VAGAL INFLUENCE ON SELECTIVE ATTENTION
UNDER HIGH AND LOW PERCEPTUAL LOAD

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ABSTRACT

I examined the effect of high and low levels of vagally mediated heart rate variability (HRV) on a computer-based selective attentional task under high and low perceptual load. In the task, letter strings were superimposed on either fearful or neutral facial distractors and participants were asked to identify target letters. Under high load, letter strings consisted of one target letter and five nontarget letters arranged in random order. Under low load, letter strings consisted of 6 target letters. Under both high- and low-load, the low HRV group did not show differences in RTs between neutral and fearful distractors. For the high HRV group, the valence of distractors played different roles in detecting targets under different perceptual loads. Under low perceptual load, the high HRV group was significantly faster to detect targets with fearful distractors compared to those with neutral distractors. Under high perceptual load, the opposite pattern was observed. The high HRV group was faster to detect targets with neutral distractors under high load. The results were explained in the context of the Neurovisceral model proposed by Thayer and Lane (2000, 2002). According to the model, HRV can index the top down modulation of the prefrontal cortex on sympathoexcitatory subcortical structures. High HRV represents the highly integrated cortical-subcortical circuits in the organism and is expected to be associated with good attentional and emotional regulation whereas low HRV indicates poor self-regulation as a result of rigid neuroviseral integration. As the
model predicted, the low HRV group failed to detect safety signals and made undifferentiated responses to neutral and fearful distractors. However, the high HRV group made responses that were appropriate for emotional contexts such that under low load, they quickly disengaged their attention away from fearful distractors and under the high load condition with neutral distractors, they recognized safety signals and made faster responses than with fearful distractors. Under the low load condition, the high HRV group exerted greater attentional control to quickly disengage their attention away from fearful stimuli and to process task-relevant stimuli. Under the high load condition with fearful distractors, the prefrontal cortex disinhibited its inhibitory control over sympathoexcitatory subcortical circuits, which allowed the processing of fearful distractors further. As a result, the processing of task-relevant stimuli might be delayed. However, with neutral distractor, the prefrontal cortex recognized the safety signal, the neutral facial expression, and focused on the processing of task-relevant stimuli while inhibiting the activity of sympathoexcitatory subcortical circuits. As a result, the high HRV group could identify targets significantly faster with neutral distractors than with fearful distractors.
DEDICATION

Dedicated to my Savior and Lord,

Soli Deo Gloria
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My father in heaven who will be really proud of me.

Most of all, I give my best thanks to the Lord, the only purpose and reason of my life.

All my work was, is, and will be done for his glory only, Soli Deo Gloria.
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CHAPTER 1

INTRODUCTION

1.1 Selective Attention

Selective attention can be defined as the ability to process goal-relevant information while attempting to exclude irrelevant and potentially distracting information (Lavie & Fox, 2000). The notion of selective attention is built on the idea that the perceptual world presents too much information for our limited processing capacity (Huang-Pollock et al., 2002). Therefore, selection has to be made at some point of information processing and only a limited amount of information is processed beyond this point (Huang-Pollock et al., 2002).

For over 40 years, it has been vigorously debated whether selection takes place early or late in the information processing (Lavie, 1995). The early selection approach was first proposed by Broadbent (1958) and developed further by Treisman (1969). According to the early selection approach, perception is a limited process that requires attentional selection to take place early. After the rudimentary analysis of physical features, selection takes place and only selected stimuli are fully perceived (Lavie, 2005; Lavie & Tsal, 1994). Deutch and Deutch (1967) and Norman (1968) proposed the late selection approach. The late-selection approach assumes that perception is unlimited and proceeds in parallel for all stimuli without the need for selection (Lavie, 1995; Lavie &
According to this view, selection takes place late in the information processing after full perception and selective attention primarily influences memory and decision-making processes (Lavie & Tsal, 1994; Huang-Pollock, 2002).

Lavie and his colleagues (1995, 2004) conceptualized a load-dependent locus of selective attention by integrating the “early” and “late” selection approaches. According to Lavie and his colleagues (1995, 2004), the locus of selection—early versus late—depends on perceptual load, or the total amount of potentially task-relevant information that is available. Lavie (1995) suggested that perception is limited such that it automatically proceeds to the extent that there remains available capacity. When perceptual load is high, either by increasing the amount of task-related information or by making a perceptual task more demanding, our limited processing capacity is exhausted and there is no attentional resource available to process irrelevant distractors (Lavie et al., 2004). As a result, there are reduced interference effects from irrelevant distractors under high load (Lavie et al., 2004). However, in low perceptual load situations, the processing of task-related information is less demanding and spare capacity left over can be used to process irrelevant distractors (Lavie et al., 2004). As a result, interference effects from irrelevant distractors are more pronounced under low perceptual load. According to this model, early selection is predicted under high perceptual load, whereas late selection is predicted under low perceptual load (Lavie et al., 2004).

Selective attention requires attentional regulation, the ability to select meaningful information while inhibiting irrelevant information. Also, it has been suggested that selective attention can be modulated by emotions (Hugdahl & Stormark,
For instance, if some information is meaningful or important to an individual, he or she is willing to spend more time and attentional resources in processing that information. What determines information to be ‘meaningful’ to an individual? Emotional significance is considered to be one prime marker that defines and determines information to be important and meaningful (Thayer & Lane, 2000; Compton, 2003). Research has indicated that selective attention to spatial location is influenced by emotional cues. Stormark et al. (1995) utilized the trial-by-trial cueing procedure that Posner (1988) used. In the task, cues were presented to indicate the most likely location of the target on each trial. On 2/3 of all trials, the cue appeared on the same display that a target appeared, and it was considered to be a valid trial because the cue correctly predicted the location in which the target appeared. In the invalid cue condition, the target appeared in the opposite of where the cue was presented. In the no-cue condition, the target appeared without the cue, which occurred on 1/6 of all trials. In valid trials, the detection of targets was facilitated (cuing benefits) whereas it took longer to detect targets in invalid trials (cuing costs) because participants who reflexively drew their attention to the cue needed to disengage their attention away from the cue and then re-engaged to the target that appeared on the other location. Stormark et al. (1995) used emotional and neutral words as cues and compared the spacing cues. They found that participants were faster RTs to validly cued targets, but only when the emotional words were used as cues. The results demonstrated that emotional cuing mainly influenced the “engage” mechanism of spatial orienting. Another study by these researchers showed that when the cue was aversively conditioned with a
white noise tone, participants were able to quickly shift their attention away from the location of the fear-conditioned cue (Stormark & Hugdahl, 1996). Taken these findings together, it has been suggested that emotional importance may direct one’s attention either toward or away from the relevant location (Hugdahl & Stormark, 2003).

According to Thayer and Lane, (2000), the inability to effectively process emotional information may lead to emotional dysregulation, which then can result in various forms of pathology such as depression, panic disorder, generalized anxiety disorder, hostile personality and coronary heart disease. A large body of research has indicated that selective attention to threatening information is associated with high anxiety (Williams et al, 1988). Mathews and MacLeod (1985) used the emotional Stroop task. In the task, 24 clinically diagnosed anxiety patients 24 controls were presented with threatening and neutral words written in different colors. Threatening words consisted of the equal number of physically threatening items and socially threatening items. The result showed that anxious individuals took longer to name the colors of ink in which threatening words were written. They were particularly slower to items that were highly relevant to their anxiety state. For instance, anxious individuals who constantly worried about their physical health were particularly slower to health-threatening items. MacLeod, Mathews and Tara (1986) used the visual dot-probe procedure in which pairs of words, one anxiety-related word and one neutral word, were simultaneously presented for 0.5 second and then a probe appeared where either of the words was presented. Participants were instructed to indicate where the probe appeared by pressing a button as quickly as possible. The result indicated that anxious individuals responded faster when
the probe replaced the threatening word. MacLeod et al. (1986) concluded that the attentional bias of people with high anxiety occurred at the perceptual level, which facilitated the encoding of information congruent to their emotional state. This study (MacLeod et al., 1986) has been replicated with various subject groups, including generalized anxiety disorder (Bradley et al., 1986), obsessive-compulsive disorder (Tara et al., 1996) and panic disorder and specific phobia (Ehlers & Breuer, 1995). Based on these findings, many theories of clinical anxiety suggested that attentional biases favoring negative information played an important role in the etiology and maintenance of clinical anxiety (Williams et al., 1988).

1.2 Self-regulation and heart rate variability

Selective attention is an important aspect of self-regulation (Thayer & Lane, 2000). The ability to select meaning information and to ignore irrelevant information is crucial for one’s survival and adaptability (Thayer & Lane, 2000). Self-regulation is defined as the ability to generate responses that are appropriate to meet constantly changing environmental demands (Thayer & Lane, 2000; 2002). The world is constantly changing, and it is important for any organism to be able to produce responses that are flexible and adaptable to constantly changing environmental demands. Self-regulation allows us to meet constantly changing environmental demands by selecting appropriate responses, inhibiting inappropriate responses, and coordinating various subsystems (Thayer & Lane, 2002).

Several researchers have identified neural circuits in the CNS that are responsible for autonomic, emotional and cognitive self-regulation (Thayer & Lane, 2000). One of
the important functional units that is associated with self-regulation is the central autonomic network (CAN; Benarroch, 1993). The structures of the CAN include the anterior cingulate, insula, ventromedial prefrontal cortices, the central nucleus of the amygdala, the paraventricular and related nuclei of the hypothalamus, the periaqueductual gray matter, the parabrachial nucleus, the nucleus of the solitary tract (NTS), the nucleus ambiguous, the ventrolateral medulla, the ventromedial medulla, and the medullary tegmental field. These components in the CAN are reciprocally interconnected, which allows information to flow from both directions, top-down and bottom-up (Theyer & Lane, 2000, 2002). Also, these components are loosely connected so that it is possible to recruit additional structures when it is necessary to make specific behavioral adaptations (Thayer & Lane, 2000, 2002). The anterior executive region (AEG) has been identified by Devinsky et al. (1995) and Posner and Peterson (1990) as a functional unit to regulate attention. Damasio (1998) also identified the similar neural substrates as the neural circuits that are responsible for emotional regulation. Thayer and his colleagues (Thayer & Siegle, 2002; Thayer & Lane, 2002) suggested that these were essentially the same functional structures that were involved in the process of response selection, organization, and distribution of physiological resources of attention and emotion.

Thayer and his group linked these neural structures to HRV (Thayer & Friedman, 2004). The output of the CAN is mediated by the preganglionic sympathetic and parasympathetic neurons which then innervate the heart through the stellate ganglia and the vagus nerves, respectively (Thayer & Lane, 2000; Thayer & Friedman, 2004). Two
inputs from the stellate ganglia and the vagus nerves interact at the sino-atrial node of the heart and create the complicated variability that determines the heart rate time series (Thayer & Lane, 2000; Thayer & Friedman, 2004). Therefore, there is a direct link between the CAN and HRV (Thayer & Friedman, 2004).

Heart rate variability (HRV) refers to the beat-to-beat alteration in heart rate (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Electrocardiography (ECG) records the electrical activity of the heart over time via skin electrodes (Thayer et al, 2006). In a continuous electrocardiographic (ECG) recording, each QRS complex is detected (See Figure 1). All intervals between adjacent QRS complexes are defined as the normal-to-normal (NN) intervals (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). HRV can be measured in both time and frequency methods, which have both been used to index vagal activity (Task Force, 1996). Time domain methods can be based on direct measurements of the NN intervals or the differences between NN intervals (Thayer et al., 2006; Task force, 1996). Additionally, time domain methods may be indexed either on short-term recording with a duration on the order of magnitude of minutes or on long-term recordings of 24-hours. The methods based on direct measurements of the NN intervals include the standard deviation of the NN interval (SDNN) and the standard deviation of the average of NN interval for each 5 minutes period over 24 hours (SDANN) (Thayer et al, 2006; Task force, 1996). The time domain methods can be based on the differences between successive NN intervals, which includes the percentage of difference between successive NN intervals greater than 50 ms.
(pNN50) and the root mean square of success differences in milliseconds (RMSSD) (Thayer et al., 2006; Task force, 1996). pNN50 is derived by dividing the number of successive NN interval differences greater than 50 ms by the total number of NN intervals (Task force, 1996). RMSSD is the most commonly used method derived from interval differences and mainly indexes vagally-mediated cardiac control (Thayer et al., 2006).

Spectral analysis of HR variability is a highly recommended method to index sympathetic and parasympathetic cardiac influences (Thayer et al., 1996). In the frequency domain methods, the HR time series is decomposed into its frequency components, which then can be described in terms of a spectral density function that provides the distribution of power as a function of frequency (Berntson et al., 1997; Thayer et al., 2006; Task Force, 1996). Specific power of a given frequency is computed by taking an area under the spectral density function within specific frequency ranges. There are four spectral components that can be distinguished from 24-hour recordings (Task Force, 1996). The high frequency power of HRV ranges from 0.15 Hz to 0.4 Hz and exclusively mediated by the vagus nerves because only the parasympathetic nervous system can react fast enough to mediate high-frequency fluctuations in heart rate corresponding to the high frequency peak of the spectrum (Thayer et al., 2006; Thayer et al., 1996; Task force, 1996). Levy, DeGeest, and Zieske (1966) showed that the effect of vagal stimulation on the heart is considerably shorter than for the effect induced by sympathetic activation. The latency of the HR deceleration after a single shock to the vagus is 240-300 ms in the dog and 100-160 ms in the cat whereas with sympathetic
stimulation, HR acceleration occurs after 2 sec. The low frequency band ranges from 0.04 to 0.15 and reflects both sympathetic and parasympathetic influences. Low frequency to high frequency heart rate variability ratio (LF/HF) represents the relative valence of sympathovagal activity, which can be obtained by diving LF by HF (Task force, 1996). Very low frequency is ranged from 0.003 Hz to 0.05 Hz and represents thermoregulatory cycles or fluctuations related to plasma rennin activity (Berntson et al., 1997). The range below 0.003 Hz is considered to be ultra low frequency.

1.3 Inhibitory Cortical Modulation on Subcortical Structures and the Neuroviceral Integration Model.

The intricately interconnected CAN allows the prefrontal cortex to exert inhibitory control on subcortical structures that are responsible for defensive behavior (Thayer & Lane, 2000; Thayer & Friedman, 2004; Mayberg et al., 1999). During emotionally stressful and threatening situations, sympathoexcitatory subcortical circuits prepare an organism to make an action, commonly known as the fight or flight response (Thayer & Seigle, 2002; Thayer & Ruiz-Padial, 2006). However, this defensive response pattern may not be suitable for many other situations, and prolonged sympathoexcitatory subcortical activity will eventually wear and tear the system. Therefore, it is necessary to have a mechanism by which sympathoexcitatory subcortical activity is controlled. Various studies suggest that the prefrontal cortex modulates the activity of sympathoexcitatory subcortical structures (Thayer & Lane, 2000; Thayer & Friedman, 2004). Research suggested that cortical structures are reciprocally interconnected with subcortical structures that mediate cardiovascular activity. Ter Horst and Postema (1997)
identified the direct and indirect pathways by which the medial prefrontal cortex exerted an inhibitory control over cardiovascular activity in rats. They used the retrograde transneuronal transport of pseudorabies virus. In the study (Ter Horst et al., 1997), pseudorabies virus injected in various parts of the heart and traced along infected neurons in the brain that were involved in the regulation of cardiovascular activity. The infected areas included: (1) **brain stem.** CVMs in the periaqueductal gray, the periaqueductal gray, the precommissural nucleus, the mesencephalic reticular formation, the peripeduncular nucleus, the perirubral area, the parvocellular paraventricular nucleus, the dorsomedial hypothalamic area, the dorsal part of the lateral hypothalamic nucleus. (2) **Midbrain.** the periaqueductal gray, the precommissural nucleus, the mesencephalic reticular formation, the peripeduncular nucleus, the perirubral area, the parvocellular paraventricular nucleus, the dorsomedial hypothalamic area, the dorsal part of the lateral hypothalamic nucleus. (3) **Forebrain.** The anterior cingulate, the pre- and infralimbic cortices, the dysgranular insular cortex, the central and medial amygdaloid nuclei, the subfornical organ, the ventral part of the lateral septal nucleus. Further more, Lane et al. (2001) investigated neural structures implicated in HRV during emotional arousal. They correlated vagally-mediated HRV with cerebral blood flow (rCBF) in a positron emission tomography (PET). Happy, sad, disgust and neutral emotions were induced by watching film clips and recalling personal experiences. Lane et al. (2001) used Positron emission tomography (PET) and $^{15}$O-water to assess cerebral blood flow and correlated them with the high frequency (HF) of heart rate variability (HRV) that indexed vagal tone in
healthy women. During emotional arousal, there was a reduced HRV and concomitant decreases in brain activation in the medial prefrontal cortex and the left posterior orbitofrontal and anterior insular cortices, which supported a general inhibitory role that the medial prefrontal cortex played via the vagus as suggested by Ter Horst et al. (1997).

Therefore, during emotional stress, the prefrontal cortex disinhibits its inhibitory control over sympathoexcitatory subcortical circuits and allows subcortical neural structures such as the amygdale to make autonomic and prepotent responses to the situation. However, when the prefrontal cortex identifies certain safety signals from environments, it exerts its inhibitory control over sympathoexcitatory subcortical circuits and makes responses that are appropriate for contexts in which the signals occur. Consequently, this inhibitory cortical-subcortical circuit is essential for self-regulation (Thayer & Lane, 2002). The prefrontal inhibitory mechanism allows the organism to make flexible, adaptive responses that are appropriate for constantly changing environmental demands (Thayer & Lane, 2000; 2002). On the other hand, the breakdown of the inhibitory mechanism can activate the excitatory positive feedback loop which may lead to emotional, attentional, and autonomic dysregulation and the emergence of perseverative behavior such as worry. As a result, the organism may be less able to keep track of changing environmental demands, which eventually lead to develop psychological and physiological problems.

In the Neurovisceral Model, Thayer and his colleagues (2000, 2002) suggested that HRV could serve as an index of the inhibitory cortical-subcortical circuit. Recently, Ahern et al. (2001) used the Wada test to show that the functioning of cortical-subcortical
inhibitory circuits can be indexed by HRV. In the Wada test, participants were injected with sodium amobarbital which allowed the temporary inactivation of each hemisphere. The data suggested that the inactivation of frontal cortex was associated with an increase in HR and the LF/HF ratio which indicated more sympathetic than parasympathetic cardiac modulations. Consistent with the Neurovisceral model, this result suggested that reduced vagally mediated HRV reflected the prefrontal inactivation which was associated with the disinhibition of subcortical structures. Also, a greater reduction of HRV after the inactivation of the right hemisphere was consistent with previous findings that the right hemispheric autonomic inputs to the hearts were more closely related to the control of heart rate than those from the left hemisphere (Thayer et al, 1996). Thus, this study provided evidence to show that HRV can index inhibitory activity of the prefrontal cortex over subcortical sympathoexcitatory circuits. In the Neurovisceral Model, Thayer and his colleagues (2000, 2002) suggested that high HRV represents the highly integrated cortical-subcortical circuit that is associated with good cognitive, emotional and autonomic self-regulation whereas low HRV reflects rigid neurovisceral integration.

1.4 HRV and Emotional Regulation

Ruiz-Padial et al. (2003) investigated whether HRV was associated with emotional regulation by correlating HRV with the startle reflex. The startle reflex is a complicated involuntary reaction to a sudden unexpected stimulus like a loud noise (Vrana et al, 1988). Lang and his colleagues have established that the startle reflex was modulated by emotional pictures that were presented on the foreground. They found that
the presentation of pleasant pictures on the foreground reduced the startle reflex, as measured by the magnitude of eyeblinks to startle probes such as a burst of white noise, whereas the presentation of unpleasant pictures significantly increased the startle reflex. The increased startle response to negative stimuli is a strong, robust phenomenon that has been replicated by numerous studies (Bradley et al, 1993; Bradley et al, 1999; Vrana et al, 1988; Larson et al., 2005). Davis and his colleagues suggested that the central nucleus of the amygdale plays an important role in modulating the startle reflex (Campeau & Davis, 1995; Hitchcock & Davis, 1986). According to the Neurovisceral Model (Thayer & Lane, 2000, 2002), the prefrontal cortex regulates the activity of the amygdale, which then can be indexed by HRV. Therefore, when the prefrontal cortex disinhibits its inhibitory control, the amygdala becomes active, which can be indexed by the magnitude of eyeblinks. In the study by Ruiz-Padial et al. (2003), participants performed the emotionally modulated startle task during which their heart rate was continuously measured. People with higher levels of vagally mediated HRV at rest showed the expected pattern of highly differentiated startle responses, decreased startle responses to positive pictures and increased startle responses to negative ones. Individuals with lower levels of vagally mediated HRV showed generally greater startle responses than those with high HRV, regardless of valence of pictures. In other words, individuals with lower vagally mediated HRV showed oversensitive startle responses, which reflected the hyperactive amygdale that resulted from the disinhibition of the prefrontal control. More importantly, they showed undifferentiated responses to negative and neutral pictures, which indicated that they failed to recognize safety signals and responded to
neutral pictures as if they were negative. This failure to recognize safety signals can lead to prolonged activation of sympathoexcitatory circuits, which in turn sustains the activity of the physiological, behavioral defense system. The result suggested that greater HRV was associated with emotional responses that were appropriate for emotional contexts. However, individuals with lower levels of vagally mediated HRV showed hypervigilant threat responses that would eventually cause emotional and health problems in the long run (Thayer & Ruiz-Padial, 2006).

1.5 HRV and Cognitive Regulation

The association between HRV and cognitive regulation was studied by Hansen et al. (2003, 2004). Hansen et al. (2003) tested whether resting HRV could be a predictor for performance on cognitive tasks in healthy adults. Forty male sailors from the Royal Norwegian Navy participated in the study and their resting HRV was measured. Then they were asked to perform an attentional task and a working memory task. In the attentional task, participants were asked to press a button as quickly as possible, when a target number was presented and when two numbers were presented in sequence. They adapted the working memory test developed by Hugdahl et al. (2000) based on the research by Baddeley and Hitch (1974). The working memory consisted of a continuous flow of different numbers, and participants were asked to detect identical numbers to the one presented two trials before. The result suggested that people with higher levels of vagally mediated HRV had faster reaction times, more correct responses and fewer false alarms in working memory tasks compared to those with lower levels of vagally mediated HRV.
In their second study, Hansen et al. (2004) investigated whether changes in HRV resulted in changes in cognitive functions. They used physical exercise as a way to change HRV. Resting HRV was indexed by the log of the high frequency spectral power (HF) because the distribution of the high frequency is often positively skewed and the data are analyzed after a natural logarithmic transformation (Vongpatanasin et al, 2004). Thirty eight sailors went through 8-weeks of basic training and performed the attentional and working memory tasks (the pre-test). Half of the sailors were randomly assigned to a duty that prevented them from continuing physical exercise training (the detraining group). The other half was able to continue their physical exercise program (the training group). After 4 weeks, all participants performed the same cognitive tasks (the post-test). The detraining group showed a decrease in maximum oxygen consumption (VO$_2$ max) during the post test compared to the pre-test. Also, the log of the high frequency spectral power (HF) was reduced from the pre-test to the post-test. The detraining group also showed lower HRV and VO$_2$ max than the trained group during the post test. Only the training group showed high HRV and performed significantly better on the task involved in executive functions during the post-test compared to the pre-test. The data supported that changes in HRV by physical exercise resulted in changes in performance on cognitive tasks.

1.6 HRV and Attentional and Emotional Regulation

Thayer and his colleagues (2000) showed that vagally mediated HRV was associated with phasic cardiac indices of attention and emotion. Nonanxious controls with higher vagally mediated HRV were associated with greater orienting responses but
faster habituation to nonthreat stimuli. However, generalized anxiety disorder (GAD) patients who typically have less tonic HRV showed different patterns of triphasic cardiac responses that were associated with different stages of attention. GAD patients failed to show habituation to neutral words. Also, during the presentation of threat stimuli, GAD patients showed an acceleration in HR which indicated heightened sensitivity and a cognitive defensive response to reject the stimuli.

Another study by Johnsen et al. (2003) showed that dental phobics with higher levels of vagally mediated HRV showed better inhibition of prepotent responses in a Stroop task as indicated by faster reaction time to color-incongruent and threat-relevant words compared to those with lower levels of vagally mediated HRV. These studies show that individuals with higher levels of vagally mediated HRV are associated with better regulated attentional and emotional functions than those with lower levels of vagally mediated HRV.

1.7 The Goal of the Study.

In sum, effective self-regulation requires selective attention that is often modulated by emotions. However, there is no study to directly examine the relationship between selective attention and HRV which is considered to be an index of self-regulation. The purpose of the present study was to investigate whether HRV could have effects on selective attention tasks with emotional stimuli under different perceptual load. Recently, Bishop et al. (2007) used emotionally neutral and fearful facial pictures to test whether different load conditions determined the degree of processing that emotionally salient distractors, such as facial expressions of different emotions, underwent, as Lavie
suggested (1995, 2005). In a high load condition, letter strings consisted of one target letter (either X or N) and five nontarget letters (H, K, M, W, Z) arranged in random order. In a low load condition, letter strings consisted of either 6 Xs or 6 Ns. These letter strings were superimposed on either fearful or neutral facial distractors. Participants were asked to identify whether a target was either X or N as fast as they could. They used a mixed block/event-related designed-the level of perceptual load for the letter searching task being varied across blocks, the distractor valence (fearful or neutral) being varied within blocks on a trial by trial basis.

Bishop et al. (2007) reported mean reaction times and error rates for the 4 conditions: low load, fearful distractors, mean reaction time(RT) = 760 ms, SD = 33 ms; mean error rate = 6.9%, SD = 2.6%; low load neutral distractors, mean RT = 767 ms, SD = 37 ms; mean error rate = 5.8%, SD = 1.6%; high load fearful distractors, mean RT = 1191 ms, SD = 64 ms; mean error rate = 30.6%, SD = 3.2; high load neutral distractors, mean RT = 1220 ms, SD =59 ms; mean error rate = 36.4%; SD = 3.1%. The result by Bishop et al. (2007) suggested that people in the low perceptual load condition performed significantly better at identifying targets, as indicated by faster reaction time and better accuracy, compared to those in the high perceptual load condition [F(1,17) = 91.94, p < 0.001 for RT; F(1, 17) = 137.53, p <0.01]. There was no significant interaction between distractor valence and load on RT. However, participants were more accurate with fearful face distractors under high load. In this study, all participants underwent the letter search task that Bishop et al. (2007) used. The hypotheses of the study are as follows:

(1) It was expected to obtain load effects such that participants under high perceptual
load had significantly higher mean RTs and percent error rate than those under low perceptual load to ensure the success of load manipulation.

(2) We also hypothesized that individuals with higher levels of vagally mediated HRV would be associated with faster RTs or better accuracy in the task, indicating their superior ability to inhibit irrelevant distractors and focus on task-relevant stimuli based on the studies by Hansen et al. (2003, 2004).

(3) The high HRV group was also expected to make responses that were appropriate for emotional contexts such that they would have faster RTs to detect targets with fearful distractors in both high and low load conditions. There are a large number of studies that indicate processing biases favoring negative information are associated with developing emotional disorders such as anxiety or depression (Williams et al., 1988). Fox et al. (2001, 2002) reported that anxious individuals showed a difficulty in disengaging their attention away from negative information whereas low anxious individuals were capable of quickly disengaging away from it. It is more likely that being exposed to more negative information can trigger more negative emotional experiences. Therefore, it was expected that individuals with higher levels of vagally mediated HRV would use their superior attentional control to make faster responses with fearful distractors so as to quickly disengage their attention away from negative information.

(4) Individuals with lower levels of vagally mediated HRV were expected to make undifferentiated responses to negative and neutral distractors because of hypo-prefrontal inhibitory activity and overactivation of subcortical structures (Ruiz-
Padial et al., 2003).
CHAPTER 2

METHODS

2.1 Participants

Participants were 77 (45 females and 32 males) undergraduate students at the Ohio State University enrolled in Introductory Psychology courses. They participated in the study for partial fulfillment of course requirements. Participants were asked to refrain from smoking or drinking caffeinated beverages for 4 hours before the experiment. All participants had normal or corrected-to-normal vision. Three participants were excluded from the data analysis because of extreme RTs and equipment failure.

2.2 Design and Stimuli

The design defined 4 conditions of 2 distractor types X 2 perceptual load conditions which were administrated in a between subject design. Two distractor types were neutral and fearful face expressions. We selected fearful and neutral facial expressions of 12 different individuals, 6 females and 6 males, from the Pictures of Facial Affect (Ekman & Friesen, 1976). Each face was edited to remove extraneous background information. Each face measured 4.3° horizontally and 6.2° vertically against a white background. Our perceptual load manipulation is identical to the ones that Bishop et al. (2007) used. In the high perceptual load condition, the letter string comprised one target letter (X or N) and 5 nontarget letters (H, K, M, W, or Z) arranged in random order. Each
letter measured 0.4° X 0.5° of visual angle and was separated from its neighbors by 0.2°. As can be seen in Figure 2 and 3, each display consisted of a face with the middle of the nose at fixation and a string of 6 letters superimposed across this middle point. In the low perceptual load condition, the letter string consisted of six X’s or six N’s. Viewing distance was 60 cm. The particular faces used for high load and low load were counterbalanced across participants. The combination of target letter identity and target letter positions was counterbalanced across 4 different conditions.

2.3 Psychosocial Measures

We used the Penn State Worry Questionnaire which is a 16-item Likert scale type instrument frequently used to measure trait worry. The PSWQ demonstrates strong internal consistency (α = 0.88 - .95) and overall validity (Meyer, Miller, Metzger, & Borkovec, 1990; Fresco, Heimberg, Mennin, & Turk, 2002). The State-Trait Anxiety Inventory is a 40-item measure of both a transitional emotional experience (State items 1-20) and a stable tendency to experience anxiety (Trait items 21-40). The STAI demonstrates good internal consistency and construct validity (Spielberger & Vagg, 1984). Respondents are instructed to respond to items on a scale of 1 (almost never) to 4 (almost always).

2.4 Procedure

All participants were tested individually. They were brought to the lab and 7 surface electrodes were attached to obtain electrocardiograph data. After placement of electrodes, the resting HRV was recorded for 5 min. After 5-min of baseline, participants performed the letter search task that we adapted from Bishop et al. (2007).
searching task, participants were presented with one practice block of 12 trials with just letter strings presented, followed by the experiment block, consisting of 48 trials. Each trial began with a fixation point for 500 msec, followed by the display with a string of 6 letters superimposed on a face for 200 msec. The interstimulus interval was randomly generated with a mean of 4.5s. Participants were instructed to focus on the letter strings and to identify whether the letter string contained an “X” or an “N” by pressing the corresponding keys on the keyboard as fast and accurately as possible. They were also told to ignore facial expressions throughout. After the task, participants went through a 5 min recovery period. After the recovery period, participants completed the Spielberger State-Trait Anxiety inventory (STAI; Spielberger 1983) and the Penn State Worry Questionnaire (PSWQ). The participants were divided into two groups, high HRV or low HRV, based on the median split of log HF during baseline. We also divided our participants into high HRV and low HRV based on the median split of log LF during baseline and examined their performance on the task.

2.5 Physiological Measurements

Physiological data was collected by the MindWare 2000D (MW2000D) Impedance Cardiograph package. The MW2000D has a built in 14 bit A/D converter with a maximum sample rate of 48k samples/second. The MW2000D injects a high precision frequency constant current of 400 micro amps that measures the impedance across the thorax. The precision electronics derive and output three signals, the impedance signal (Zo), its derivative (dZ/dt), and electrocardiography (ECG), to be digitized by the USB A/D card. For the purposes of this study I focused on heart rate
variability. Data were then be analyzed by the suite of MindWare Technologies Signal Processing Applications (www.mindwaretech.com/product_physiosoftware.html). Time and frequency domain analysis were performed using the Kubios heart rate variability package (http://basmig.uku.fk/biosignal). Specifically, we chose to use autoregressive estimates because it had the advantage of providing good spectral estimates without the need of being concerned with the windowing problem. With the fast Fourier transform (FFT), it is necessary to specify the boundaries of the frequency bands in advance (Thayer et al, 2006). This is called ‘windowing’ problem, which can result in serious misinterpretations of the data if the frequencies of interest are missed (Thayer et al, 2006). However, the autoregressive algorithm does not have the windowing problem because it uses a true components analysis that empirically determines the central frequency and width of the bands on an individual basis (Thayer et al, 2006). Through these programs, we can obtain very low frequency (VLF) and low frequency (LF) bands of HRV, high frequency/respiratory sinus arrhythmia (HF/RSA) power, heart rate (HR), respiration rate (RR), inter-beat interval (IBI) series, HR and respiration power spectra.
CHAPTER 3

RESULTS

3.1 Reaction Times and Percent Error Rate Data for High Frequency HRV

<table>
<thead>
<tr>
<th>Task load</th>
<th>High HF_HRV</th>
<th></th>
<th>Low HF_HRV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fear distractors</td>
<td>Neutral distractors</td>
<td>Fear distractors</td>
<td>Neutral distractors</td>
</tr>
<tr>
<td>High</td>
<td>Mean</td>
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<td>745</td>
<td>883</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>75.9</td>
<td>156</td>
<td>188.4</td>
</tr>
<tr>
<td></td>
<td>% E</td>
<td>17</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>10</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Low</td>
<td>Mean</td>
<td>401</td>
<td>468</td>
<td>448</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>30.8</td>
<td>39.3</td>
<td>80.5</td>
</tr>
<tr>
<td></td>
<td>% E</td>
<td>3.9</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.1 Means of RTs (in milliseconds), standard deviation, N’s, and percentage of errors as a function of task load, distractor valence, and HF_HRV levels.

Table 1 shows the number of subjects (N), mean reaction times, standard deviations and percent error rates. First, to assess the success of the experimental manipulations, we sought to replicate the findings of Bishop et al. (2007). As can be seen in Figures 4 and 5, mean RTs and percent error rate in the letter identification task were significantly higher in the high load condition (mean RT = 855 msec, 22% errors) than in the low load condition (mean RT = 434 msec, 3% errors), suggesting that we successfully...
manipulated perceptual load \([F(1, 72) = 257.15, p < .001\) for RTs; \(F(1, 72) = 92.67, p < .001\) for errors]. Like Bishop et al. (2007), we found no significant interaction of distractor expressions by different perceptual loads in RTs. We also replicated the result of Bishop et al. (2007) and had the significant interaction of distractor valence by load on accuracy, \(F(1, 70) = 5.944, p < 0.017\), with performance being more accurate with fearful distractors under the high perceptual load (see Fig. 6). These results which replicate the findings of Bishop et al. (2007) suggest that our experimental manipulations were effective.

We next sought to investigate the role of HF_HRV on task performance on the high and low perceptual load conditions with fearful and neutral distractors. The RTs and percent error rate data were subjected to a 2 (task load: high and low) \(\times\) 2 (distractor valence: fearful and neutral) \(\times\) 2 (HRV groups: high and low) between-subject analysis of variance (ANOVA). Although there was no significant 3-way interaction on percent error data, \(F(1, 66) = 1.798, p = 0.185\), there was a significant interaction on the RT data, \(F(1, 66) = 6.299, p < 0.015\). Then, we examined the effect of HF_HRV on the task under low load and under high load separately. The RT data were analyzed in a 2 (HRV groups) \(\times\) 2 (distractor valences) between-subject analysis of variance (ANOVA). In the low load condition, there was a significant interaction between HRV and distractor valence on RT, \(F(1, 34) = 7.525, p < 0.010\) (see Fig. 6). However, there was no main effect of HRV groups. A planned comparison using a one-tailed t-test revealed that under low load, high HRV individuals were significantly faster to detect targets with fearful distractors than with neutral distractors, \(t(16) = -3.911, p < 0.001\). However, there was no significant
difference in RTs between fearful and neutral distractors by the low HRV group, \( t(18) = 1.116, p = .139 \). Although there was no significant difference in RTs between the high HRV and the low HRV groups when distractors were fearful, \( t(16) = -1.538, p = .072 \), the low HRV was significantly faster when distractors were neutral, \( t(18) = 2.472, p < 0.012 \).

In the high perceptual load condition, there was no significant interaction between the HRV groups and distractor valence on the RTs, \( F (1, 32) = 2.478, p = 0.125 \) (see Fig. 8). To test our prediction, planned comparisons using one-tailed t-tests were conducted to test a difference between the high HRV and low HRV groups. The high HRV group had significantly faster RTs than the low HRV group when distractors were neutral, \( t(14) = -2.186, p < 0.023 \). However, RTs for both groups were not different from each other when distractors were fearful, \( t(18) = -0.067, p = 0.473 \). The high HRV group also showed significantly faster RTs when distractors were neutral compared to when distractors were fearful, \( t(16) = 2.396, p < 0.015 \) whereas the low HRV did not show any reaction time difference between fearful and neutral distractors, \( t(16) = -0.218, p = 0.415 \).

### 3.2 Anxiety Data

<table>
<thead>
<tr>
<th></th>
<th>High HF_HRV</th>
<th>Low HF_HRV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load conditions</td>
<td>High load</td>
<td>Low load</td>
</tr>
<tr>
<td>PSWQ Mean</td>
<td>45.76</td>
<td>46.33</td>
</tr>
<tr>
<td>SD</td>
<td>14.84</td>
<td>11.2</td>
</tr>
<tr>
<td>N</td>
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<td>18</td>
</tr>
<tr>
<td>State Mean</td>
<td>36.72</td>
<td>41.83</td>
</tr>
<tr>
<td>SD</td>
<td>11.84</td>
<td>13.62</td>
</tr>
<tr>
<td>N</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Trait Mean</td>
<td>36.35</td>
<td>38.5</td>
</tr>
<tr>
<td>SD</td>
<td>11.85</td>
<td>9.49</td>
</tr>
<tr>
<td>N</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3.2. Means, standard deviation, N’s on the STAI Trait and State Anxiety Scales and the PSWQ as a function of task load and HF_HRV levels.
Table 2 displays means, standard deviations and the number of subjects on the Spielberger Trait and State Anxiety Inventory state and trait scales and the PSWQ. Median splits were performed on the total scores of the STAT-I and the PSWQ to create high and low categories. We computed the mean RTs and standard deviations as a function of levels of anxiety and HF_HRV, task load and distractor valence, and presented them in Table 3.3.

<table>
<thead>
<tr>
<th>Anxiety levels</th>
<th>High HF_HRV</th>
<th>Low HF_HRV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fear distractors</td>
<td>Neutral distractors</td>
</tr>
<tr>
<td>PSWQ</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>874.3</td>
<td>881.6</td>
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<tr>
<td>SD</td>
<td>89.6</td>
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</tr>
<tr>
<td>N</td>
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<tr>
<td>State</td>
<td>883.1</td>
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<tr>
<td>SD</td>
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<td>75.5</td>
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<tr>
<td>N</td>
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<td>6</td>
</tr>
<tr>
<td>Trait</td>
<td>107.7</td>
<td>69</td>
</tr>
<tr>
<td>SD</td>
<td>107.7</td>
<td>69</td>
</tr>
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<td>N</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3.3 Means of RTs, standard deviations, and N’s as a function of levels of anxiety, HF_HRV, task load, and distractor valence.
Three separate 2 (anxiety: high and low) X 2 (distractor valence: fearful and neutral) X 2 (task load: high and low) between-subject ANOVAs were conducted on the mean RT data with trait-anxiety, state-anxiety and the PSWQ scores. There was no significant 3-way interaction [F(1, 65) = 2.278, p = 0.136 for the PSWQ; F(1, 66) = 0.019, p = 0.892 for the state anxiety; F(1, 65) = 0.002, p = 0.966 for the trait anxiety]. However, there were main effects of the PSWQ, F(1, 65) = 4.571, p = 0.036, and the trait-anxiety, F(1, 65) = 5.196, p = 0.026. There was also a significant two-way interaction between the PSWQ and distractor valence, F(1, 65) = 7.048, p = 0.010.

We used the two-tailed t test to study the relationship between the high and low PSWQ groups with different distractor valence because we did not make a specific a priori prediction. Under high load, there was a significant difference between high and low PSWQ participants in RTs when distractors were neutral, t(13) = 2.808, p < 0.015, with low PSWQ individuals showing faster RTs. However, there was no significant difference between high and low PSWQ individuals when distractors were fearful, t(18) = -0.296, p = 0.771 (see Fig. 9). Under low load, there was a significant mean RTs difference between high and low PSWQ groups when distractors were neutral, t(18) = 2.139, p < 0.046, with the low PSWQ group showing faster RTs. However, there was no difference with fearful distractors, t(16) = -0.210, p = 0.837 (see Fig. 10).

3.3 Percent Error Rate Data
<table>
<thead>
<tr>
<th>Anxiety levels</th>
<th>PSWQ</th>
<th>SD</th>
<th>N</th>
<th>State</th>
<th>SD</th>
<th>Trait</th>
<th>SD</th>
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<td><strong>High load</strong></td>
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<tr>
<td>PSWQ 20.5</td>
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<td>28.3</td>
<td>35</td>
<td>17.8</td>
<td>19.5</td>
<td>24.7</td>
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<tr>
<td>SD 12</td>
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<td>18.2</td>
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<td>9.3</td>
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<td>SD 4.9</td>
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<td>3</td>
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<tr>
<td><strong>Low load</strong></td>
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<td>PSWQ 3.33</td>
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Table 3.4 Percent error rates, standard deviations, and N’s as a function of levels of anxiety, HRV, task load, and distractor valence.

Percent error rates, standard deviations, and the number of subject are displayed in table 4. We conducted three separate 2 (anxiety: high and low) X 2 (distractor valence: fearful and neutral) X 2 (task load: high and low) between-subject ANOVAs on the percent error rate data with trait-anxiety, state-anxiety and the PSWQ scores. There was no significant 3-way interaction [F(1, 65) = 0.862, p = 0.357 for the PSWQ; F(1, 66) = 0.027, p = 0.871 for the state anxiety; F(1, 65) =0.282, p = 0.597 for the trait anxiety].

3. 4 Reaction Times and Percent Error Rate for Low Frequency HRV.
Table 3.5 Means of RTs (in milliseconds), standard deviation, N’s, and percentage of errors as a function of task load, distractor valence, and LF_HRV levels.

We examined the effect of LF_HRV on task performance on the high and low perceptual load conditions with fearful and neutral distractors. The RTs and percent error rates data were subjected to a 2 (task load: high and low) X 2 (distractor valence: fearful and neutral) X 2 (HRV groups: high and low) between-subject analysis of variance (ANOVA). There was marginally significant 3-way interaction on the RTs, F(1, 66) = 3.595, p = 0.062. However, there was no significant 3-way interaction with percent error rates data, F(1, 66) = 1.620, p = 0.208.

3.5 Correlation Between HRV and Various Anxiety Measures

Table 3.6 Correlations between HRV and the PSWQ and the state and trait anxiety measure (p values).
HRV, and various anxiety measures, the PSWQ, the state and trait anxiety. None of them reached significance (see Table 3.6).
CHAPTER 4

DISCUSSION

The ability to select important information and to ignore irrelevant distractors is an important aspect of self-regulation (Thayer & Lane, 2000). In this study, we examined the relationship between the selective attentional task under high and low load and vagally mediated HRV considered to be an indicator of self-regulation. We successfully replicated what Bishop et al. (2007) found, which suggested that our experimental manipulation of different perceptual load conditions was successful. Like Bishop et al. (2007), the high perceptual load condition in our study required more demands on processing resources than the low perceptual load condition. Then, I examined the effects of vagally mediated HRV on the task under high and low load. The results of the study demonstrate that under both high and low load conditions, individuals with lower vagally mediated HRV show no difference in RTs between conditions with fearful distractors and conditions with neutral distractors (see Fig. 11). However, for individuals with higher levels of vagally mediated HRV, the valence of distractors played a different role in reducing RTs under different load conditions. Under low perceptual load, individuals with higher vagally mediated high HRV were significantly faster to detect targets with fearful distractors compared to those with neutral distractors. Under high perceptual load, the opposite pattern was observed; individuals with higher levels of
vagally mediated HRV were significant faster to detect targets with neutral distractors than with fearful distractors (see Fig. 12)

I can explain the result in the context of the Neurovisceral Model proposed by Thayer & Lane (2000, 2002). The model is based on the idea that there is top-down inhibitory activity of the prefrontal cortex on sympathecitatory subcortical circuits which are essential for defensive behavior. The model suggests that this prefrontal inhibitory modulation plays an important role in making self-regulatory responses, which then can be indexed by HRV. Greater HRV is associated with greater prefrontal inhibitory tone that modulates subcortical activity, which allows an organism to make self-regulatory responses, including the selection of appropriate information and the inhibition of inappropriate information (Thayer & Lane, 2000). Reduced HRV is associated with hypo-prefrontal inhibitory activity and overreactive subcortical structures, which leads to the failure of detecting safety signals in environments and allows to make hypervigilant responses (Thayer & Lane, 2000).

Under both high and low perceptual load conditions, as we predicted, the low HRV group made undifferentiated responses to neutral and fearful distractors. According to the Neurovisceral model (Thayer & Lane, 2000; 2002), reduced HRV reflects diminished inhibitory cortical activity and the prolonged activation of subcortical sympathecitatory circuits, which results in making hypervigilant behavioral patterns because of their failure to recognize safety signals in environments. Ruiz-Padial et al. (2003) reported that individuals with lower levels of vagally mediated HRV made undifferentiated threat responses regardless of the actual valence of stimuli. Similarly,
our results suggest that individuals with lower levels of vagally mediated HRV fail to make a distinction between neutral and fearful distractors under both high and low load conditions. Therefore, our data confirm the findings of Ruiz-Padial et al. (2003) and suggest that the lack of prefrontal inhibitory activity and the overactivation of sympathoexcitatory circuits manifested in lower vagally mediated HRV are associated with the failure to recognize safety signals from environments. As a result, their performance on the selective attentional task was equally interfered with the presence of neutral and fearful distractors.

Under low load, as we predicted, the high HRV group shows significantly faster mean RTs to detect targets with fearful facial distractors than with neutral distractors. It appears that when there are more processing resources available to process distractors, people with high HRV regulate their emotions by focusing on goal-related stimuli and quickly disengaging their attention away from the location of negative information, thereby preventing from processing negative information. Lavie (2005) suggested that it was necessary to have more active mechanism of attentional control that depended on higher cognitive functions, such as working memory, to inhibit the processing of salient distractors. The high HRV group is characterized by greater prefrontal inhibitory activity over subcortical structures, which allows them to exert more active attentional control to quickly detect targets and to disengage their attention away so as to inhibit the processing of fearful distractors further.

Consistent with this, studies reported that groups characterized by poor attentional control, such as older adults, showed increased disruption by task-irrelevant
distractors under low load, but not under high load (Bishop, 2009; Forster & Lavie, 2007). Maylor and Lavie (1998) studied the effect of perceptual load on age differences and showed that there was a larger distractor effect for the older than for the younger group. However, with increased relevant set sizes, which made the task more difficult, there was no group difference. Under low load, there was no main effect between the high HRV and low HRV groups in our study. However, individuals with higher levels of vagally mediated HRV exerted good attentional control in conjunction with emotions as a way to regulate them. Participants with higher levels of vagally mediated HRV were selectively faster with fearful distractors as a mechanism to inhibit the processing of negative information whereas lower levels of vagally mediated HRV exhibited faster responses than the high HRV group to neutral distractors which was not functional in keeping anxiety low.

This result is in line with findings from other lines of the research that examine the cognitive biases in affective states (Williams et al., 1988). Using different experimental tasks, various studies suggested that highly anxious individuals were associated with attentional biases favoring negative stimuli (Williams et al., 1988). Fox and her colleagues (2001) used Posner’s cuing task (Posner & Petersen, 1990) to demonstrate that people with low anxiety were capable of quickly disengaging their attention away from the location in which threat-relevant information was presented whereas high anxious individuals were not. Fox et al. (2001) used schematic faces with neutral, happy, and angry expressions as cues in Posner’s cuing task. Highly anxious individuals took longer to detect targets on invalid trials after an angry face cue compare
to either neutral or happy face cues. However, the low anxious group showed no significant difference among the neutral, happy, and angry face cues for either valid or invalid trials. The result suggested that highly anxious individuals had difficulty in disengaging their attention away from the location of threat stimuli whereas low anxious individuals were capable of rapidly disengaging from threat-related stimuli. Fox et al. (2001) suggested that “rapid disengagement from threat may be functional in keeping anxiety low, and an inability to do this may result in increased anxiety (p.698).” In my study, there was no correlation between the anxiety measures and HRV. However, people with higher level of vagally mediated HRV demonstrated their ability to quickly detect targets and disengage from fearful facial distractors whereas individual with lower level of vagally mediated HRV failed to do so.

Furthermore, this response pattern made by the high HRV group under low load was similar to the one observed by individuals with good effortful control. Derryberry and Reed (2002) defined effortful control “a self-regulatory dimension in relation to more reactive dimensions of positive emotionality and negative emotionality (p. 226).” Effortful control constrains overly reactive emotions and plays a significant role in disengaging from threatening cues and engaging in safety cues. According to Derryberry and Reed (2002), anxious individuals with poor effortful control showed attentional biases favoring threatening information whereas anxious individuals with good effortful control were capable of shifting their attention away from threatening cues and engaging in safety cues at long delays. Lonigan and Vasey (2009) also studied the interaction between negative affectivity (NA) and effortful control (EC) on attentional biases
favoring negative information in children. They showed that only children with low levels of EC and high levels of NA demonstrated an attentional bias toward negative information. Likewise, in our data, there was no difference in the RTs between the high and low PSWQ groups with fearful distractors. However, individuals with higher vagally mediated HRV were capable of quickly disengaging their attention away from fearful distractors under low load. We suggest that in low perceptual load conditions, the high HRV group exerts effortful control suggested by Derryberry and Reed (2002) to rapidly disengage their attention away from fearful information. In order to examine the relationship between HRV and effortful control and their impact on anxiety, it would be necessary to study the interaction between HRV and anxiety on task performance as Derryberry and Reed (2002) did.

Under high perceptual load, the high HRV group showed the response pattern that was opposite to what we predicted; they showed significantly faster RTs to detect targets with neutral distractors than with fearful distractors. As can be seen in Figure 8, under high perceptual load, both the HRV and the low HRV groups showed similarly increased disruption by the presence of fearful distractors, which was reflected by slow RTs. Those impaired performances by both groups seem to suggest that the processing demand in this condition may exceed regulatory capacity. With fearful distractors, the prefrontal cortex disinhibits its inhibitory control over sympathoexcitatory subcortical circuits, which allows the rapid processing of negative stimuli. The lack of prefrontal activity in this condition may result in delaying the processing of task-relevant stimuli. However, with neutral distractors, the high HRV group is able to inhibit the processing of
neutral distractors and to focus on the processing of task-relevant stimuli. Typically, the prefrontal cortex plays an important role in representing goals and maintaining contextual information that is necessary to achieve goals (Miller, 2000; Nitschke et al., 2004). With neutral distractors, the prefrontal cortex recognizes safety signals, inhibits the activity of sympatoexcitatory subcortical circuits, and focuses on the processing of task-relevant stimuli. As a result, their performance to detect targets was significantly better with neutral distractors. Thus, our result indicates that even at high load, the high HRV reliably exerts its prefrontal inhibitory control over subcortical structures to make context appropriate responses with neutral distractors.

Interestingly, under high perceptual load, high and low PSWQ individuals showed the similar response pattern that high and low HF_HRV people demonstrated: Low PSWQ individuals were significantly faster than high PSWQ individuals when distractors were neutral, and there was no difference when distractors were fearful. Individuals with lower vagally mediated HRV are characterized by their inability to distinguish neutral from negative stimuli. Similarly, high PSWQ individuals failed to make a distinction between neutral and fearful distractors and responded to neutral as if they were negative. Although most people tend to be a slight optimistic bias, anxious or depressed individuals are characterized by being biased in a negative direction (Grey & Mathews, 2000). Various studies showed that anxious or depressed individuals tend to impose a threatening interpretation on ambiguous words (Richards & French, 1992), ambiguous sentences (Eysenck et al, 1991; MacLeod & Cohen, 1993) or ambiguous scenarios (Hirsch & Mathews, 1997). Although our stimuli were not emotionally
ambiguous, highly anxious individuals responded to neutral distractors as if they were negative and showed their favoritism for negative responsiveness.

This response pattern by the high and low PSWQ groups can be explained by a cognitive model that Mathews and Mackintosh (1998) proposed. According to the cognitive model, two stimuli, neutral and threat-relevant, were competing for processing resources via inhibitory links prior to awareness. One representation gains activation and inhibits the other until the representation receives enough processing resources to become dominant and to receive attention. It has been suggested that there are circuits within the anterior cingulate that reciprocally inhibit attention to neural targets and to emotional distractors. According to the model, a threat evaluation system (TES) and effortful task demand activate and reinforce the representations of a threat-relevant distractor and a target, respectively. The threat evaluation system evaluates threat stimuli and is influenced by levels of anxiety. For an initial encounter of potential threat stimuli, high levels of cortically mediated, conscious processing are required. In the initial processing, the internal images of the stimuli are produced and compared with representations in the TES. If the stimuli match to threatening attributes that are stored in the TES, symptoms of anxiety are elicited. The TES stores perceptual cues and attributes associated with the stimuli, and subsequent encounters of those perceptual cues will result in capturing attention and provoking anxiety by the activation of the direct route from the thalamus to the amygdala. This subsequent processing is parallel and nonconscious. Powerful threatening stimuli themselves will attract attention from everyone, regardless anxiety levels, because the stimuli can elicit strong feedbacks from the TES, thereby activating
threatening representations. However those with high anxiety direct attention even to mildly threatening stimuli. Their threat value representations in the TES are more intense and more profound that even mildly threatening stimuli can find their corresponding representations in the TES. However, when there are increasing task demands, efforts are made to attend task-relevant targets and to overcome interferences from a competing neutral distractor.

It is possible that two models, the Neurovisceral Integration model and the cognitive model, are related in such a way that the Neurovisceral Integration model may provide physiological foundation for the cognitive theory. Greater prefrontal inhibitory tone is necessary to satisfy effortful task demands, which then can be reflected by high levels of vagally mediated HRV. However, the activation of the threat evaluation system requires the disinhibition of the prefrontal inhibitory control, which is represented by reduced vagally mediated HRV. It seems to me that there is structural similarity between two models so that they are conceptually linked.

Our results suggest that individuals with lower vagally mediated HRV demonstrate emotional and attentional dysregulation that can be easily susceptible to develop processing biases favoring negative information. They fail to demonstrate the ability to rapidly disengage their attention away from fearful distractors under the low load condition. Fox et al. (2001) speculated that the tendency to dwell on threat-related stimuli might influence the cognitive system in general and escalate into constant rumination and worry (Fox et al., 2001). The low HRV group also made undifferentiated responses to fearful and neutral distractors under both high and low load conditions.
According to the Neurovisceral Model, lower levels of vagally mediated HRV is associated with the lack of prefrontal inhibitory tone and overactivation of sympathoexcitatory circuits, which may cause them to constantly process and dwell on negative information and to make hypervigilant threat responses (Thayer & Lane, 2000, 2002). Based on our data, it is possible that individuals with low vagally mediated HRV are more susceptible to develop anxiety disorder because they are more like to process negative information. The processing biases may influence the cognitive system in general and eventually escalate into preservative cognition such as worry or constant rumination. Additional investigation is necessary to examine whether there are differential effects of HRV on the induction of processing biases.

Of particular importance is our result showing the differences under high perceptual load. Bishop et al. (2007) found no difference in behavioral and neural responses under high load. However, using HRV, our study suggested that there was a significant difference between the high and low HRV groups in RTs under the high load condition. The high HRV group was significantly faster to detect targets with neutral distractors compared to the low HRV group. Also, the high HRV group was faster to detect targets with neutral distractors compared to those with fearful distractors.

In many neuroimaging studies, high perceptual load reduces and even eliminates neural responses detected with fMRI to potent distractor stimuli such as meaningful words, places and motion (Lavie, 2005; Bishop, 2008). In addition, there was no differential amygdala response to emotionally salient distractors, such as happy, angry, or fearful facial expressions while participants were performing a high-load task (Lavie,
Based on these data, Lavie (2005) and Bishop (2008) challenged the notion of the Fast subcortical thalamoamygdala pathway that processes threat-related stimuli automatically bypassing attention. LeDoux (2000) proposed two pathways in which information about fear can be processed: High levels of cortically mediated processing or fast and short-cut route directly from the thalamus to the amygdala. Information about fear is first processed through cortical structures, which then is stored in the amygdala during learning. Once the information is processed, a fast but inaccurate route is available, bypassing the cortex directly from the thalamus to amygdala. There are a significant number of studies to support the findings of LeDoux (2000).

Based on their studies that showed no differential neural responses in high load conditions, Bishop et al. (2007) stated that their study “runs contrary to suggestions that anxiety modulates a preattentive threat evaluation system centered on the amygdala and instead supports the load model of selective attention (Lavie et al, 2004; Lavie, 2005) according to which distractor processing is constrained by early perceptual capacity limitations” (p. 1601). However, our data suggest that even with high perceptual load conditions where there were no detectable neural responses by fMRI, the HRV measure captures differences in reaction time. This result seems to suggest that HRV can be considered as more sensitive measure to reflect prefrontal inhibitory functions in high perceptual load conditions, which cannot be captured otherwise.

We were not able to find any significant result from the low frequency, which is considered to reflect the combination of both sympathetic and parasympathetic influences (Thayer et al, 1996; Task force, 1996). This gives additional evidence that it is the vagal
component predominantly affecting selective attentional tasks, as opposed to a more sympathetically mediated phenomenon.
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APPENDIX A

FIGURES
Figure 2. Example stimuli. A string of 6 letters was superimposed on a fearful facial distractor. Under high load, letter strings consisted of one target letter and five nontarget letters arranged in random order. Under load load, letter strings consisted of either 6 Xs or 6 Ns.
Figure 3. Example stimuli. A string of 6 letters was superimposed on a neutral facial distractor. Under high load, letter strings consisted of one target letter and five nontarget letters arranged in random order. Under low load, letter strings consisted of either 6 Xs or 6 Ns.
Figure 4. Mean RTs and standard errors as functions of load conditions in the letter string task.
Figure 5. Percent error rates and standard errors as functions of load conditions in the letter string task.
Percent error rate as a function of load and distractor valence

![Graph showing percent error rates and standard errors as a function of perceptual load and valence.](image-url)

Figure 6. Percent error rates and standard errors as a function of perceptual load and valence.
Figure 7. Mean RTs and standard errors as a function of HF_HRV groups and distractor valence under the low perceptual load condition.
Figure 8. Mean RTs and standard errors as a function of HF_HRV groups and distractor valence under the high perceptual load condition.
Figure 9. Mean RTs and standard errors as a function of high and low PSWQ groups and distractor valence under the high perceptual load condition.
Figure 10. Mean RTs and standard errors as a function of high and low PSWQ groups and distractor valence under the low perceptual load condition.
Figure 11. Mean RTs standard errors of low HF_HRV individuals as a function of perceptual load and valence.
Figure 12. Mean RTs standard errors of high HF_HRV individuals as a function of perceptual load and valence.