducted, including a systematic literature survey of the studies involved in practical applications of HRV. The key details underlying the intricacies of the functioning, operation and accurate data recording from the HRV monitor were examined. In addition, this chapter includes the importance of WM and its components. The details of the above mentioned studies are described in this section. A brief review of the Stroop test and mental stress is also included.

2.1 Heart Rate Variability

Heart rate variability (HRV) is a measure of variation in heart rate. Variation in heart rate is a physiological phenomenon. In the field of psychophysiology there is a great interest in HRV. Akselrod et.al found that under the condition of acute time pressure and emotional strain, the autonomic nervous system (ANS) is triggered: the parasympathetic nervous system is suppressed and sympathetic nervous system is activated [17]. Due to the vasoconstriction of blood vessels, an increase in blood pressure, an increase in muscle tension and a change in heart rate (HR), heart rate variability (HRV) occurs. This process is known as the 'fight-or-flight' response [18]. Taelman sates that there are several methods for detecting HRV which include ECG and the pulse wave signal derived from a photoplethysmograph (PPG) [61]. Stress, along with certain cardiac diseases, and other pathologic states affect the HRV. HRV measures are calculated from the tachogram, also known as the RR interval time series. R-R intervals are generated from the QRS complex, and an HRV analysis is done from these R-R intervals. Salahuddin et.al found that heart rate decreases when the body releases acetylcholine released by the parasympathetic nervous system (PNS) [19]. They also observed that during mental or physical tasks, the sympathetic nervous system (SNS) is activated while the PNS is inhibited, resulting in an increased heart rate [19]. When the body is dehydrated there is a significant increase in the heart rate. Kamath et al. also found a change in heart rate variability as also reflected in the variation of the power ratio of Low Frequency(LF)/High Frequency(HF), and also in the peak LF frequency, when a person is standing, as compared to the supine position [20]. There is a significant reduction in the mean R-R during any mental task [19]. According to Yang et al. the noise from ECG signals and the physiological variability of the QRS complex makes the task more difficult for an accurate detection of a QRS complex [21]. They also suggested numerous filtering methods which include non linear filtering with a specific threshold, time recursive prediction techniques, as well as wavelet transforms to remove artifacts generated by electrodes, motion artifacts and baseline drift [21]. The various statistical properties of the HRV for a stress test have been compared for analysis of mental and physical tasks by making use of an inter-beat interval (N-N) [22]. The most widely used methods are time domain and frequency domain methods. A time domain method includes a standard deviation of an N-N interval (SDNN), a standard deviation of the average N-N intervals (SDANN), the square root of mean squared difference of successive N-Ns (RMSSD), a pair of successive N-N that differ more than 50ms (NN50), and a proportion of NN50 divided by total number of NN (pNN50) [22]. In frequency domain analysis, a power spectral density (PSD) of the R-R series is calculated. Methods for calculating a PSD estimate may be divided into non parametric [e.g. Fast Fourier transform or Wavelet transform] and parametric [e.g. based on auto regressive (A.R) models] models. Malik et al. suggested that the power spectrum yields three major frequency bands: a very low frequency band (VLF, 0-0.04Hz), a low frequency band (LF, 0.04-0.15Hz) and a high frequency band (HF, 0.15-0.4Hz) [23]. According to Kamath and Fallen, the LF is associated with blood pressure control, reflecting sympathetic activity [24]. They also suggested that HF is correlated with respiratory sinus arrhythmia reflecting parasympathetic activity, and VLF is linked with vasomotor control or temperature control [24].

Although researchers have previously analyzed both stressed and relaxed states of an individual, determining the HRV parameters against an increasing mental workload is nevertheless a challenge. Very little research exists in this specific area. This thesis focuses on providing an analysis of major HRV parameters, such as Mean R-R, Mean H-R, LF, HF, and the ratio of LF/HF during a mental task. In this study, an attempt was made to analyze the changes in HRV parameters, with an increase in WM demand (i.e., by increasing the mental workload). There are various ways to record, filter and analyze HRV data. In this thesis, a POLAR S810, as well as HRV analysis software was used to record and calculate the data based on time and frequency domains, then used for analysis for which a standard t-test.

2.2 The Human Heart and QRS complex.

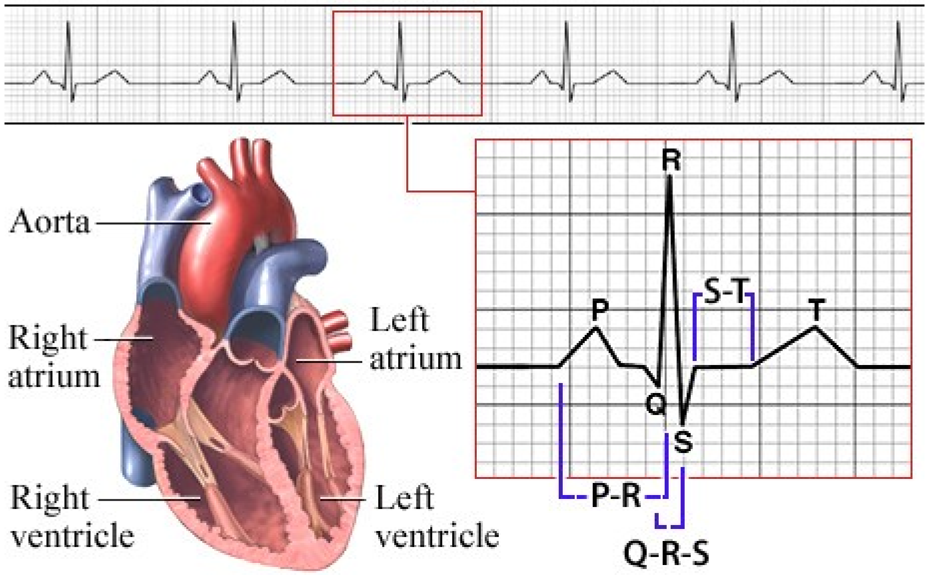

Figure 3: Human heart, QRS complex and its components [25]

The anatomy of the human heart as illustrated in Figure 3 represents a 4-chambered muscle, which pumps blood throughout the body. The smaller two upper chambers together are called atria and the larger two lower chambers are the ventricles. The blood-flow in the four chambers of the heart runs in sequence from right atrium to right ventricle, followed by left atrium to left ventricle. The right atrium receives the deoxygenated blood from the body. Regarding the two large veins: the superior vena cava returns blood from the head, neck, arms, and upper portions of the chest, and the inferior vena cava returns blood from the remainder of the body. The right atrium pumps this blood into the right ventricle, which, a fraction of a second later, pumps the blood into the blood vessels of the lungs. The lungs serve to oxygenate and replenishes the blood. After passing the lungs, the blood enters the left atrium, which pumps it into the left ventricle. Further from here, the blood is pumped back into the circulatory system of the body via the aorta, which is the largest artery in the body. The pressure generated by the left ventricle to keep blood moving throughout the body is measured as blood pressure. Oxygen supply to the heart muscles is performed by a group of arteries called coronary arteries that begin less than one-half inch of the aorta.

The electrocardiogram (ECG) is a measure of electrical activity of the heart muscles and is represented as a series of graph-like tracings, or waves, called QRS complexes. The shapes and frequencies of these tracings reveal abnormalities in the heart's anatomy or function. The heart normally beats between 60 and 100 times per minute, with many normal variations. Salahuddin et.al found that the HRV represents the variations in the beat-to-beat alteration in the heart rate, and is a representation of a dynamic interplay between the sympathetic and parasympathetic branches [19]. They also found that the analysis of HRV depicts the activity of the autonomic nervous system that may be indirectly related to mental stress [26]. The HRV features can be extracted by detecting QRS complexes from ECG signals.

In HRV analysis, the heart rate as a function of time or the intervals (R-R) between successive QRS complexes has to be determined. The interval between two consecutive R waves is the inverse of the heart rate. The R-R intervals are the intervals between two consecutive R peaks. Figure 3 illustrates the QRS complex and its components. The cardiac cycle (heartbeat) consists of a P wave, a QRS complex, a T wave, and a U wave. The Q, R and S waves occur in rapid succession and appear as a single event, thus being normally considered a whole complex. The Q wave reflects the downward deflection after the P-wave. The R-wave is an upward deflection and the S wave is any downward deflection after the R-wave. The duration, amplitude, and the morphology of the QRS complex are useful in diagnosing cardiac arrhythmias. The baseline voltage of the ECG is known as the isoelectric line. Typically, the isoelectric line is measured as the portion of the tracing following the T wave and preceding the next P wave. The P wave during normal a trial depolarization directs the main electrical vector from the SA node towards the AV node, and spreads it from the right atrium to the left atrium.

Electrical waves are measured by placing electrodes at specific points on the skin. These electrical waves measure HRV via a personal monitoring device called a *heart rate monitor*. Changes in HRV indicate a direct correlation with mental stress. According to Wenhui.L et.al it has been extensively investigated in psychology, computer vision, physiology, behavioral science, ergonomics and human factor engineering [27]. The quantification of mental stress by making use of heart rate monitors is of prime interest among researchers. The modern version of heart rate monitors comprises of two elements: a chest strap transmitter, and a wrist receiver. This model is portable and has an elastic electrode belt, helping to detect R-R intervals more accurately. In this study, the Polar RS810 monitor (Polar Electro inc., Lake Success, NY), a portable instrument that transmits data wirelessly, was used to record data.

2.3 The Stroop Test

The Stroop test has been widely used to study human psycho-physiological responses to mental stress. The Stroop test is a presentation of interference in the response of a task. According to Renaud and Blondin this tool is widely used for various cognitive-perceptual processes [28]. According to Williams et.al, it is a color naming task, and is a classical paradigm in neuro-physiological assessments of mental fitness [29]. The Stroop paradigm is comprised of three groups: neutral, congruent and incongruent. In the Stroop test, the stimulus word is displayed in a color which is either similar to or different from the word it refers to. Neutral stimuli are those which are in the same text or color as is displayed. In congruent stimuli color and the color name are the same. For instance, the word “RED” is written in “RED”. The incongruent stimuli are those where the color of the word never matches. For example, the word “RED” is written in “BLUE”. In this test, the subject has to select an answer corresponding to the color of the word. For example, if given a GREEN word in BLUE color, the subject has to select the word BLUE from the answer list. When the color and the word are in conflict, for example when the GREEN word is in BLUE color, the subject’s response is slower and less accurate than when the color and the word match. For instance, when the BLUE word is in BLUE color. The slow response due to a high incongruence level results in the Stroop effect, or Stroop interference. The Stroop effect demonstrates the response time of the task. The Stroop task has been employed to study attention and brain imaging[30]. Salahuddin et.al used the Stroop test as a stress stimuli to analyze HRV, a quantitative marker depicting the activity of autonomous nervous system(ANS) [19]. William et.al. found that it can also be used to investigate the effect of emotions on interference [29, 31]. It is used to study the relationship between the speed of processing, WM and cognitive development in various domains. In this thesis, a Stroop test comprises 6 difficulty levels, from which the High Stroop Interference and Low Stroop Interference segments were created to induce high WM demand and low WM demand respectively.

2.4 Mental Stress

According to Smith and Sainfort, stress results from an imbalance between various elements of a work system [32]. They found that psychological and physiological reactions are produced due to an imbalance in the work system [32]. Mental stress causes memory weakening, leading to forgetfulness and difficulty in focusing on the activity at hand. Excess mental stress also leads to physiological problems such as muscle aches, heart disease, obesity, arthritis, depression, and other diseases. Lazarus defined stress as physiological changes resulting from emotions due to perceptions of threats [33].The physiological and behavioral changes in an individual are influenced by a cognitive appraisal of an individual. Mental stress is a normal physical response to both internal and external events that make people feel fatigued or threatened. After a certain point, it may also cause major damage to the nervous system and may severely affect a person's productivity in work, as well as affecting his or her quality of life. Work related illnesses are directly or indirectly related to stress [34] .According to Sanders, stress arises when the effort mechanism fails or is overloaded [35]. In this study the physiological changes are analyzed due to mental stress by increasing demand on WM.

2.5 Working Memory

Working Memory is an important concept in cognitive psychology and cognitive neuroscience. According to Pezzulo, the main functions of WM is to temporarily maintain, store and manipulate information which supports human thought processes for a brief period of time [36]. Ricks and Wiley suggested that WM focuses on complex cognitive task that require willingness, awareness and attention. These include reasoning, planning, manipulation of linguistic information, and the executive control and coordination of perception and action [9]. The important features for working memory as shown in Figure 4 are: it operates for a few seconds, temporarily stores the data, and manipulates and performs information processing functions like encoding, storing and retrieving data. Individual differences in WMC may affect performance [37]. Some people have more of this construct than others. Rosen et.al found WMC to be an important factor of an individual's ability to retrieve items from his/her long term memory [38], and his/her ability to resist any interference during processing [9]. WMC is comprised of short term memory (STM) and controlled attention (CA). Baddley et.al refer to STM as short-term storage of information that does not entail the manipulation or organization of material held in memory [39]. Norman and Shallice suggested that CA to be the supervisory attention system involved in handling conflicts among different task goals, external stimuli, and previously learnt response schemes [40]. On the other hand, working memory refers to the structures and processes used for temporary storage and manipulation of information.

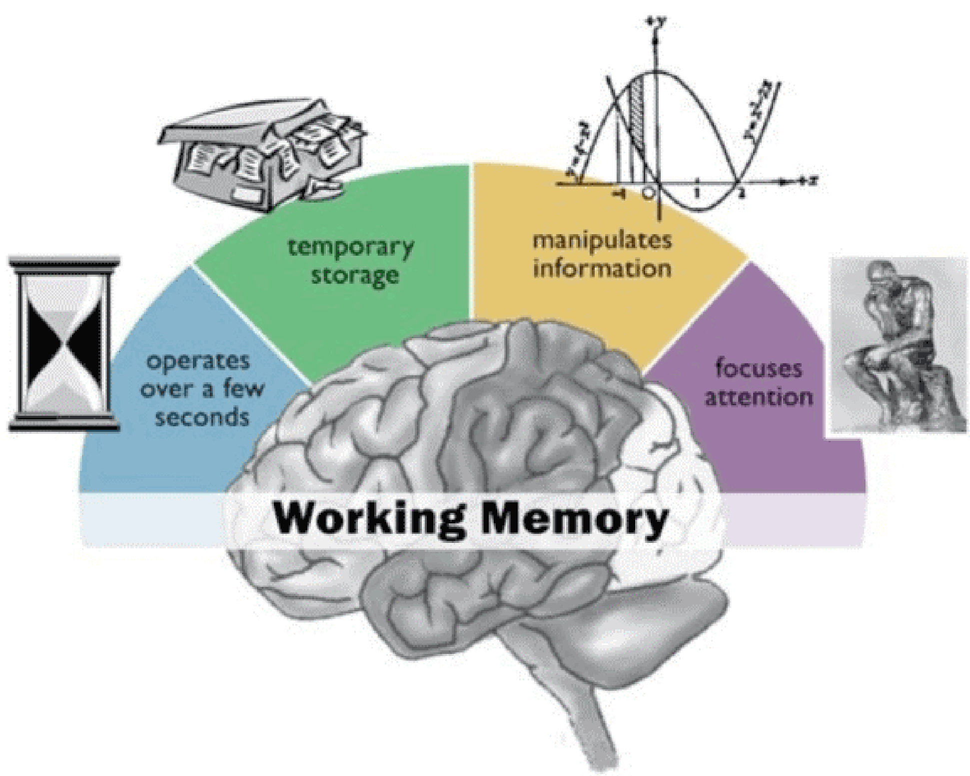

Figure 4: Working Memory and its Components [41]

The multi component model as proposed by Baddeley and Hitch is the most commonly used model to represent working memory [39]. It emphasizes the dynamic interaction of memory maintenance and attention control in complex cognitive tasks [39, 42]. While performing the Stroop task, an attentional component of the WM plays a very important role. According to Kane and Engle the attentional process is engaged when the goal to perform the Stroop task is sufficiently maintained in active memory [9].

3. Literature Review

3.1 The Stroop Test

Human-Computer interaction involves heavy mental activities all the work places. Hence a tool to measure or quantify the mental activity becomes very important. During any mental activity the physiological variables also change. Parameters of the autonomic nervous system such as pupil diameter, galvanic skin response and heart rate change because of excessive mental workload, mental stress or fatigue. In this study a Stroop test was used as a cognitive stressor tool in a simulated human-computer interaction environment in laboratory. The Stroop test is widely used as a psychological or cognitive stressor [57]. The Stroop test is presentation of interference in the reaction of the task. This test is controversial about the exact mechanism responsible for this test, however, this tool is widely used for various cognitive-perceptual processes. In the past, some research has been directed towards measuring HRV during Stroop test and analyzing it using power spectral analysis. Similarly some research is also done to study Stroop interference effects on WM, mental stress and performance. The key findings are summarized below.

3.1.1 The Stroop Test and Working Memory

In cognitive psychological studies, the Stroop test is most widely used in cognitive task. Kane and Engle used the Stroop task to examine the interaction of WM, active goal maintenance, and blocking or inhibition of competing stimulus representations and action plans (see Figure 5.) [9] They found that WMC predicts Stroop interference [9]. Many studies indicate a significant

Stroop correlation with intelligence and a significant Stroop deficit in patients with pre-frontal cortex (PFC) damage [43-45]. According to Kane and Engle continued presentation of incongruent or congruent trials minimizes WM involvement, as task demands remain consistent across trials. They found the relation between WMC and Stroop interference is determined when the demand of WM is increased by presenting congruent trials in which color and words match in addition to incongruent trials, or vice versa. Lavie et.al found that the involvement of WM is more in selective attention tasks [46]. According to Conway et.al. individual differences in working memory span correlate with performance in selective attention tasks [47]. Higher order cognition also affects the measure of working memory (response time) of a Stroop task. The current study focuses on evaluating the relationship between performance of the Stroop task and higher working memory demand. Cohen et.al found that group differences in Stroop interference arise from the ability, or inability to keep the task goal sufficiently active [48]. In this thesis we predict that the physiological arousal or activation associated with Stroop performance reflects the additional demands on WM imposed by color-word interference.

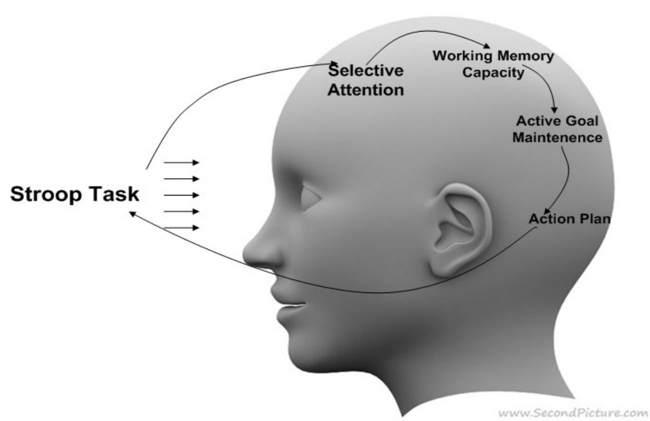

Figure 5: The Stroop Test and Working Memory[9]

3.1.2 The Stroop test and HRV

The Stroop test has been widely used to study human psycho-physiological responses to mental stress. The Stroop test activates the anterior cingulated cortex (ACC) [26]. It induces changes in autonomic responses of SNS and PNS, which relate to physiological measures, such as changes in HRV [49]. The Stroop test has been utilized as a psychological and cognitive stressor that induces emotional responses, heightens autonomic reactivity, and increases heart rate as well as the number of natural killer cells. The availability of mobile, wireless and portable ECG sensors provides a personalized heart monitoring system for high risk cardiac patients. Elliott showed that pacing a Stroop test resulted in substantial heart rate accelerations [50]. According to Patrice et al. Stroop performance was accompanied by heightened HR levels during the performance of a Stroop task [28]. Thackray and Jones showed that heart rate and respiration rate were increased due to the higher pace of a Stroop task [51].

3.1.3 Stroop test and Performance

The increase in time taken to perform high incongruence level as compared to congruent task results in a Stroop effect, known as Stroop interference. In the research of Renaud, Stroop, performance was examined as the presence of color-word interference [28]. The pacing of task execution, and response time during task execution play an important role in the quantification of performance [28]. The speed of task pacing, whether a self paced condition, a relatively slow, externally paced condition and a relatively fast, externally-paced condition also considered for quantification of Stroop performance [28]. Stroop performance is also calculated in the presence of interference levels [28]. Accuracy (i.e., the incorrectness ratio) is also calculated to evaluate the performance of a Stroop task [52]. The effects of Stroop performance can determine the relationship between attention and concomitant physiological activity [28]. More effort has to be exerted to cope with an increasing work load if the speed of the task is increased, since actual time available for processing diminishes.

3.1.4 The Stroop test and other physiological parameters

Other than HRV, many other physiological signals are studied during the Stroop test. These include EEG, skin conductance, pupil diameter, and others. Liotti et al. suggested that the anterior cingulated cortex is initially activated by the Stroop test, followed by the activation of the left temporal-parietal cortex [53]. Schack et al. studied the instantaneous EEG coherence analysis during the Stroop test, and they found that the 13-20 Hz frequency band is sensitive to the discrimination between the congruent ("red" written in red color) and the incongruent task ("red" written in any other color). They also found higher coherence in left frontal and left parietal areas during the performance of incongruent, rather than congruent tasks [54]. Salahuddin and Kim measured galvanic skin resistance and finger temperature. It was observed that skin conductance was increased during the Stroop test, while finger temperature decreased. From these results they concluded that the Stroop test possesses the capacity to produce cognitive stress [55]. Siegle et al. found that pupil dilation was larger in an incongruent task than in the congruent task, the pupil dilation reflected the cognitive load of the task [56].

3.1.5 The Stroop test and Mental stress

The Stroop task is widely used as a psychological or cognitive stressor [57]. The Stroop task is capable of inducing emotional responses, as well as heightened levels of physiological responses, especially autonomic reactivity [57]. According to Hockey and Hamilton, changes in the physiological response pattern are considered to be reflections of cognitive patterning of stressed states [58]. According to Renaud and Blondin, patterns of physiological response could reflect the concomitant stress response if there is failure in coping with tasks demand imposed by the Stroop test [28].

3.2 Mental stress

In human computer interaction task stress quantification plays an important role to design work place and ergonomics. As mentioned earlier a person's mental stress depends on his/her knowledge and experience related to the problem and many other cognitive parameters. In the past, some research has been directed towards quantification of mental stress using different physiological variables. In this thesis the physiological variable used is HRV. Yerkes-Dodson law states the correlation between mental stress and performance. Lot of research is done in performance quantification area, for different cognitive tasks to find the correlation between mental stress and performance. Similarly some research is also done in area of mental stress induced due to increasing demands on WM. The key findings are summarized below.

3.2.1 Mental Stress and HRV

According to Langewitz et.al mental stress induced due to the inability to cope with high demands has been shown to be closely associated with ANS, exhibiting a strong inter-relationship with HRV [59]. McEwen found that high blood pressure and cardiovascular diseases have been major problems resulting from long term exposure to adverse psychosocial circumstances at work [60]. As mentioned before, stress levels can be measured indirectly by monitoring changes in physiological signals. For instance, HRV, which determines the level of stress induced in an individual, can be monitored while performing mental or physical tasks. There is a considerable decrease in mean R-R due to mental stress [61]. During rest periods there was a considerable rise in mean R-R [61]. It is also a sensitive indicator of mental stress during computer related work. The ANS (Autonomic Nervous System) is a closed-loop automatic control system which balances action and re-action processes within our body. The ANS mainly affects the heart rate. It is comprised of two subsystems, namely, the sympathetic nervous system (SNS) and the parasympathetic nervous system (PSNS). According to Salahuddin,L et.al, during emergency situations SNS is a flight or fight branch of ANS [19], the activation of which results in accelerated heart rate, constriction of blood vessels, and a rise in blood pressure. Šiška, E found that the parasympathetic branch counter-acts by inducing the relaxation response, slows down the heart rate, and decreases the force of the heart's contractions [52]. Coote, John H. suggests that when the SNS and the PSNS balance each other, the balanced state is said to be in homeostasis. They further mention that the imbalance in this controlled homeostatic state is caused by stressful disturbances. HRV differs according to genetic composition, age, and the environment during stressful conditions. As previously mentioned, HRV provides a dynamic interplay between SNS and PSNS. According to Meshkati , acute periods of mental effort result in reduced HRV [62]. Mental stress varies among individuals. In the objective of this thesis, the amount of mental/emotional stress is hypothesized to affect, and result in, variation in heart-related activity, which can in turn be used as an indirect way to quantify and assess the level of mental stress. Moreover, higher-order cognitive activity will lead to corresponding changes in heart related parameters. With the goal of achieving this objective, the HRV data was characterized, and a methodology was developed to quantify a subject’s mental stress. The characterization involved a preliminary study in order to correlate the measurement of mental stress, performance, response time and higher WM demand due to Stroop interference.

3.2.2 Mental Stress and WM demands

The Lazarus model suggests a framework for conceptualizing effects of performing WM tasks on stress [63]. Matthews et.al found that stressor effects on performance are typically dependent on the information-processing demands of the task [64, 65]. Ilkowska suggested the effects of stress on WM could be attributed to neural processes such as functioning of the prefrontal cortex [66]. Humphreys and Revelle found the depletion of a "virtual" attentional resource, as well as and changes in strategy such as mental disengagement also result in excessive stress [67]. Matthews et al. showed that high WM demands due to vigilant tasks result in a decrease in task engagement, as the person becomes increasingly fatigued and de motivated [68]. Matthews et.al found that the post-task engagement and performance were consistently positive; distress is strongly associated with performance. They also found that distress is correlated with the state of anxiety which increases along with an increase in WM demand [68].

3.2.3 Mental Stress and Performance

The transactional model of stress and emotion provides a starting point in understanding the relationship between stress and performance [63, 70]. Depending on the person and situational factors, an individual can cope with stress through task-focus, emotion-focus or avoidance. Work load factors influence coping; for example, overloading attention with very high time pressure decreased time task-focus and increased avoidance, which ultimately results in decreased performance [71]. According to Lazarus, stress is a process that unfolds over sometimes protracted time periods [63]. Test anxiety research suggests that mounting anxiety impairs test performance, leading to progressively higher anxiety and further cognitive interference [72]. As already mentioned according to Yerkes and Dodson law there is an inverted U-shaped curve correlation between performance and mental stress. An optimal level of arousal addresses the best performance for a given task, whereas performance will decrease when levels of arousal become either too low or too high [15]. Their research indicates that under the pressure of a tight schedule, complex tasks, and/or other intensive tasks, people can be stressed out; as a result, their performance may degrade or even fail [73]. Gaillard et.al found that Modest levels of supra-optimal stress can be counteracted by the performer with an increase in effort, resource mobilization, or straining [74]. Stress arises when the effort mechanism fails or is overloaded.

In the past, HRV recording was done by using heart rate monitors with robust structure, where electrodes were attached to the chest, restricting the movement of an individual. The heart rate monitor used in this experiment was portable, unlike other heart rate monitors which restrict an individual's movement, inducing additional stress in the subjects during the performance of a task. Current physiological and psychological states of the subject should be taken into consideration before beginning the recording to ensure accurate differentiation between relaxed and stressed states of an individual. In this experiment, a psychological and physiological questionnaire was developed to examine the two key aspects mentioned above. Most research centered around Stroop tests is done to calculate Stroop performance using response time, while the error rate is neglected. In this research, the error rate is taken into consideration for each Stroop segment while calculating the performance rate. The changes in physiological parameters during the stressed and the relaxed states have been researched extensively in the past, but very little research has been carried out to examine the corresponding changes in physiological parameters and performance with a mental workload increase. This thesis aims to observe the changes in physiological parameters, along with the changes in the mental workload.

4. Experimental Methods and HRV Data Analysis

This chapter includes: (i) a detailed explanation of the Stroop test and its various difficulty levels, (ii) a description of the experimental setup and experimental procedures, (iii) mathematical and physical details of the processing of the raw HRV data and its analysis, (iv) a description of the HRV instrument, data acquisition, safety and other precautions and, (v) relevant details of the subjects participating in this research.

4.1 The Stroop Test

The Stroop test was used in this thesis as a stressor/stimulus for the subject. The Stroop test, a designed computer game, presented a color word (referred to as the stimulus word) on the subject's computer screen. This color name was displayed in a color that was the same as or different from the word the stimulus word refers to. The subject had to select an answer corresponding to the color of the word. For example, with a GREEN word in BLUE color, the subject had to select the word BLUE in the answer list. Our Stroop test contained six colors: RED, BLUE, YELLOW, PURPLE, GREEN and BLACK, and six difficulty levels as listed and described below:

1) Difficulty level 1 (DL1): The stimulus word is displayed in a color to which it refers and the corresponding word in the answer list is displayed in the same color as the stimulus. For example, the stimulus word 'RED' was written in the color red and the word 'RED' in

response list was also written in the color red see Figure 6

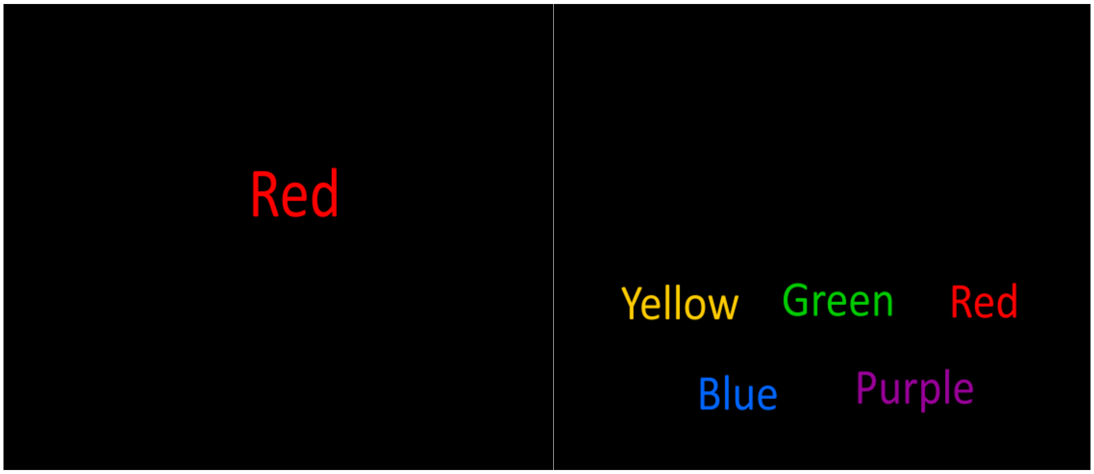

Figure 6: Difficulty Level 1 (DL2), also referred to as "Congruent- Congruent".

2) Difficulty level 2 (DL2): The stimulus word was displayed in the color to which it refers, while the corresponding word in the answer list was displayed in the color black. For example, the stimulus word 'RED' was written in the color red, and the word 'RED' in response list was written in the color black see Figure 7.

Figure 7: Difficulty Level 2 (DL2), also referred to as "Congruent-Black".

3) Difficulty level 3 (DL3): The stimulus word was displayed in a color different from the one to which it refers, and the corresponding word in the answer list was displayed in the color black. For example, the stimulus word 'RED' was written in blue, while the word 'RED' in the response list was written in black see Figure 8.

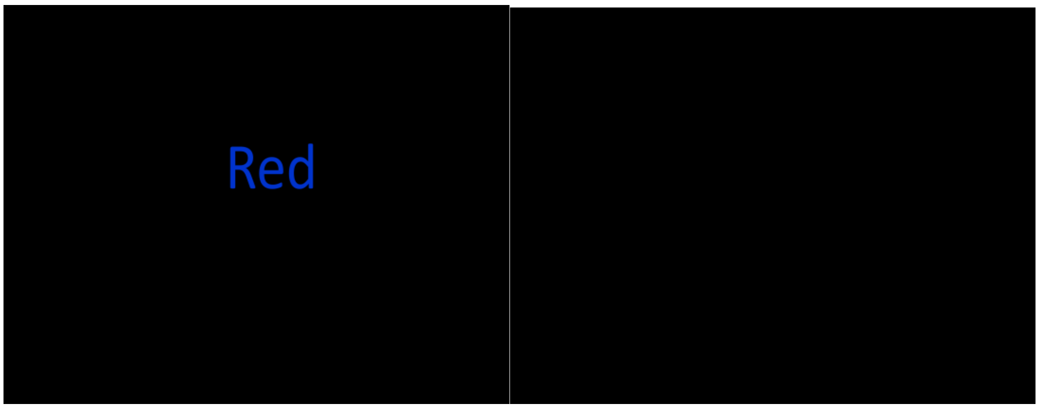

Figure 8: Difficulty Level 3 (DL3), also referred to as "Incongruent-Black".

4) Difficulty level 4 (DL4): The stimulus word was displayed in a color different from the one to which it refers, and the corresponding word in the answer list was displayed in the color it originally refers to. For example, the stimulus word 'RED' was written in blue, and the word 'RED' in the response list was written in red see Figure 9.

Figure 9: Difficulty Level 4 (DL4), also referred to as “Incongruent- Congruent”.

5) Difficulty level 5 (DL5): The stimulus word is displayed in the color to which it refers, and the corresponding word in the answer list was displayed in a color different from the one to which it refers. For example, the stimulus word ‘RED’ was written in the color red, and the word ‘RED’ in the response list was written in the color yellow see Figure 10.

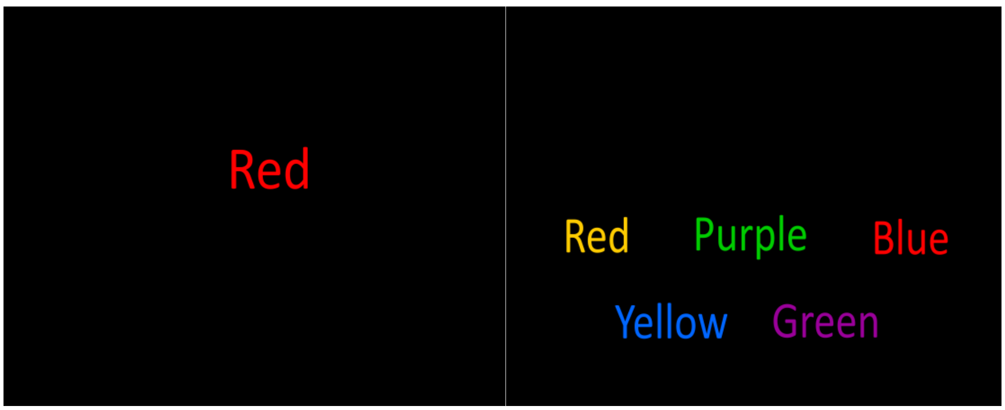

Figure 10: Difficulty Level 5 (DL5), also referred to as “Congruent- Incongruent”.

6) Difficulty level 6 (DL6): The stimulus word was displayed in a color different from the one to which it refers, and the corresponding word in the answer list was displayed in a color different than the one to which it refers. For example, the stimulus word ‘RED’ was written in green, and the word ‘RED’ in the response list was written in yellow see Figure 11.

Figure 11: Difficulty Level 6 (DL6), also referred to as "Incongruent- Incongruent".

While performing all of the above mentioned difficulty levels of the Stroop test, the subject was presented with the stimulus word for duration of 500 milliseconds. The stimulus word was followed by the response screen, which was displayed for a maximum of 1500 milliseconds, during which the subject had to click on the answer. This process of observing the test screen for 500 milliseconds and responding in less than 1500 milliseconds was referred as a Stroop task. A time interval of 1000 milliseconds was kept in between two Stroop tasks.

4.1.1 Design of the Stroop Experiment

The complete Stroop test, comprising of the above described difficulty levels, was divided into 4 profiles. Each profile consisted of 30 screens, with each difficulty level comprising 5 screens on the computer. The sequence of each difficulty level for every profile is described below:

A] Design for High Interference Stroop segments

Profile 1 – *Difficulty level 1* ➔ *Difficulty level 5*➔ *Difficulty level 2*➔ *Difficulty level 6*➔ *Difficulty level 4*➔ *Difficulty level 3*

Profile 2 –*Difficulty level 5*➔ *Difficulty level 1*➔ *Difficulty level 4*➔ *Difficulty level 2*➔ *Difficulty level 6*➔ *Difficulty level 3*

Profile 3 –*Difficulty level 4*➔ *Difficulty level 1*➔ *Difficulty level 6*➔ *Difficulty level 2*➔ *Difficulty level 5*➔ *Difficulty level 3*

Profile 4– *Difficulty level 6* ➔ *Difficulty level 1* ➔ *Difficulty level 4* ➔ *Difficulty level 3* ➔ *Difficulty level 5* ➔ *Difficulty level 2*

B] Design for Low Interference Stroop segments

Profile 1 –*Difficulty level 1* ➔ *Difficulty level 2*➔ *Difficulty level 3*➔ *Difficulty level 4*➔ *Difficulty level 5*➔ *Difficulty level 6*

Profile 2 – *Difficulty level 3*➔ *Difficulty level 2*➔ *Difficulty level 1*➔ *Difficulty level 4*➔ *Difficulty level 5*➔ *Difficulty level 6*

Profile 3 –*Difficulty level 6*➔ *Difficulty level 5*➔ *Difficulty level 4*➔ *Difficulty level 1*➔ *Difficulty level 2*➔ *Difficulty level 3*

Profile 4–*Difficulty level 3* ➔ *Difficulty level 2* ➔ *Difficulty level 1* ➔ *Difficulty level 6* ➔ *Difficulty level 5* ➔ *Difficulty level 4*

4.1.2 Performance from the Stroop test

The performance of a subject during the Stroop test was calculated by considering the average response time of the subject and the percentage of incorrect responses. The response time is the time interval between the application of a stimulus and detection of a response. The

Stroop effect demonstrates the response time of the task. In this thesis the response time was automatically calculated by software for each Stroop segment. The percentage of incorrect responses was calculated manually in an excel sheet by taking the percentage of incorrect answers for each difficulty level.

The following is a formula used to calculate the performance:

$Performance = (2 - \beta - t/T)$

Here, β is the incorrectness rate, t is the average response time over one Stroop segment, and T is the maximum response time.

4.2 Experimental setup and procedure

4.2.1 Subjects

The experiment was conducted with 20 individuals from Concordia University aged (21-30 years) from different ethnic backgrounds. Subjects included native and non-native English speakers. External stimuli, such as room lighting and environmental temperature were kept constant. All participants were asked to sign a consent form before beginning the experiment. The consent form contained all the information pertaining to the experiment. The participants also signed a physical activity readiness questionnaire (PhAR-Q), a psychological activity readiness questionnaire (PsAR-Q), a demographic form and a comfort questionnaire before starting the experiment.

The subjects were explicitly informed about the requirement of not moving and sitting straight in front of the desktop during the experiment. Before starting the experiment, the subject was allowed to perform several trials to get acquainted with the Stroop test. In total, 240 screens were used for this test, with the duration of visualizing each screen kept at 5 seconds. The duration of the Stroop test was 20 minutes, with 10 minutes of rest before and after the Stroop test. HRV watch settings were adjusted to record data at appropriate times and dates.

4.2.2 Sequence of Procedures

The experiment was performed once a day using the same procedure. The data obtained from each session was used for the current study. The procedure followed is described below:

1) The experimenter provides a consent form and the participants sign it as part of the approval process.
2) Participants provide information about his/her physical and psychological condition in the questionnaire which includes demographic information.
3) The experimenter gives verbal instructions about the heart rate monitor and guides participants around the experimental setup in the laboratory. The participant has to wear a strap/belt with a sensor around the chest. The strap is moistened before wearing for better conductance.
4) The experimenter explains the Stroop test to the participants and he/she is allowed to perform several Stroop test trials to get acquainted with it.
5) The HR monitor is turned on in order to record the heart rate.
6) During the first 10 minutes, the participant is at complete rest, followed by 20 minutes of the Stroop test and further 10 minutes of the rest state.
7) After completing all the tasks (i.e. Rest- Stroop task- Rest), the HR monitor is removed.

Note: Every individual was required to sit for the entire period of the experiment i.e. during Rest- Stroop task- Rest task without making major body movements. If the subject wanted to leave the experiment, he/she was allowed to leave at any point in time. During the rest state, the subject was allowed to sit comfortably without making any body movements. Once the participant started performing the Stroop task, he/she was not allowed to ask any questions while performing the task.

Figure 12: Experimental Setup for the HRV data recording.

The Experimental and analysis procedure is shown in figure below:

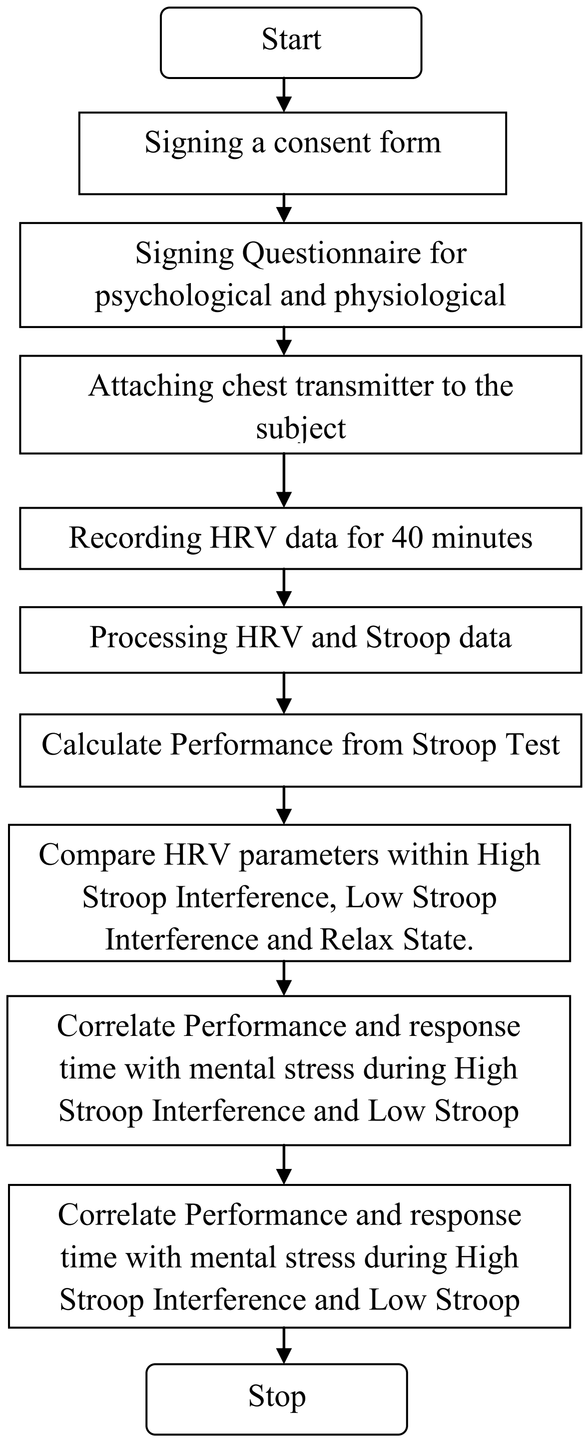

Figure 13: Experimental and Analysis procedure.

4.2.3 Experimental Apparatus

The heart rate was monitored using a Polar RS810 (Polar Electro Inc., Lake Success, NY), Figure 14, which is a portable wireless device. It included a watch, coded wear link chest transmitter and Polar Pro Trainer 5.0 software, which enabled data download via an infra red USB (IrDA) interface. POLAR S810 automatically stores consecutive R-R intervals. The data was recorded in a ASCII format text file. The analysis was done by using HRV analysis software using Matlab Compiler Suite 2.3 and the free Borland C- Builder 5.5 compiler. The frequencies used for analysis were: very low frequency (VLF, 0-0.04 Hz), low frequency (LF, 0.04-0.15), and high frequency (HF, 0.15-0.4).

Figure 14: Polar RS810 (Polar Electro Inc., Lake Success, NY)

4.3 Data Processing: Data collection and segmentation

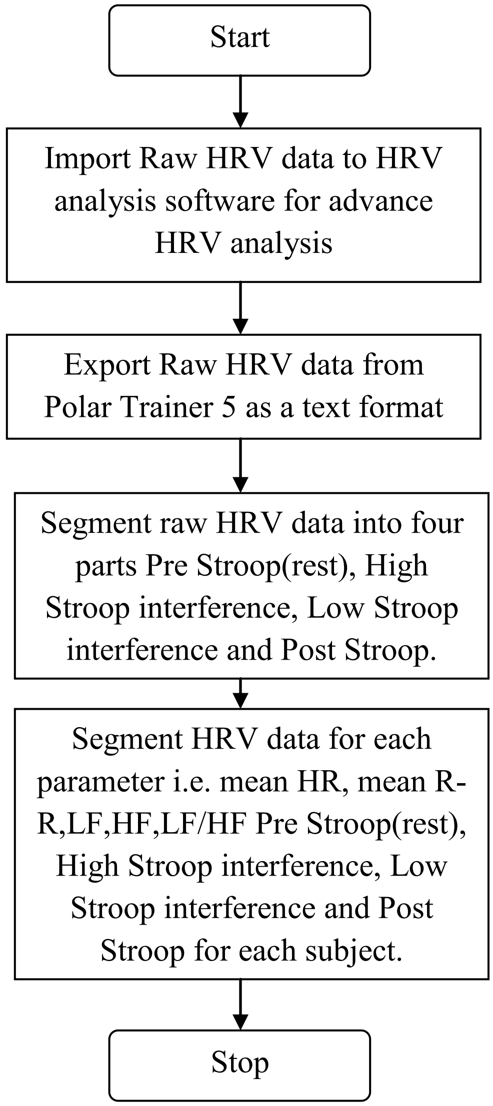

Figure 15: Segmentation scheme of HRV data collected during the Stroop test

The RR interval data in ASCII format is imported to a Matlab based software package from Kuopio University hospital and the Brain@Work-laboratory of the Finnish Institute of Occupational Health was used [22]. The program is developed in C- language using Matlab

Compiler Suite 2.3 and the free Borland C-Builder 5.5 compiler. The program is independent from Matlab.

The analysis option segments of the program user interface were divided into five subcategories: Frequency Bands, Detrending of R-R series, Interpolation of RR options, RR Sample Selection and Spectrum Estimation options.

Frequency Bands: The frequency bands used for this study were 0-0.04 Hz for VLF, 0.04-0.15 Hz for LF and 0.15-0.4 Hz for HF band.

Detrending of RR series: The detrending option was used to remove a disturbing low frequency baseline trend component. In this thesis, the smoothness prior method was used to remove first and second order linear trends.

Interpolation of RR series: RR interval time series is an irregularly time-sampled series and should therefore be interpolated prior to spectrum estimation. The program uses cubic interpolation at the default rate of 4 Hz.

RR Sample Selection: For R-R Sample selection Start and End values are edited according the requirement sample size required for analysis during an experiment.

Spectrum Estimation: The Power Spectrum density could be estimated using two methods: the traditional non parametric method that uses Fast Fourier Transformation (FFT), and the parametric method based on auto regressive models. In this thesis, the non-parametric analysis was used.

The imported data in ASCII format was segmented into four parts: Pre-Stroop (rest) for 10 min, High Stroop interference for 10 min, Low Stroop interference for 10 min, and 10 minutes for Post Stroop (rest). The start and end values were edited in the RR sample selection section. The results were saved in ASCII format and were imported to a Microsoft Excel for further inspection.

4.4 Analysis

4.4.1 Heart Rate Analysis Software

The HRV analysis software calculates the data based on time and frequency domains. The final version of the software is compiled to a stand-alone C language application using the Matlab compiler Suite 2.3 and the free Borland C-Builder 5.5 compiler, as explained elsewhere [22]. The graphic user interface (GUI) allows the user to analyze the data with ease. For this, the program generates a single page report sheet which can be exported to various file formats. The most important results of the analysis can be saved in ASCII format which can later be imported to spread sheets using Microsoft Excel. In the current study, the data was imported to an Excel sheet for further analysis.

4.4.2 Time Domain Analysis

The raw R-R interval time series were used to calculate time-domain parameters. Mean and standard deviation of the R-R intervals were calculated, which are the simplest time domain measures. The mean and standard deviation of the heart rate was also calculated.

The NN50 parameter, which represents the number of consecutive R-R intervals differing by more than 50 ms, was also used for analysis. The pNN50 was represented as the percentage of NN50 intervals. Some geometric measures, such as the HRV triangular index, were determined from the histogram of the R-R interval.

4.4.3 Frequency domain methods

Power spectral density (PSD) of the R-R series was calculated for frequency-domain analysis. The estimation of PSD was divided into two categories: *non-parametric*, based on the fast fourier transform (FFT), and *parametric*, based on the autoregressive (AR) model methods. An evenly sampled signal was obtained from the raw data by interpolating the R-R signal before the spectral analysis [22]. The first or second order linear trend was removed using de-trending. The trend could also be removed using the smoothness prior to this method [75]. In this experiment, the frequency domain features were calculated using Welch's averaging method, which is the simplest and most commonly exploited technique for spectral analysis. It is widely used because of its computationally simple algorithm for spectral analysis. It decomposes a time-series into a global sinusoidal component with fixed amplitudes. The PSD was analyzed by calculating the powers and the peak frequencies of different frequency bands. The frequency bands used in this experiment were: very low frequency (VLF, 0-0.04 Hz), low frequency (LF, 0.04-0.15Hz), and high frequency (HF, 0.15-0.4 Hz). In the current study, frequency domain parameters were calculated using normalized values of LF, HF and ratio of LF/HF.

5. Results and Discussions

5.1 Results

The Stroop test was conducted on all the subjects and the HRV data was recorded. The heart rate monitor used was the Polar RS810 (Polar Electro Inc., Lake Success, NY), a portable wireless device. It included a watch, a coded wear link chest transmitter, and Polar Pro Trainer 5.0 software, which enabled data download via an infra red USB (IrDA) interface. Although, the software generated the normalized units for each component, the absolute power values of each component were considered, in order to completely describe the distribution of power among spectral components. Due to skewed distribution, LF and HF power components (i.e., the absolute power values) were analyzed after natural logarithmic transformation. The performance of all the subjects in the Stroop test was also calculated. This chapter describes the method of calculating the performance based on the Stroop test. The variation of heart rate variables like mean R-R, mean H-R, L.F(n.u), HF(n.u) and ratio of LF(n.u)/HF(n.u) during High Stroop interference and Low Stroop interference segments was studied. The performance and response time during High Stroop interference and Low Stroop interference segments and for 6 difficulty levels was also studied and reported in this chapter.

Averages of each HRV parameters are listed in following table:

HRV Features	Relax	Low Stroop Interference	High Stroop Interference
Mean RR (s)	0.755435(±0.09)	0.73830445(±0.09)	0.69972185(±0.09)
Mean HR (1/min)	80.6638(±7.21)	82.80415(±7.87)	87.349215(±8.47)
STD (1/min)	5.27963(±1.68)	6.13307(±1.86)	6.169(±1.98)
LF (n.u.)	53.0701(±15.89)	53.77874(±11.60)	64.52805(±11.69)
HF (n.u.)	46.92991(±15.89)	46.22126(±11.60)	35.47195(±11.69)
LF/HF	1.448775(±1.05)	1.46606(±1.49)	2.252905(±0.95)

Table 1: HRV features and comparing pair wise data of baseline (relax), High Stroop interference and Low Stroop interference.

Table 1 summarizes the HRV features and their changes during the Stroop test. As discussed earlier, the base line represents a relaxed state of the mind, where the participant was not subjected to any mental activity. All of the above variables were included in the statistical analysis. We used paired and unpaired t-test for data. We chose a critical p-value lower than 0.05 as significant and a p-value between 0.05-0.10 as indicative. A t-test was performed to compare HRV features within two states; Relax - High Stroop Interference, Relax - Low Stroop Interference, High Stroop Interference – Low Stroop Interference. The t-test was performed on

HRV features as mentioned in Table 1. The t-test p-values are listed in Table 2, with the significant p-values indicated by “*”.

t-test P-Values:

HRV Variables	P-Values (High Stroop Interference)	P-Values (Low Stroop Interference)
Mean RR (s)	*t(38) = 2.31, $p < .05$ (p = 0.02624)	t(38) = 0.6735, $p > .05$ (p = 0.5046899)
Mean HR (1/min)	*t(38) = 2.80, $p < .05$ (p = 0.007949)	t(38) = 0.860, $p > .05$ (p = 0.3949041)
STD (1/min)	t(38) = 1.59, $p > .05$ (p = 0.1199076)	t(38) = 1.47, $p > .05$ (p = 0.1496814)
LF (n.u.)	*t(38) = 2.60, $p < .05$ (p = 0.0133919)	t(38) = 0.160, $p > .05$ (p = 0.8732615)
HF (n.u.)	*t(38) = 2.60, $p < .05$ (p = 0.0133919)	t(38) = 0.160, $p > .05$ (p = 0.873261)
LF/HF	*t(38) = 1.97, $p < .05$ (p = 0.045941)	t(38) = 0.2263, $p > .05$ (p = 0.793643)

Table 2: HRV features and comparing pair wise data of baseline (relax), High Stroop interference and Low Stroop interference.

Based on the p-values as shown in Table 2, the following conclusions were made for each of the hypotheses as shown below:

Hypothesis 1:

- **H0:** Higher-Stroop Interference will NOT have any effect on HRV parameters like mean R-R (s).
- **H1:** Higher-Stroop Interference will have an effect on HRV parameters like mean R-R (s).

The p-value for the mean R-R (s) component, was <0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and an alternate hypothesis was concluded, i.e., that high interference (Stroop) has an effect on the mean R-R (s) component when compared during rest.

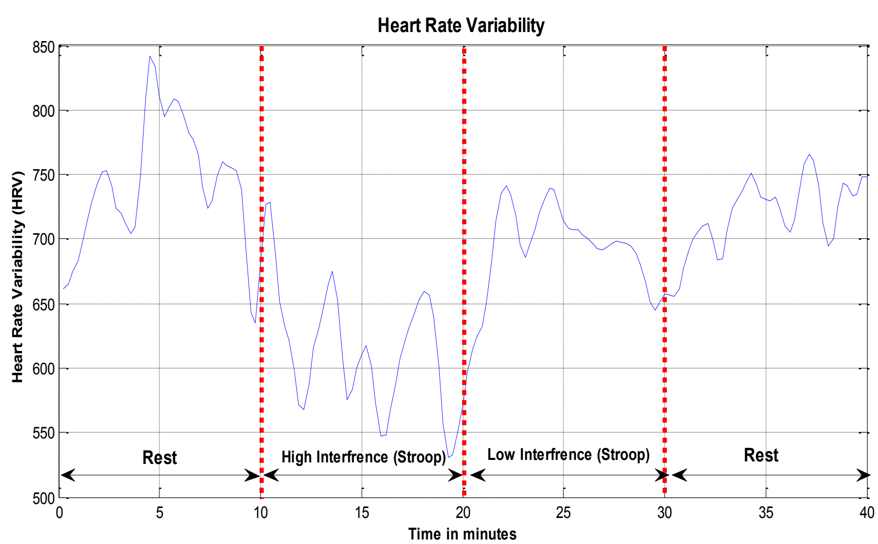

Figure 16: Heart Rate Variability during Rest-High Interference-Low Interference-Rest.

- **H0:** Lower-Stroop Interference will NOT have any effect on HRV parameters like mean R-R (s).
- **H1** Lower-Stroop Interference will have an effect on HRV parameters like mean

The p-value for the mean R-R (s) component, was >0.05 for the Low Stroop interference. Based on the significant p-value obtained, the null hypothesis was accepted, concluding that Low Stroop interference had no effect on the mean R-R (s) component when compared during rest or High Stroop interference segments. Figure 17 shows the Mean R-R during the Relax-Low Stroop Interference and High Stroop Interference and Figure 16 demonstrates the HRV levels throughout the entire experiment.

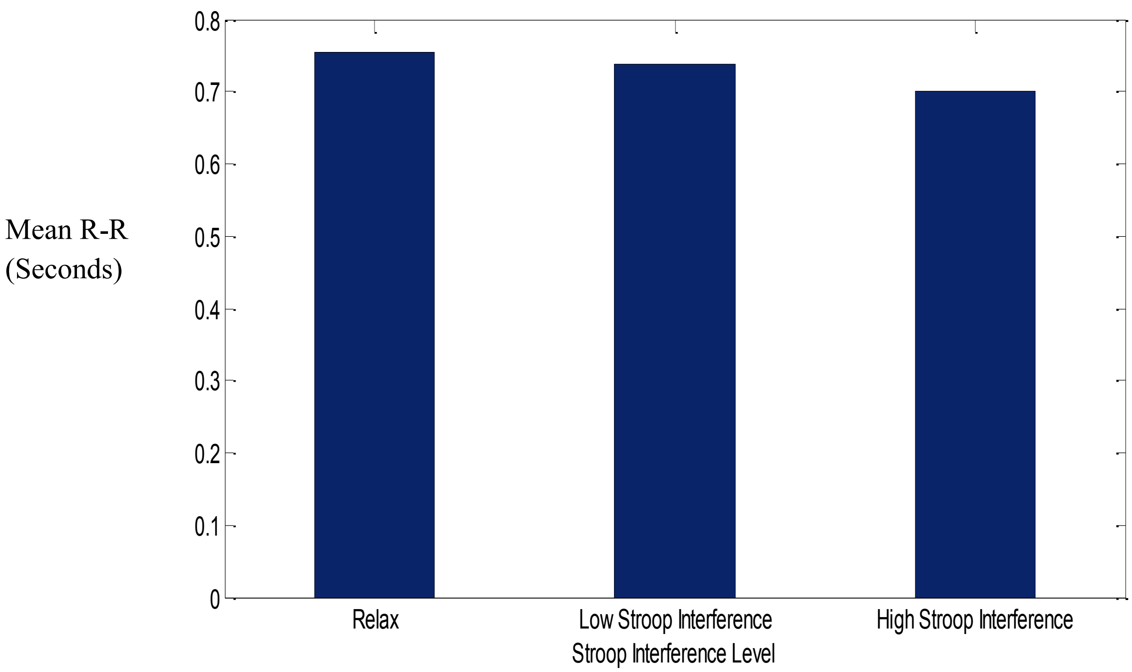

Figure 17: Mean R-R during Rest- Low Interference-Rest-High Interference.

Hypothesis 2:

- **H0:** Higher-Stroop Interference will NOT have any effect on HRV parameters like mean HR (1/min).
- **H1:** Higher-Stroop Interference will have an effect on HRV parameters like mean HR (1/min).

The p-value for the mean HR (1/min) component was <0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and an alternate hypothesis was concluded, i.e., high interference (Stroop) has an effect on the mean HR (1/min) component when compared during rest.

- **H0:** Low-Stroop Interference will NOT have any effect on HRV parameters like mean HR (1/min).
- **H1:** Low-Stroop Interference will have an effect on HRV parameters like mean HR (1/min).

The p-value for the mean HR (1/min) component was >0.05 for low Stroop interference. Based on the significant p-value obtained, the null hypothesis was accepted and was concluded, i.e., low interference (Stroop) has no effect on the mean HR (1/min) component when compared during rest or high Stroop interference segments. Figure 18 shows the Mean HR during the Relax-Low Stroop Interference and High Stroop Interference.

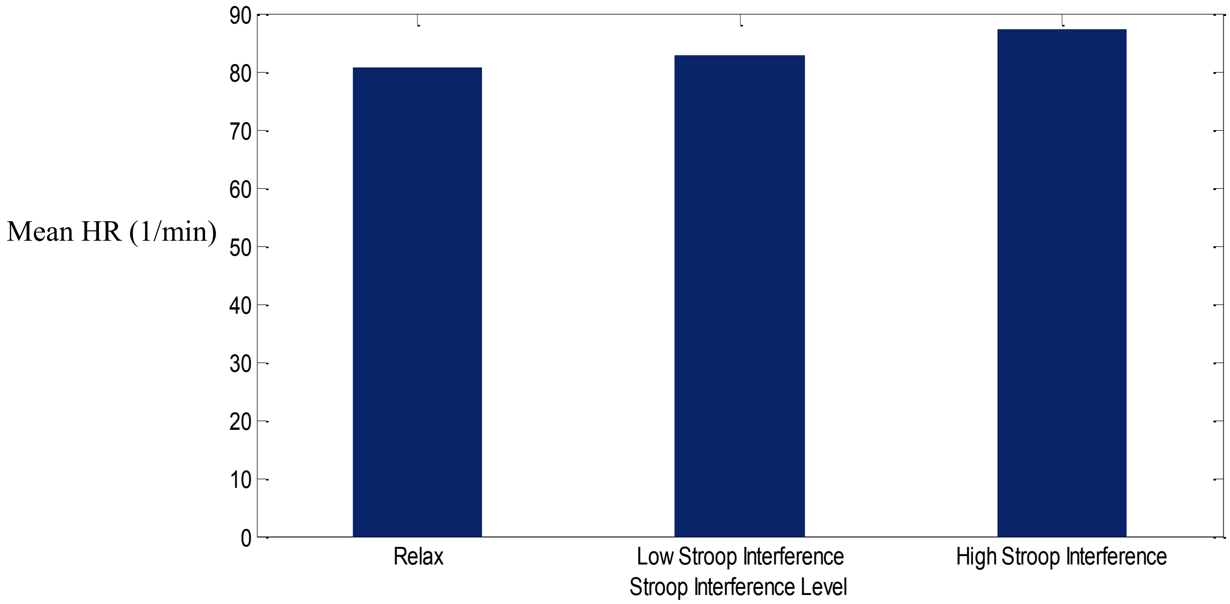

Figure 18: Mean H-R during Rest- Low Interference-High Interference.

Hypothesis 3:

- **H0:** Higher-Stroop Interference will NOT have any effect on HRV parameters like STD (1/min).
- **H1:** Higher-Stroop Interference will have an effect on HRV parameters like STD (1/min).

The p-value for the STD (1/min) component, was >0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was concluded i.e., high interference (Stroop) has no effect on the STD (1/min) component when compared during rest.

- **H0:** Low-Stroop Interference will NOT have any effect on HRV parameters like mean STD (1/min).

- **H1:** Low-Stroop Interference will have an effect on HRV parameters like mean STD (1/min).

The p-value for the STD (1/min) component, was >0.05 for low Stroop interference. Based on the significant p-value obtained, the null hypothesis was concluded i.e., Low interference (Stroop) has no effect on the STD (1/min) component when compared during rest or High stroop interference segments.

Hypothesis 4:

- **H0:** Higher-Stroop Interference will NOT have any effect on HRV parameters like LF (n.u.)
- **H1:** Higher-Stroop Interference will have an effect on HRV parameters like LF (n.u.).

The p-value for the Mean LF (n.u) component, was <0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and the alternate hypothesis was concluded i.e., high interference (Stroop) has an effect on the LF (n.u) component when compared with rest.

- **H0:** Lower-Stroop Interference will NOT have any effect on HRV parameters like LF (n.u.)
- **H1:** Lower-Stroop Interference will have an effect on HRV parameters like LF (n.u.).

The p-value for the Mean LF (n.u) component, was >0.05 for Low Stroop interference. Based on the significant p-value obtained, the null hypothesis was accepted, and it was concluded that low interference (Stroop) has no effect on the LF (n.u) component when compared with rest and high Stroop interference segments. Figure 19 shows the Mean L.F (n.u) during the Relax-Low Stroop Interference and High Stroop Interference.

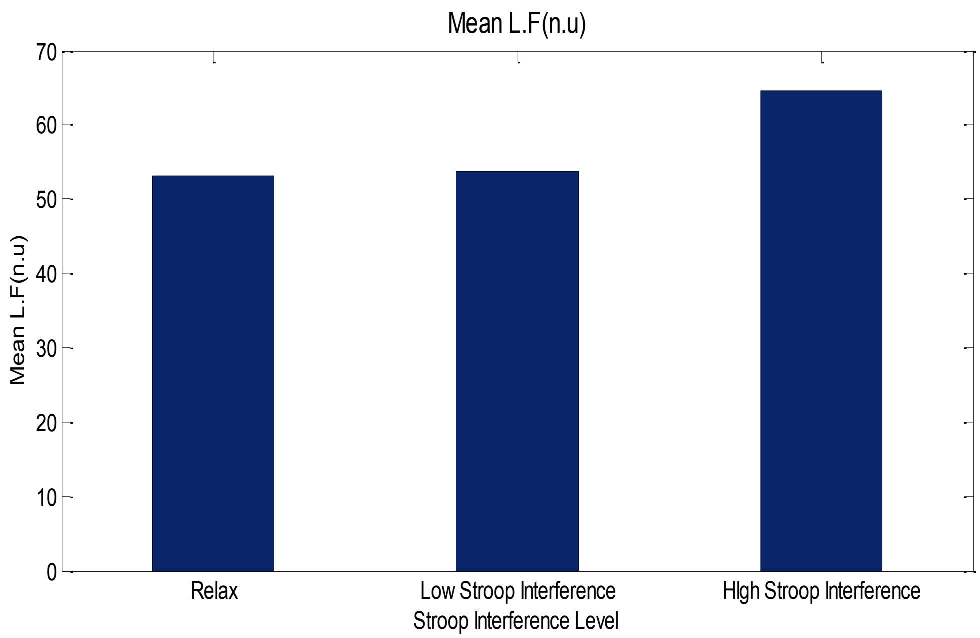

Figure 19: Mean LF(n.u) during Rest- Low Interference-High Interference.

Hypothesis 5:

- **H0:**Higher-Stroop Interference will NOT have any effect on HRV parameters like HF (n.u.).
- **H1:**Higher-Stroop Interference will have an effect on HRV parameters like HF (n.u.).

The p-value for the Mean HF (n.u) component, was <0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and the alternate hypothesis was concluded i.e., high interference (Stroop) has an effect on the HF (n.u) component when compared with rest.

- **H0:** Low-Stroop Interference will NOT have any effect on HRV parameters like HF (n.u.).
- **H1:** Low-Stroop Interference will have an effect on HRV parameters like HF (n.u.).

The p-value for the Mean HF (n.u) component, was >0.05 for low Stroop interference. Based on the significant p-value obtained, the null hypothesis was accepted concluded that low interference (Stroop) has no effect on the HF (n.u) component when compared with high Stroop interference segments and rest. Figure 20 shows the Mean H.F (n.u) during the Relax-Low Stroop Interference and High Stroop Interference.

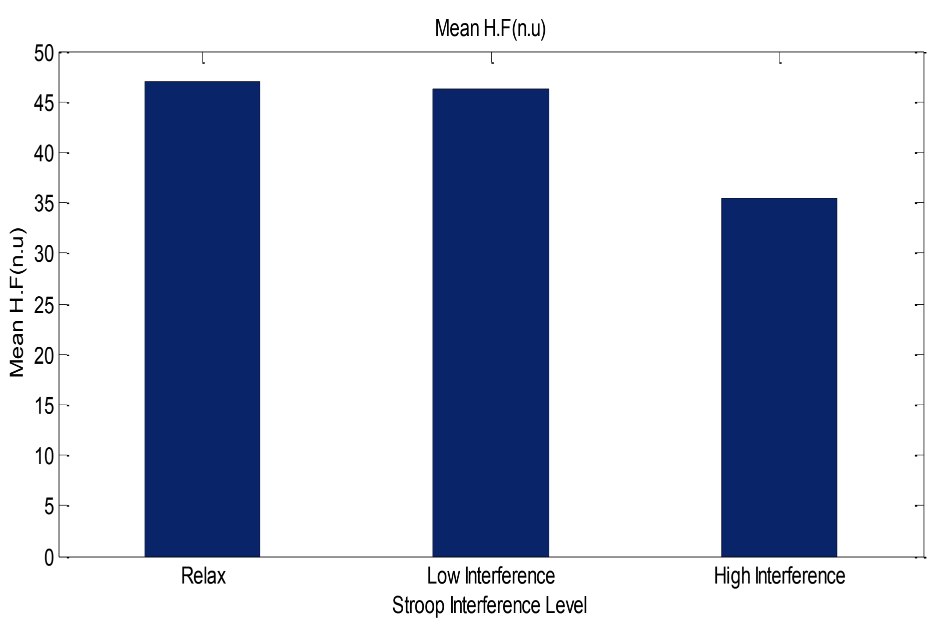

Figure 20: Mean HF (n.u) during Rest- Low Interference-High Interference.

Hypothesis 6:

- **H0:** Higher-Stroop Interference will NOT have any effect on HRV parameters like LF/HF.
- **H1:** Higher-Stroop Interference will have an effect on HRV parameters like LF/HF.

The p-value for the LF/HF component, was <0.05 for high Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and the alternate hypothesis was concluded i.e., high interference (Stroop) has an effect on the LF/HF component when compared with Rest.

- **H0:** Lower-Stroop Interference will NOT have any effect on HRV parameters like LF/HF.
- **H1:** Lower-Stroop Interference will have an effect on HRV parameters like LF/HF.

The p-value for the LF/HF component, was>0.05 for Low Stroop interference. Based on the significant p-value obtained, the null hypothesis was accepted and concluded i.e., low interference (Stroop) has no effect on the LF/HF component when compared with Rest and High stroop interference. Figure 21 shows the Mean LF/HF during the Relax-Low Stroop Interference and High Stroop Interference.

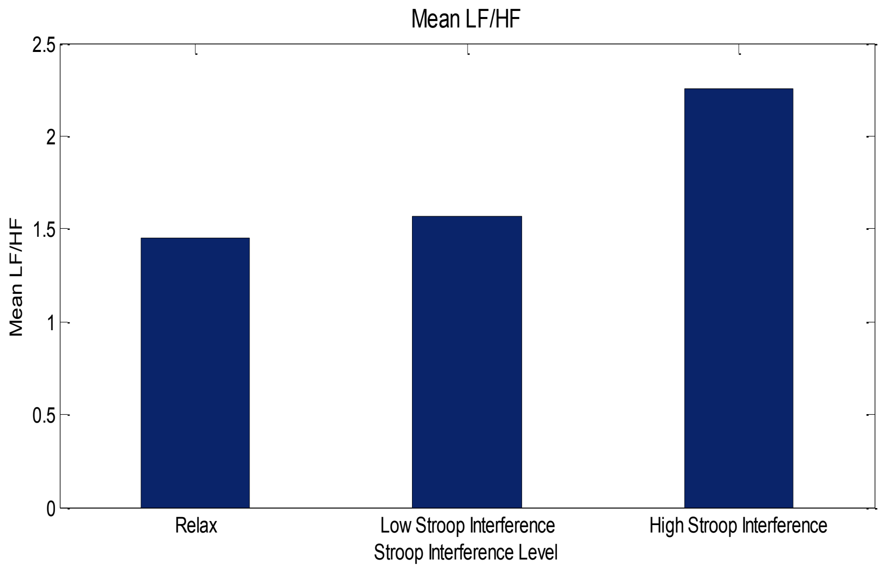

Figure 21: Mean LF/HF during Rest- Low Interference-High Interference.

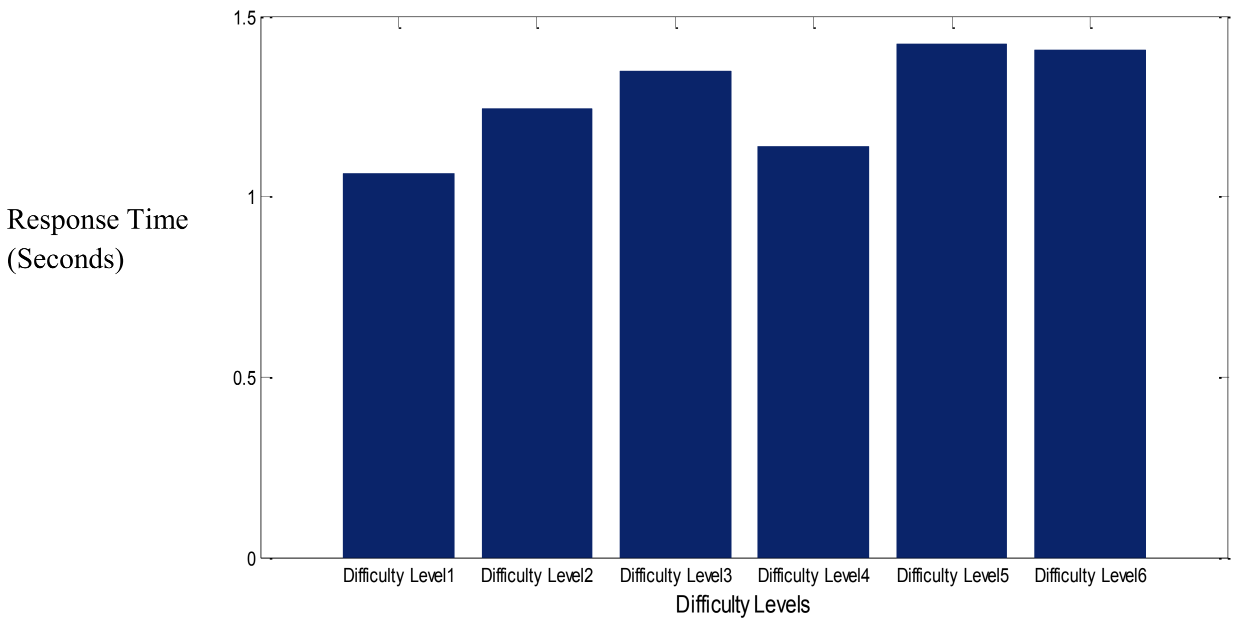

Figure 22: Mean Response Time (RT) during each difficulty level.

Figure 22 shows that the mean response time was highest during difficulty levels 5 and 6. Difficulty levels 5 and 6 were the incongruent segments, where the maximum utilization of the working memory takes place, resulting in an increase in the response time. However, difficulty level 4 was an exception. It is difficult to precisely cite a reason for this, yet it could be interpreted as the subject's psychological adaptability or readiness to deal with the task at hand. It must be noted that difficulty levels 1 through 6 were defined intuitively and there was no quantitative evidence demonstrating this ranking. For example, it is intuitive that "congruent-congruent" is easier to identify than "congruent-black" or "congruent-incongruent". However, such type of intuitive ranking might be difficult when "congruent-incongruent" is compared with "incongruent-congruent". Hence, from this point onwards, the statistical analysis was performed using the standard t test for Low Stroop Interference level and High Stroop interference level, the mean value of response time during Low Stroop interference and High Stroop interference was calculated see Figure 23.

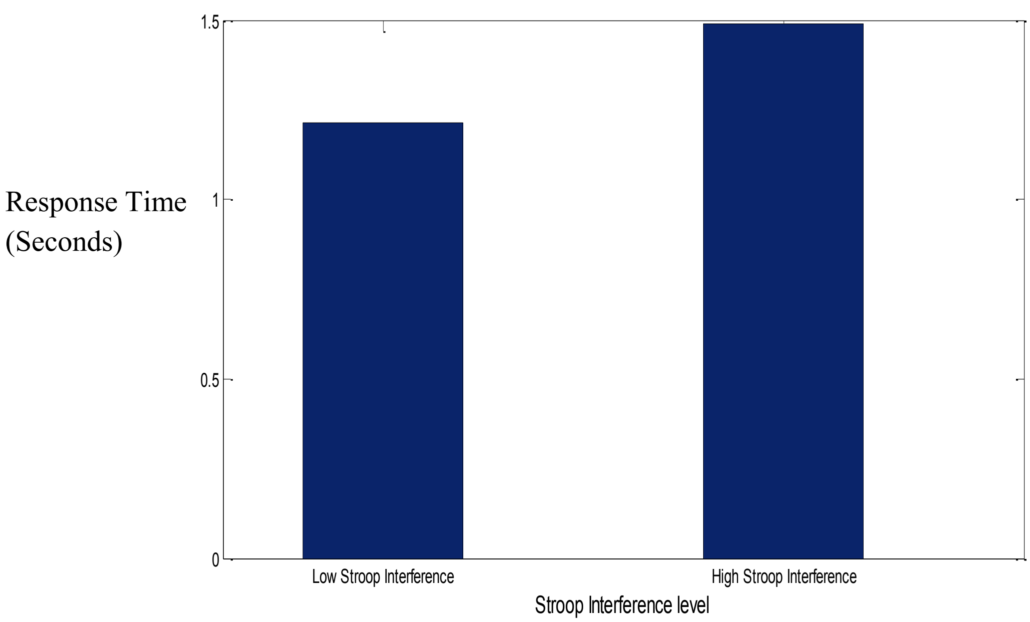

Figure 23: Mean Response time during High Interference-Low Interference.

Hypothesis 7:

- **H0:** High- Stroop Interference will NOT have any effect on response time.
- **H1:** High- Stroop Interference will have an effect on response time.

The p-value for the Mean Response time, was <0.05 for High Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and an alternate hypothesis was concluded, i.e., that higher-order cognition has an effect on response time.

The performance of a subject during the Stroop test was calculated by considering the average response time of the subject, as well as the percentage of wrong answers. The performance of the participant was observed to decrease with an increase in difficulty levels.

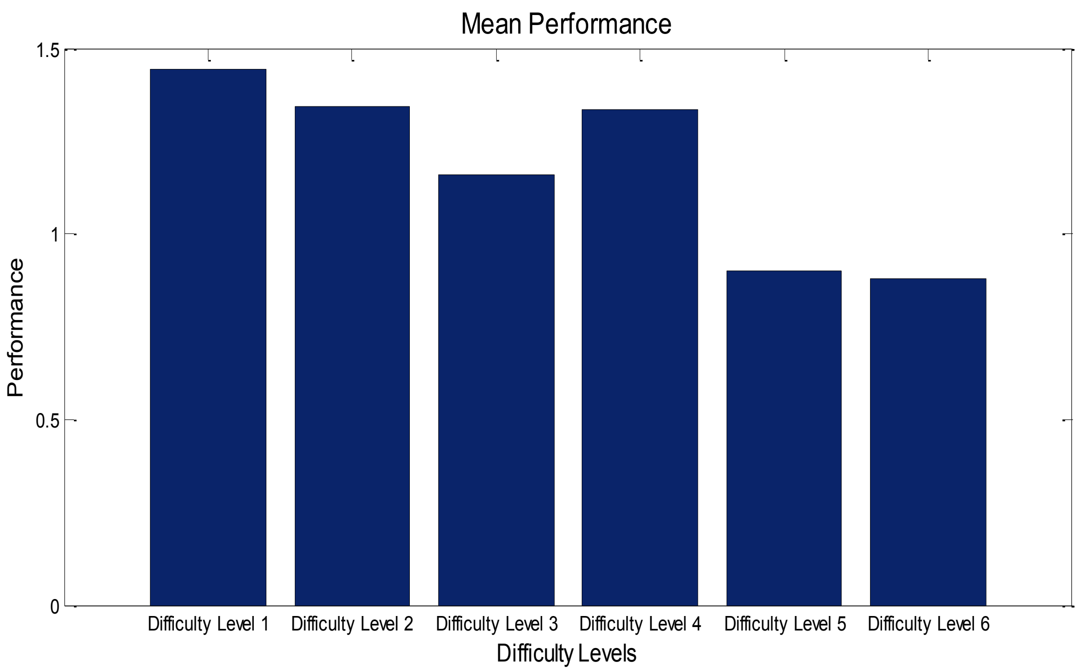

Figure 24: Heart Rate Variability during Rest-High Interference-Low Interference-Rest.

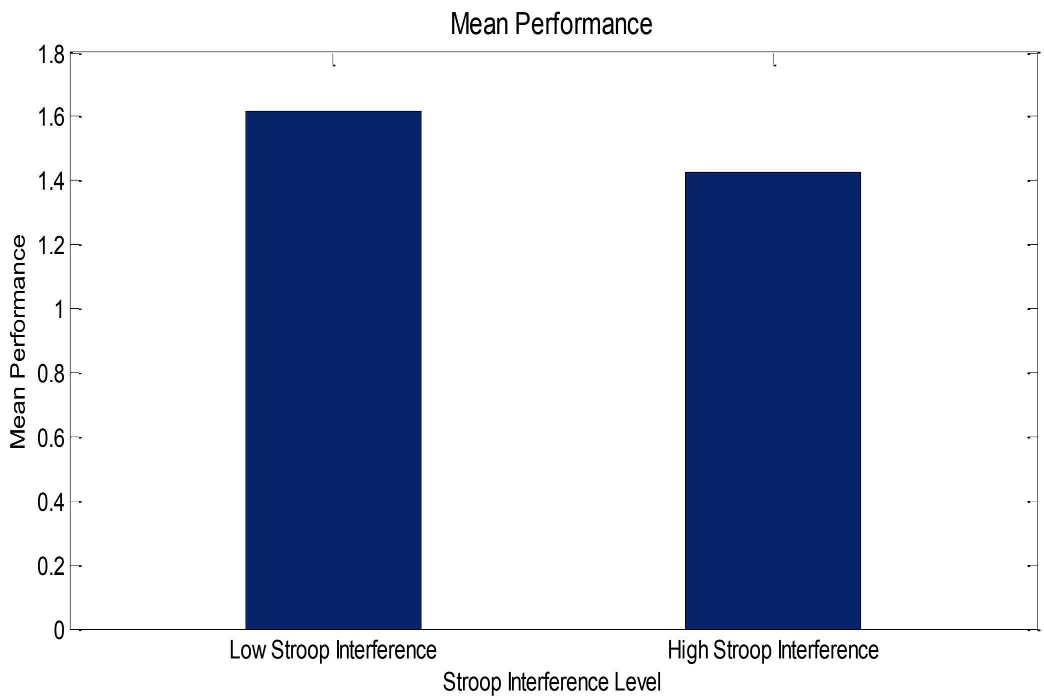

Figure 25: Mean Performance during High Interference-Low Interference.

Hypothesis 8:

- **H0:** Higher-Stroop Interference will NOT have any effect on measures of performance of the Stroop task.
- **H1:** Higher-Stroop Interference will have an effect on measures of performance of the Stroop task.

The p-value for the Mean Performance, was <0.05 during High Stroop interference. Based on the significant p-value obtained, the null hypothesis was rejected and the alternate hypothesis was concluded i.e., the Higher-Stroop Interference has an effect on performance.

5. 2 Discussion

The purpose of this study was to quantify individual mental stress and to monitor heart rate variability (HRV) during high and low working memory (WM) demands during the Stroop task (cognitive task). In this study we used a combination of congruent, neutral and incongruent segments to create Higher Stroop Interference. Since it has been suggested in the literature (and demonstrated in this thesis) that the demands on working memory depend on the mental workload, we used Stroop interference levels to increase demands on working memory. Additionally, in this experiment, HRV parameters during increasing and decreasing demands on working memory were monitored.

In this experiment, the type of task performed affected the power spectral components, as well as the mean heart rate, and the mean HRV. The mean values obtained under rest conditions for this study are shown in Table 1 : LF (n.u) - 53.0701(±15.89), HF (n.u) - 46.9299(±15.89), LF /HF - 1.4487(±1.041). Although these readings were not recorded on a person lying in a supine position, it was ensured that the participants were in a calm environment and were in a sitting position without any major movements or distractions. In this study, the power spectral components were compared in the form of normalized units (n.u) i.e., as a percentage of the total power disregarding the VLF component. The normalization minimizes the effects of changes in the total power of the values of LF and HF components by excluding the less reliable VLF components from its estimates. Thus, it gives an idea of how LF and HF components may change with respect to the total power [23]. However, it should be noted that the normalized units in this study are only used to compare the changes in each of the components with respect to the baseline values and the natural logarithmic transformed values used in the actual statistical analysis.

The HF component decreased significantly from the base line (rest) value for both the tasks, indicating that stress was induced in the participants. HF at rest was 46.92991(±15.89) (n.u) and it was decreased to 35.47195 (±11.69) (n.u) See Figure 20 for High Stroop interference segments (high WM demand). There was no significant decrease in HF power for low Stroop interference segments as compared to Rest or High Stroop Interference. HF power at Low Stroop Interference was 46.22126(±11.60). HF power represents the influence of respiration on heart rate, and is related to parasympathetic activity [77]. It is characterized by respiratory sinus arrhythmia (RSA) [24]. When frequent parasympathetic modulation occurs, it results in an increased heart rate [77]. This could have happened during the High Stroop interference of the Stroop task. The LF component increased significantly from the baseline 53.0701(±15.89) to 64.52805 (±11.69) for High Stroop interference segments (high WM demand) See Figure 19. There was no significant increase in LF power for Low Stroop interference segments as compared to rest or High Stroop Interference. LF power at low Stroop interference was 53.77874(±11.60).

The LF/HF ratio increased from the baseline from 1.44875 (±1.05) to 2.252905 (±0.95) for high Stroop interference see Figure 21. This ratio was not significantly affected during low Stroop interference segments as compared to Rest and high Stroop interference. The LF/HF ratio during low Stroop interference was 1.46606(±1.49). As suggested in the literature, the LF/HF ratio increased during mental tasks [61]. As discussed before in our study, the mental task we selected was the Stroop task. It could be concluded from this study, that the LF/HF ratio was increased along with an increasing demand on working memory, whereas the HF power decreased. During low intensity tasks some authors have stated that a shift of autonomic interaction occurs toward sympathetic dominance, as indicated by the reduced HF power, with a concomitant increase in LF power, and thus an increase in the LF/HF ratio [52, 78].

The main finding of this study is that the HRV indices i.e. HF, LF and the LF/HF ratio are sensitive indicators of mental stress. This conclusion is in agreement with a number of other studies using either prolonged [79] or short term exposure to psycho-social stressors. The psychological stress testing in the clinical laboratory provokes changes in the sympathetic and vagal activities, regulating the heart rate. This can be assessed non-invasively using a spectral analysis of R-R variability[80].

In this study, heart rate increased significantly from the base line (rest) 80.6638 (±7.21) to 87.349215 (±8.47) for high Stroop interference. See Figure 18. The heart rate increases during stressful conditions [24]. The mean R-R (ms) decreased significantly during high Stroop interference segments. The mean R-R was significantly decreased from 0.755435 (±0.09) to 0.6997285 (±0.09) for high Stroop interference. Standard deviation (SD) of HR, which is a measure of longer term variability, did not differ between conditions.

The t-test results showed that the difference in the type of task performed makes a significant difference in the LF and HF components. Therefore, for the current study, it can be said that the task type can be identified easily based on the LF and HF spectrum estimates, but further research is needed to extrapolate these conclusions to different kinds of mental activities. All the power spectral components followed the expected trend that healthy people would follow when subjected to stress.

The second major finding of this study was the measure of response time and performance and its relation with demands on WM. In this study, response time was significantly increased during High Stroop Interference (higher-order cognition). Working memory capacity is utilized at maximum during the performance of complex tasks, as it requires willingness, awareness and attention such as reasoning, planning, and manipulation of the linguistic information, as well as the executive control and coordination of perception and action during complex cognitive operations (such as that of difficulty level 6 in this study). This resulted in a significant increase in response time and a decrease in performance for High Stroop Interference as compared with Low Stroop Interference. The mean response time for High Stroop Interference was 1.490373 (±0.76) and 1.213745 (±0.79) for Low Stroop Interference. The mean response time was increased as the difficulty levels were increased. See Figure 22. However, the difficulty level 4 is an exception. It is difficult to precisely cite a reason for it, however, it has to be noted that the difficulty levels 1 through 6 were defined intuitively and there was no quantitative evidence demonstrating this ranking. The performance for High Stroop Interference was 1.424219 (±0.73) and 1.165844 (±0.74) for Low Stroop Interference segments. The mean Performance was decreased as the level of difficulty was increased see Figure 24. As discussed earlier, the performance at difficulty level 4 was increased, which is an exception.

The t-test results showed that the difference in the performance of higher-order cognition makes a significant difference to both response time and performance. Therefore, it can be concluded for the current study that the type of task can be identified easily based on performance and response time. There was no significant change in the mean values of LF and HF spectrum estimates, due to higher order cognition, but results showed a significant difference during Rest and High stroop interference for HRV parameters like mean R-R, mean HR and spectrum estimates LF and HF. It can therefore be concluded that the difference between rest and stress states due to High Stroop interference can easily be identified based on the HRV parameters discussed before. All the power spectral components followed the expected trend that healthy people would follow when subjected to stress. From the current study it can also be concluded that demands on working memory significantly affect an individual's performance, consequently affecting physiological parameters like HRV. Further research is required to extrapolate these conclusions to different kinds of mental activities. The Yerkes-Dodson law suggests that as mental stress increases performance increases, and after reaching an optimal point in stress, it drops. This could mean that if two subjects are given a similar task which is independent of their expertise, the person developing more stress would perform better than the other if they are in the initial positive-slope side of the Yerkes-Dodson law curve. During Low Stroop Interference segments performance was increased to a great extent. When subjects were exposed to High Stroop Interference segments response time and error rate was increased significantly. The result was a decrease in performance. The mental stress i.e. ratio of LF/HF was high during High Stroop Interference segment as compared with Low Stroop Interference segment. In this thesis, the quantitative ranking of the difficulty levels of the Stroop test were not done. The Stroop task was designed by taking into consideration the interference level due to the combination of congruent, incongruent and neutral segments. It is difficult to propose any correlation between trends of mental stress level and performance during the complete Stroop task. However, assuming that identifying the High Stroop Interference segments is more difficult than the Low Stroop Interference segments, the Stroop test designed in this thesis is sufficient enough to induce enough stress in the subject to a level where his/her performance would drop. The increase in working memory demand resulted in a decrease in performance, and consequently changes in HRV parameters like mean HR, mean R-R, L.F (n.u), H.F (n.u), and Ratio of LF/HF. The results do not show any significant differences in HRV if comparison is made between High Stroop Interference and Low Stroop Interference. However with these results it is not possible to conclude that mental stress levels gradually increase with an increase in task difficulty, or an increase in demand on working memory. However the results do show a significant difference in HRV parameters between two conditions (Rest- High Stroop Interference).

6. Conclusion

6.1 Conclusions

In this thesis, an extensive literature review of the assessment of different physiological variables using the heart rate monitor (HRM) was carried out. The goal was to determine a relationship between performance and an individual's level of mental stress in the workplace, while also examining the changes in physiological parameters (HRV) during human computer interaction. The experimental set-up was established by Dr. Yong Zeng's research group. The Stroop test was used as a mental task given to the subjects. A protocol was developed to attach the electrode belt to the chest, to record the HRV data while the subject performs the Stroop test, and to filter the raw HRV data that was obtained. A segmentation scheme for the filtered HRV data was developed and implemented, based on the timings of the mental task (stroop test). The HRV analysis software was used to calculate all the commonly used time and frequency domain measures of heart rate variability (HRV). A standard t-test was implemented to calculate the statistical significance for different HRV parameters, response time, and performance of the Stroop task at Rest, High Stroop Interference, and Low Stroop Interference.

The analysis of the mean R-R showed that the reduction in the mean R-R is more pronounced during high Stroop interference segments. Similarly, there was a significant increase in the mean H-R (1/min) during high Stroop interference segments. The increase in LF (n.u) and the ratio of LF/HF was more pronounced during high Stroop interference segments. It was observed that mental stress (i.e. ratio of LF/HF) increased significantly during high Stroop interference. Similarly, there was a significant decrease in the H.F during high Stroop interference segments. In this study, an attempt was made to observe the effects of working memory demand on HRV parameters. As discussed earlier, the HRV parameters were affected when the demand on WM was increased as compared to the Rest phase of the experiment. There was no significant change in any of the HRV parameters (time and frequency) during low Stroop segments as compared to either the rest state, or High Stroop interference. The tendency towards a slight change in HRV parameters indicated that demands on WM have some effect on HRV parameters. The performance was significantly decreased during High stroop interference segments, and increased in response time as compared to Low stroop interference segments. The HRV results also indicated that the portable heart rate monitor with a mobile setting was able to monitor significant changes in the HRV during the performance of mental tasks.

Performance during high Stroop interference segments was significantly decreased due to both an increase in response time and the error rate. This also indicated that higher-order cognition, due to high Stroop interference, is sufficient enough to make a subject stressed, and to decline his/her performance.

Participants answered a comfort questionnaire. The tasks were performed in a brief time period, contrasting with the work place environment, where a person normally works for a period of eight hours. Participants also answered physical and psychological readiness questionnaires, which provided information about the eligibility of the individual to perform a Stroop task.

As discussed earlier, the quantification of an individual's mental stress plays an important role in the field of human-computer interaction. As mentioned earlier, excess use of computers has been correlated with greater job dissatisfaction and distress. Job design, organizational policies, management practices and career opportunities are influenced by good designed computerized work systems, all of which can be determining factors in psychological distress.

The quantification of mental stress plays an important role in modeling the relationship between mental stress and performance. The experimental tasks were intended to simulate mental stress, and the actual tasks were designed as closely as possible to a realistic work place situation. A mental task may not mirror a real-life situation, a more realistic example of mental stress being answering phones, greeting customers (stock exchanges, call centers etc.), working overtime (fire fighters, health care), multi-tasking, and rushing to meet deadlines (manual material handling, IT services or any corporate industry).

In this thesis, the partial correlation of increasing WM demands with a change in an individual's physiological parameters, was established by investigating HRV. Further research is required to gain a comprehensive understanding of the role that mental stress plays in human-computer interaction.

6.2 Contributions

The outcomes of the current study can be summarized as follows:

- All the heart rate variables were sensitive to mental stress.
- The HF component decreased with an increase in demand. It was more sensitive to high Stroop interference segments than low Stroop interference.
- The LF component increased along with an increase in stress levels in general, being more sensitive to high Stroop interference segments, than low Stroop interference.
- The LF/HF ratio increased with an increase in demands irrespective of the type of task performed.
- The measure of response time was pronounced during high Stroop interference tasks.

- The performance of the Stroop task decreased during high Stroop interference.
- The physical and psychological activity readiness questionnaires described the physical and psychological attributes of an individual, prior to the performance of the Stroop test.

6.3 Future Work

The present study examined the effects of mental activity on heart response and WMC, although many other factors (physical, psychological and individual) contribute to an individual's performance. There are various physiological responses, such as blood pressure, heart rate, and catecholamine and cortisol secretion resulting from different kinds of stress. The current study examines only one such response, i.e., the response of the heart to mental stress induced in a laboratory setting. Besides serving as stress indicators, HRV responses are also of interest as a possible link between psychosocial stress and various performance outcomes. It might be possible that the culmination of various factors causes more pronounced effects on physiological outcomes than any single factor alone.

As mentioned earlier, the tasks used in the current study may not be an accurate representation of the tasks performed in the workplace. Future research should focus on real-time field studies that monitor the heart rate of an individual performing a given task over a period of time, which could provide support for laboratory studies. One real-time application of heart rate monitors is to monitor the HRV of an individual at regular intervals and look for any changes in task performance. Stress levels can be maintained as low as possible by redesigning the work place, decreasing the intensity of the tasks to be performed, or introducing rest periods between tasks. Future research should investigate how changes in HRV can be used to analyze the root cause of decreased performance levels.

Also, the design of the tasks could be altered to include both low and high intensity effort throughout the duration of task performance. In the current study, the HR was analyzed as a function of task intensity. Future studies could focus on how HR variables behave at different tasks intensities, and in different positions, as well as how the perceived workload ratings are correlated with HRV.

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APPENDIX 1 (Ph.AR-Q)

Physical activity readiness Questionnaire (Ph.AR-Q I)

1) Did you have alcohol in the last 24 hours?

   ☐ YES ☐ NO

2) Do you have color blindness?

   ☐ YES ☐ NO

3) Did you have at least 7 hours of sleep last night?

   ☐ YES ☐ NO

4) Are you undergoing any kind of regular prescribed Medication?

   ☐ YES ☐ NO

5) Do you frequently suffer from chest pains?

   ☐ YES ☐ NO

6) Has doctor ever said your blood pressure is too high?

   ☐ YES ☐ NO

7) Is there any physical reason why you should not follow any physical or mental activity program even if you want to?

   ☐ YES ☐ NO

If you answer "Yes" to any question, the task maybe postponed. Medical clearance may be necessary.

I have read this questionnaire. I understand it does not provide a medical assessment in lieu of a physical examination by a physician.

Participant's signature: ....

Investigator's signature: ....

Date: ....

APPENDIX 2 Ps.AR-Q II

Psychological activity readiness Questionnaire (Ps.AR-Q II)

1) Are you undergoing any depression?

    □ YES □ NO

2) Have you taken any Psychiatric treatment?

    □ YES □ NO

3) Are you undergoing any kind of regular prescribed Medication for psychiatric treatment?

    □ YES □ NO

4) Have you taken a Stroop task to perform before?

    □ YES □ NO

If you answer "Yes" to any question, the task should be postponed. Medical clearance may be necessary.

I have read this questionnaire. I understand it does not provide a medical assessment in lieu of a physical examination by a physician.

Participant's signature: ……………………………………………………………

Investigator's signature: ……………………………………………………………

Date: ………………………………

APPENDIX 3: DEMOGRAPHICS DATA FORM

Please answer the following questions as honestly as possible.

First Name: __________

Last Name: __________

Date of Experiment: __________

Time of experiment: __________

Age: __________

Gender: __________

Race/Ethnicity: ______________________

Are you a native English speaker (Is English your first language)? Yes _____ No _____

Are you a student or working professional? Please insert check mark for correct answer

- ☐ Student
- ☐ Working Professional.

Do you have any cardiovascular or musculoskeletal condition (conditions of the heart, lungs, muscles, or bones/joints) that affects your heart rate? If you are pregnant or think you might be pregnant, also check "yes".

☐ YES ☐ NO

Participant's signature: --

Investigator's signature: --

Date: ------------------------------

APPENDIX 4: COMFORT QUESTIONAIRE

What was your level of ease in doing the task in the current ambience condition of the room?

1) Very difficult
2) Somewhat difficult
3) Neutral
4) Somewhat easy
5) Very easy

What was your level of ease while wearing the chest strap?

1) Very difficult
2) Somewhat difficult
3) Neutral
4) Somewhat easy
5) Very easy

What was your awareness level of the chest strap during the experiment?

1) Very difficult
2) Somewhat difficult
3) Neutral
4) Somewhat easy
5) Very easy

What was your level of distraction resulting from the chest strap during the experiment?

1) Very distracted
2) Somewhat distracted
3) Neutral
4) Disagree
5) Strongly disagree

Was the chest strap adjustable to accommodate your chest size?

1) Strongly disagree
2) Disagree
3) Neutral
4) Strongly agree

5) Agree

Describe your level of anxiety while at the initial level of a Stroop task?

1) Very anxious
2) Somewhat anxious
3) Somewhat calm
4) Very calm
5) Neutral

Algorithms for Analysis

```
clear all; clc; close all;
Fs = 120;
HRV = load('HarshadHRV.txt');
x = HRV;  % Heart Rate Variability
% Find empty matrix
NanX = isnan(x);
NanX = find(NanX == 1);
for k = 1:length(NanX)
    mk = NanX(k);
    if mk < 3
        disp(' Inner Limit ... interpolating');
        x(mk) = mean([x(mk+1),x(mk+2)]);
    elseif mk > (length(x)-3)
        disp('Outer Limit... interpolating');
        x(mk) = mean([x(mk-2),x(mk-1)]);
    else
        x(mk) = mean([x(mk-1),x(mk+1)]);
    end
end
% Find zeros and interpolate
Zx = find(x == 0);
Znz = find(x~=0);
for k = 1:length(Zx)
    mk = Zx(k);
```

```
    if mk < 10
        mn = Znz(k);
        disp(' Inner Limit ... interpolating');
        x(mk) = mean(x(mn:mn+10));
    elseif mk > (length(x)-11)
        disp('Outer Limit... interpolating');
        x(mk) = mean(x(mn-10:mn));
    else
        x(mk) = mean([x(mk-5),x(mk-4),x(mk-3),x(mk-2),x(mk-
1),x(mk+1),x(mk+2),x(mk+3),x(mk+4),x(mk+5)]);
    end
end
CPDVar = [];
for k = 1:20:length(x)-120
    y = x(k:k+59);
    vx = mean(y);
    CPDVar = [CPDVar; vx];
end
% Moving Average
CPDVars = moving(CPDVar,2);
t = 1:length(CPDVars);
t = t/4.2;
plot(t, CPDVars);grid on;
xlabel('Time in minutes');
ylabel('Heart Rate Variability (HRV)');
```