HEART-BRAIN INTERACTIONS: INDIVIDUAL DIFFERENCES IN THE RELATIONSHIP BETWEEN THE AUTONOMIC NERVOUS SYSTEM AND ONGOING BRAIN OSCILLATIONS

by

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Christina Karns

Researching the processes that govern the body's stress response is important as it allows us to understand how our physiology could be altered by various stress disorders. While studies have started to analyze interactions between the heart and the brain, little research has been done in a resting state, and few have used both sympathetic and parasympathetic measures. Due to this, I analyzed individual differences in the relationship between the heart and the brain during a resting state. I utilized heart-rate variability (HRV) as an indicator of the parasympathetic nervous system, pre-ejection period (PEP) as an indicator of the sympathetic nervous system, and EEG frequencies as a measure of different brain states. I found a significant relationship between delta power and PEP, lower alpha band 1 power and PEP, and lower alpha band 2 power and PEP. Delta power and PEP had a positive relationship, meaning that as sympathetic nervous system activity decreased, delta power increased. Both lower alpha band 1 and lower alpha band 2 power had a negative relationship to PEP, meaning that as sympathetic nervous system activity increased, lower alpha band 1 and 2 power

increased. This indicates a possible relationship between the sympathetic nervous system and lower frequencies of alpha, as well as delta. If this relationship is explored further, it could be possible to use alterations in this relationship to diagnose people with various mental disorders.

Acknowledgements

I would like to thank Dr. Christina Karns for helping me throughout the thesis and helping me integrate psychology and human physiology in ways I had never considered before. I am so grateful to be able to have you as a mentor and to have had the opportunity to be a research assistant for you these past two years. I would also like to thank Professors Nicole Swann and Helen Southworth for being a part of my thesis committee and helping me through the process of creating a thesis. Finally, I also would like to thank my mom and uncle for always being there for me and supporting me throughout my four years at the University of Oregon. I would not be where I am today without all of you.

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Introduction

Stress – one word that nearly everyone is trying to minimize and manage to the best of their ability. Even though periodic stress may be unavoidable, that does not devalue the importance of understanding the physiology behind this mechanism. While the body's stress response itself has been well documented, the interactions between different parts of our bodies that govern this stress response have not been extensively studied. Specifically, the interaction between the heart and the brain relating to stress has recently become a focus of researchers because it could help us comprehend the basis of various stress related disorders, and how to minimize the effects of stress on our body. What exactly is the relationship between our mind, body and stress, though? To tackle this crucial question, one must analyze the physiological processes that govern our stress response.

Introduction to Cardiac Measurements of the Autonomic Nervous System

Within our body, we have a central nervous system (CNS) and a peripheral nervous system. The CNS functions to coordinate our higher level thinking through the brain and spinal cord (Moore, 2015). On the other hand, the peripheral nervous system links other parts of the body, such as the heart, to the CNS through the use of nerve cell bodies and fibers (Moore, 2015). The peripheral nervous system can be further subdivided into the autonomic nervous system (ANS) and somatic nervous system (Tresilian, 2012). While the somatic nervous system controls functional movement, the ANS governs the responses of our heart, organs, blood vessels and glands without conscious thought (Moore, 2015). The ANS is composed of two branches: the

parasympathetic nervous system (PNS) and sympathetic nervous system (SNS). The PNS is associated with resting and preserving energy, and thus a decreased stress response, while the SNS typically deals with the "fight or flight" response during stressful situations (Moore, 2015;Porges, 1995;Hall, 2016d).

One way to determine the influence of the PNS on an individual is based upon their heart rate variability (HRV), which is the fluctuations in the amount of time between each beat of the heart (See Figure 1)(Thayer, Åhs, Fredrikson, Sollers, & Wager, 2012). These varying inter-beat intervals follow an oscillatory pattern that is related to respiration (Thayer et al., 2012;Montano et al., 2009). Other research has found that the high frequency variation in the inter-beat interval signal is associated with parasympathetic modulation of the heart (Thayer et al., 2012). When an individual has lower high frequency heart rate variability, this indicates a decreased influence of the PNS (Thayer et al., 2012). Decreased HRV is associated with a diminished ability of an individual to switch their attention in various situations, and thus have less adaptive behaviors (Thayer & Lane, 2000). This can be associated with various anxiety disorders, such as generalized anxiety disorder (Thayer & Lane, 2000). If an individual has a high HRV, indicating greater influence of the PNS, then they are better able to filter out non-essential information, and can alter their behaviors to match the state of the environment (Thayer & Lane, 2000). Within my thesis, I will use HRV as a way to measure the engagement of the PNS during a standard task to test the extent to which it is associated with other neural and physiological states.

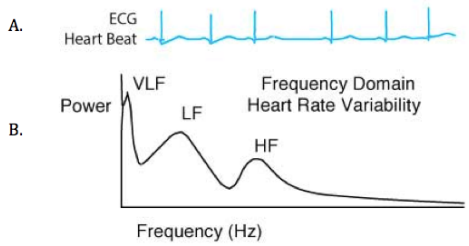


Figure 1: Heart-Rate Variability (HRV) Representation

The ECG measurement portrayed in panel A indicates that this individual has variability in the time interval between heartbeats. There are some intervals that are shorter, while others are longer. When this ECG measurement is transformed from the time domain to the frequency domain, is it possible to measure the HRV of individuals. Having greater high frequency power, as portrayed by panel B, indicates greater influence of the parasympathetic nervous system. Figure adapted from Karns et al. (2015)

The engagement of sympathetic nervous system, the fight or flight system, is measured by the pre-ejection period (PEP) of the heart. PEP represents the amount of time between the ventricles of the heart becoming depolarized and blood being ejected out of the heart to the rest of the body (Newlin & Levenson, 1979). Once the pressure in the ventricles becomes larger than the pressure in the aorta, the ventricles eject blood (Lozano et al., 2007). The amount of time this takes impacted by the sympathetic nervous system (SNS). When there is more SNS influence to the heart, this causes the heart to have stronger contractility (Lozano et al., 2007). As a result of this, the ventricular pressure becomes greater than the pressure in the aorta faster, and blood ejects from the ventricles sooner (Lozano et al., 2007). We are able to calculate PEP through measuring impedance across the chest, which is related to electrical resistance. We then take the derivative of the impedance across the chest to identify the B-point for

the PEP calculation, which represents the point where blood is ejected out of the heart (See Figure 2)(Lozano et al., 2007). I will use PEP to measure how much the SNS is engaged during a standard task.

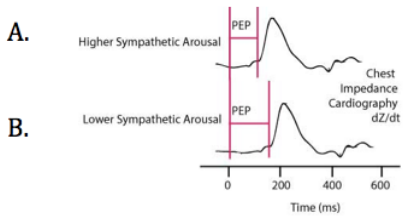


Figure 2: Pre-Ejection Period (PEP) Representation

This is a graph of the derivative of cardiac impedance, which is used to calculate PEP. As indicated by top panel A, as sympathetic arousal increases, PEP gets shorter. Contrastingly, as sympathetic arousal decreases, PEP gets longer, as indicated on the bottom panel B. Figure adapted from Karns et al. (2015)

Introduction to Electroencephalography

Within the human body, our nervous system communicates through neurons, which are the cells of the nervous system (Tresilian, 2012). Neurons are unique cells in that they can communicate to each other through chemical and electrical signals (Keil, 2014). Each neuron has two ends –dendrites on one side receive the signal, and the axon terminals on the other end send the signal to the next neuron (Keil, 2014). Every single neuron has a resting membrane potential, since outside of the neuron is more positive, while the inside is negative (Tresilian, 2012). When one neuron sends a signal to the next neuron that causes the membrane potential to become more positive, this is an excitatory post-synaptic potential (Hall, 2016c). Contrastingly, when a neuron sends a signal to the next neuron that causes the membrane potential to be more negative, this is

an inhibitory post-synaptic potential (Hall, 2016c). Neurons communicate to each other through these excitatory and inhibitory post-synaptic potentials (EPSPs and IPSPs) that are summed to determine whether an action potential is generated (Hall, 2016c). If an action potential is generated, this means the neuron became depolarized enough to reach a threshold potential that generates an action potential (Hall, 2016c). This action potential traverses to the axon terminal of the neuron, where neurotransmitter will be released within the synapse between the next neuron (Keil, 2014). This neurotransmitter acts as a signal to either excite or inhibit the next neuron (Tresilian, 2012).

We are able to measure these changes in neuron activity with electroencephalography, which is a measurement of voltage from the EPSPs and IPSPs across an array of electrodes on the scalp (Tresilian, 2012). The excitatory and inhibitory potentials from the brain oscillate at varying frequencies corresponding to different brain states (Teplan, 2002). For example, delta waves tend to correspond to sleep states, but are also implicated in cognitive processing (Teplan, 2002;Harmony, 2013). The brain wave frequency bands that are typically seen are delta brain waves (0.5-4 Hz), theta brain waves (4-8 Hz), alpha brain waves (8-13 Hz), and beta brain waves (>13 Hz) (Teplan, 2002). Once you have the EEG data, by creating a power spectrum you can see a graphical representation of these frequencies on the x-axis, and their power on the y-axis. For most individuals, this power spectrum looks similar, with a peak in the alpha frequency range. While the absolute power varies for each individual, and the frequency ranges for the frequency bands differ slightly, the general shape is similar across subjects (See Figure 3). For my thesis specifically, I am interested in looking at the alpha brain waves since these are associated with being in a

state of relaxation, and thus would likely be involved in resting state (Teplan, 2002).

While alpha brain waves are my hypothesized frequency that will have a relationship with HRV and PEP, I analyzed other brain wave frequencies associated with alertness to determine whether they are related to PNS/SNS activity.

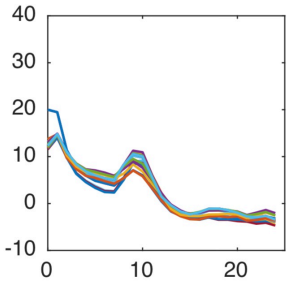


Figure 3: Sample subject power spectrum

This graph portrays an example of a power spectrum, with frequency on the x-axis, and power on the y-axis. Across all individuals, there is normally a peak in the alpha brain wave range (8-13 Hz). For this subject, their peak is around 9-10 Hz.

Introduction to the Brain and Heart Connection

While the brain and heart are separate organs, this does not mean that they operate independently of each other. The brain receives signals from the heart that inform the brain of what is occurring in the periphery, while the brain sends signals to the heart to modulate its function (Thayer et al., 2012). The heart is innervated by the vagus nerve and cardiopulmonary splanchnic nerves (Moore, 2015). These nerves allow the brain to communicate to the heart by sending signals to either increase or decrease heart rate (Hall, 2016b). The vagus nerve is associated with PNS activity, and thus functions to decrease heart rate (Hall, 2016a). Contrastingly, the cardiopulmonary splanchnic nerves are associated with SNS activity, and function to increase heart rate

(Moore, 2015;Hall, 2016a). In terms of the afferent signal from the heart to the brain, this is modulated by the baroreceptor reflex (Hall, 2016b). This reflex is controlled by the amount of stretch present in blood vessels, which indicates how high or low blood pressure is to the body (Hall, 2016b). If blood pressure drops and stretch decreases in the blood vessels, baroreceptors in the major arteries of the heart send signals to the brain to increase heart rate (Hall, 2016b). This is done through modulation of the ANS – in this case, to increase blood pressure the brain would decrease PNS output and increase SNS output (Hall, 2016b;Thayer et al., 2012). In this manner, the heart and brain are interconnected in the body's stress response, and thus should be studied together to gain a full understanding of how stress is regulated.

One theory that has attempted to link behavior, and thus the function of the brain, to the function of the autonomic nervous system is the polyvagal theory. The polyvagal theory proposes a link between behavior and the autonomic nervous system, with the physiological state of an individual determining the influence of the of the ANS and the resulting actions of the individual (Porges, 2007). In this theory, social behavior is closely related to the function of the autonomic nervous system, specifically the parasympathetic nervous system. Within this theory there is an idea of the social engagement system, which states that an increase in the PNS output can cause an increase in social behaviors, specifically through activation of striated facial muscles (Porges, 2007). The vagus nerve innervates the muscles of the face, and thus an increase in PNS influence can cause the individual to express themselves in a prosocial manner, such as opening the eyes and listening (Porges, 2007). The activation or withdrawal of the PNS, and thus the social engagement system, is linked to the state the individual is

in. For example, if the individual believes their environment to be dangerous, then this can elicit a fight or flight response due to a decreased output of the PNS (Porges, 2007). On the other hand, if an environment is deemed safe through neuroception, then this can cause an increased PNS output and thus foster more social actions (Porges, 2007). This theory attempts to explain a relationship between the parasympathetic nervous system and behavior, and could explain why an individual might have a higher or lower HRV value based upon how they viewed the environment of the experiment.

Introduction to Previous Studies

Previous research has primarily focused on analyzing either the heart or brain as separate entities. There are several proposed factors for this historical distinction between the heart and the brain in research. For individuals looking at cognitive measurements, the autonomic nervous system used to be considered a confound, with designs that emphasize controlling arousal in order to examine a pure selective attention effect on EEG (Stevens & Bavelier, 2012). Along with this, it has also been proposed that there has been a trend in the medical field for individuals to become experts in their respective fields, thus limiting the cross over between two fields of research (Valenza, Toschi, & Barbieri, 2016). More recently, there has been a shift in the literature towards the field of neurocardiology, which integrates both the heart and the brain (van der Wall & van Gilst, 2013). Since the heart and the brain are modulated by a combination of afferent and efferent signals and do not operate independently from each other, analyzing them at the same time with expand our understanding of these systems that govern our stress response (Thayer et al., 2012).

One of the focuses of the brain-heart literature thus far has been pathology. Various studies have investigated whether the relationship between the heart and the brain is altered when individuals have conditions such as a stroke, cardiac arrhythmia, or heart failure (Buckley & Shivkumar, 2016; Doehner et al., 2018; Dorrance & Fink, 2015). While this research has important clinical applications, there is a lack of research on the interaction between the heart and the brain within a normal individual in resting state. Analyzing this relationship under standardized conditions is important, as it allows researchers to further understand the basis of our physiology and how it can be altered by various disorders.

Most studies in healthy adults have focused on HRV as a measure of the autonomic nervous system. Multiple studies have used HRV as a measure of the ANS activity, and functional brain imaging, such as fMRI or PET, as an indicator of brain activity. In a meta-analysis of fMRI and PET studies by Thayer et al. (2012), they analyzed the regions of the brain that had a connection to HRV activity. Some studies have used HRV as a measure of both the parasympathetic and sympathetic nervous system, with high frequency HRV representing the parasympathetic nervous system, and low frequency HRV representing the parasympathetic nervous system and sympathetic nervous system. Studies by Duggento et al. (2016) and Valenza et al. (2017) used this approach to analyze the areas of the brain active during rest through the use of fMRI. While these studies focused on HRV as a measure of ANS activity, another study by Beissner et al. (2013) included both HRV and electrodermal response (a measure of the SNS) to measure the activity of the ANS in their analysis.

Among the few studies with both PNS and SNS measurements, Beissner et al. (2013) used a meta-analysis to determine which areas of the brain were active during increased activity of the PNS and SNS. While they found areas of the brain that were involved in regulation of the ANS in general, they also found differences in PNS regulation versus SNS regulation. Ventral areas of the brain were associated with the SNS, while dorsal regions were associated with the PNS. This indicates the importance of analyzing the sympathetic nervous system as separate from the parasympathetic nervous system, since there is a possibility that there are different modulating brain networks for the PNS and SNS.

While these studies used fMRI or PET as a measure of brain activity, there has been less focus on analyzing the relationship of various brain waves to the autonomic nervous system. Some studies have looked at how this relationship can be altered with activities such as meditating or playing video games (Kubota et al., 2001;Subhani, Xia Likun, & Malik, 2012). Very few studies have utilized brain rhythm frequencies as a measure of brain activity and compared this to HRV at rest, though. One study by Triggiani et al. (2016) examined this relationship by analyzing rolandic mu rhythms and HRV. Within this study, they found a significant relationship between HRV low frequency (0.04-0.15 Hz) band power and low-frequency beta (13-20 Hz), which they used as an indicator of the activity of the sympathetic nervous system. This study indicated there should be further research into analyzing the sympathetic nervous system and parasympathetic nervous system through two different measurements.

Due to the need for a study to analyze the sympathetic and parasympathetic nervous systems through separate measures, the purpose of my research was to analyze

individual differences across subjects between the interaction of the heart and the brain during a resting state to establish which relationships are important in healthy young adults. To measure the heart, I used HRV as a measure for the sympathetic nervous system, and PEP as a measure for the sympathetic nervous system. For the brain, EEG was used to measure power in several different brain frequencies, corresponding to various brain states. I hypothesized that there would be a positive relationship between HRV and alpha brain frequencies, due to alpha frequencies' association with being in a state of relaxation and increased PNS input also being associated with relaxation (Teplan, 2002; Moore, 2015;Porges, 1995). I also hypothesized that there would be a positive relationship between PEP and alpha brain waves, since alpha brain waves would likely decrease with more arousal, since that is the opposite state of relaxation.

Methods

Participants and Procedure

Within this experiment there were 100 subjects, aged 18 to 35. Four subjects were excluded from the final analysis due to excessive noise in the data from technical problems during collection, leaving 96 subjects to be analyzed. These participants were prescreened via SONA to ensure that they had no current psychiatric disorders and were willing to participate in the experiment. The subjects also signed an informed consent statement before taking part in the experiment. The data for my thesis was gathered as a part of a larger experiment on social and emotional processing. The specific data I analyzed was used as a baseline portion of the experiment, and was used to obtain the participants resting EEG, HRV and PEP data. For the experiment, the subjects first had to have electrodes placed on them so that their physiological data could be measured. For the EEG, electrodes were placed by using the international 10-20 system. For measuring HRV and PEP, 11 electrodes were used. Once the electrodes for both HRV/PEP and the EEG measurements were set up, the subject sat down in a chair that was located in a soundproof booth. The booth had a monitor in it that the participants were instructed to look at. Once the participant was ready, a relaxing 5-minute video played that depicted ocean animal life. This video is commonly used in HRV/PEP tasks. After this baseline video was over, the participants continued on with the experiment for the longer study.

HRV and PEP Recording

For both the measurement of HRV and PEP, 11 electrodes were placed on the subject. For the ECG, this was measured through three electrodes that were placed on the right clavicle, bottom left rib, and lower right abdomen. For the impedance cardiogram, this was obtained from 8 electrodes that were placed on the sides of the neck and torso. A Biopac MP-150 acquisition unit obtained the ECG and impedance information wirelessly through a Biopac Nomadix BN-RSPEC and BN-NICO transmitters (Biopac Systems Inc, Goleta, CA).

HRV and PEP Processing and Measurement

Measurements were extracted with Mindware HF-HRV and IMP softwares (Gahanna, OH). The data was first analyzed visually to certify that each R peak had been correctly marked and were adjusted or removed by trained raters. High-frequency HRV values were derived from a spectral transformation of the interbeat intervals from the ECG over time (R to R) as the natural log transformed values in the high frequency range commonly used for adults (.12 - .4 Hz). PEP was computed from the first-order derivative of the cardiovascular impedance signal (dZ/dt), as the length of time from the Q-point of the ECG waveform to the B-point of the dZ/dt waveform (Berntson, Lozano, Chen, & Cacioppo, 2004). Then, PEP was analyzed through the ECG files, and visually examined to ensure that both Q and B points were accurate within each 30-second average of ECG and dZ/dt. For both HRV and PEP, the 30-second epochs were averaged across epochs. This created one baseline value for HRV and one for PEP.

EEG Recording

For the baseline portion of the experiment, the electrodes used on the scalp were configured based upon the international 10-20 system. The offset of the electrodes was kept at or below ±30 μV. There were also electrodes positioned on the corner of the eyes, underneath the right eye, and on the right and left mastoids. Once the EEG data was gathered, the raw data was put into EEGLAB for further processing, including referencing the data to the average mastoids. This data was then high-pass filtered at 0.5 Hz and with an additional a low pass filter at 60 Hz for problematic subjects.

EEG Data Processing

Since the data for the larger experiment was collected at the same time as the baseline portion and was included all in one file, the first 300 seconds of the data had to be selected out as the baseline portion. Then, the baseline data was screened manually for any movement artifacts or paroxysmal noise. If any movement artifacts or noise were present it was removed from the data.

Once the data had been cleaned, it was then processed through independent component analysis (ICA) in EEGLAB (binica), reduced to 30 components using principle components analysis (PCA). The ICA file was then visually screened for vertical eye components, horizontal eye components, and any components that indicated problematic channels within the data; all of these components were removed. After this, if there were still problematic channels, the channels were removed and interpolated based upon the surrounding channels. The data was then transformed from the time domain into the frequency domain using a fast fourier transform (binica). The EEGLAB function, spectopo, was used to calculate the power spectral density using the entire

time range of the cleaned data. We used the default options, resulting in 128 equally spaced values (from 1Hz to 128 Hz, the Nyqist frequency, or sampling rate/2). The power spectral density values (PD) were transformed to absolute power using the following equation (10^PD)/10.

EEG Measurement

Once the EEG, HRV, and PEP data were processed and ready for analysis, the data was imported into SPSS statistical software. As shown in Figure 4, there is a high level of variability at the alpha band across subjects compared to other EEG frequencies due to varying peak alpha frequencies across individuals. Due to this, peak alpha was measured in individual subjects. Most individuals have a peak alpha power around 7.5 Hz to 12.5 Hz, but due to the large variability in possible peak alpha powers, it is necessary to create individual power bands for each subject based upon their peak alpha frequency, or individual alpha frequency (IAF) (Klimesch, 1999). The peak alpha frequency was calculated for each subject by finding the peak frequency from 7-13 Hz in channel Pz. As shown in Figure 4, once the IAF has been determined for a subject you create distinct power bands of 2 Hz width. The upper alpha band power is measured between the IAF and the IAF + 2 Hz. The lower alpha band 2 is from the IAF to the IAF – 2 Hz. For lower alpha band 1, the limits are from the IAF – 2 Hz to the IAF – 4 Hz. For the theta band, the boundaries are from the IAF – 4 Hz to the IAF – 6 Hz.

While Klimesch (1999) did not specify the calculation for the delta band, I used this same model to create the delta band from the IAF – 6 Hz to 1 Hz, as frequencies lower than 1 Hz can be problematic due to skin conductance in high impendence recordings. Additionally, while Klimesch (1999) did not suggest a calculation for the

beta band, I wanted to include this since Triggiani et al. (2016) found a potential relationship between beta and the sympathetic nervous system. To calculate the beta band, I used the IAF + 2 Hz as the lower boundary to 20 Hz as the upper boundary, as this was the upper boundary Triggiani et al. (2016) used for their beta band.

Once the bands were created, it was necessary to create a way to analyze these power bands relative to the total power throughout all the frequencies for the subject. This was based upon the method used by Clarke et al. (2001), where the power in the desired frequency band is divided by the total frequency for the subject, and then multiplied by 100 to obtain the subject's relative power. First, power measurements were converted to absolute power units. EEGLAB default power units, 10*Log10(uV^2/Hz), were transformed to (10.^(EEGLAB Power))/10. Next, the total power was calculated for each subject by taking their total power from the start of the delta band (1 Hz) to the end of the beta band (20 Hz). Then, the power within the IAF related frequency bands were averaged within each band to get one value. Finally, this averaged value within each peak related frequency band was divided by the total power from 1 to 20 Hz in each channel. For example, for an individual subject the frequencies within the 2 Hz band for lower alpha 1 would be averaged, divided by total power from 1 to 20 Hz for that subject, and then multiplied by 100 to get a single relative power value for lower alpha 1. This was done for each of the peak-related frequency bands (delta, theta, lower alpha 1, lower alpha 2, upper alpha and beta) on a channel by channel basis.

Statistical Analysis of EEG, HRV and PEP

Once this calculation for each relative power band was complete, this was then compared to the PEP and HRV values using Pearson's R correlations. A topographical map was generated that indicated the significance of the relationship as p-values between the various power bands and HRV or PEP. Correlations were visualized as a scatter plot of the relationship between the relative band power for each EEG band, and the HRV and PEP values. This was done for several channels that represented the relationship between certain locations on the head, so as to get a better understanding of the scalp distribution of the relationships. Only results with a cluster of at least 4 neighboring channels were reported as statistically significant at $p < 0.05$. For example, alpha brain waves tend to come from the posterior regions of the brain, and thus analyzing all channels at once may have decreased the sensitivity of the analysis of alpha power seen. The channels visualized for the frontal region of the brain was Fz, central region was C3, Cz, C4, CP5 and CP6, and posterior was Pz, O1 and O2.

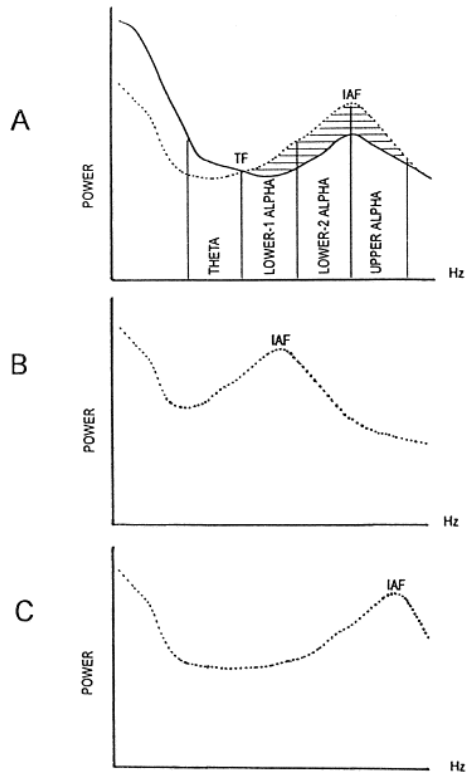


Figure 4: Relative frequency bands (Klimesch, 1999)

Picture A exemplifies the various power bands and how they should relate to one another. Picture B is an example of an individual that has a very slow peak alpha frequency, and thus their peak alpha frequency might be below the traditional 7.5 to 12.5 Hz band for alpha. Picture C shows an example of an individual with a very fast peak frequency for alpha, and thus most of their alpha band would be outside the traditional 12.5 Hz upper boundary. We identified individual alpha frequencies based upon picture A, since pictures B and C represent how the actual peak frequency of alpha can be higher or lower than the traditional 7.5 – 12.5 Hz alpha band, thus creating large variability in the peak alpha frequency across subjects.

Results

HRV and EEG Power

We tested the relationship between high frequency HRV and relative power in each frequency band. In all cases there was no relationship between high frequency HRV and relative power that met the criteria for statistical significance.

PEP and EEG Power

Delta and PEP

As shown in Figure 5a, there was a significant relationship between PEP and relative power of delta ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold). The topographies in Figure 5a show the relationship between delta power and PEP for all subjects across all channels. The relationship between delta power band and PEP has a broad distribution of significance across the scalp, with no significance in the posterior region. The topography on the bottom indicates p-values > .05 thresholded to zero, as represented by the dark blue color.

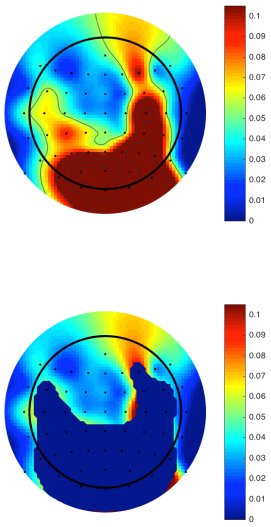
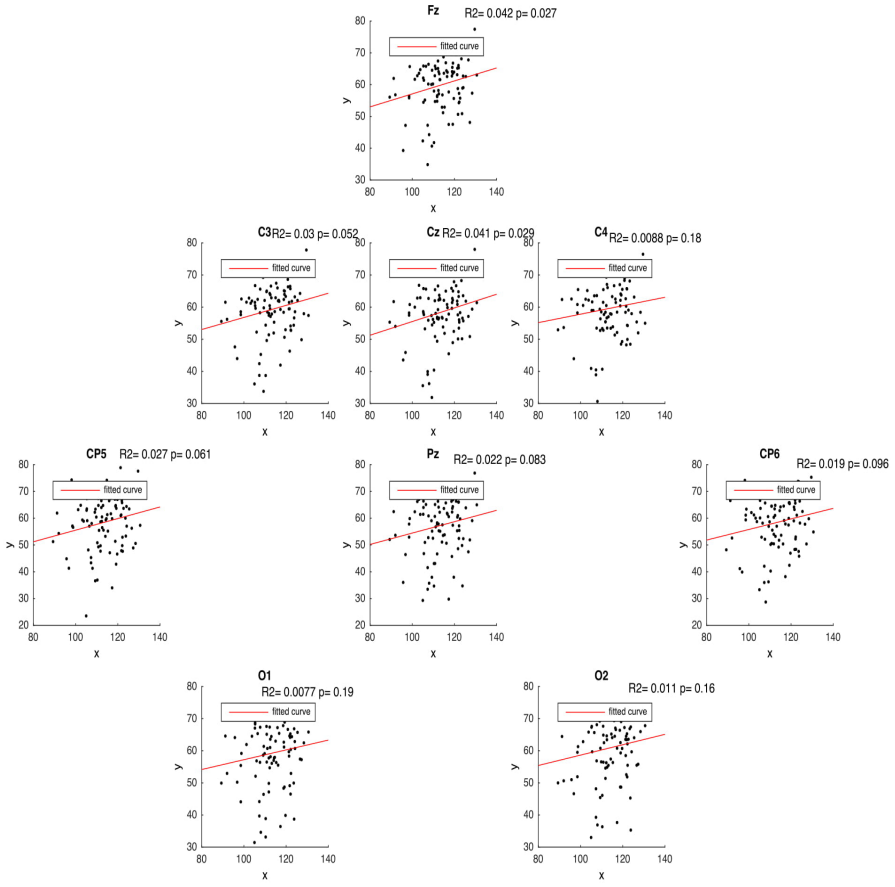


Figure 5a: P-values for the relationship between delta band power and PEP

As shown in Figure 5b, there is a positive relationship between delta band power and PEP. This means that as PEP increased (x-axis), the delta band power increased (y-axis). This indicates that as the delta band power increased, there was less sympathetic nervous system influence. This relationship was significant in Fz, a frontal channel, and Cz, a central channel.

Figure 5b: Scatter plots of



relationship between delta band power and PEP with adjusted R^2 and p-values as annotations

Theta Band

We tested the relationship between the theta band and PEP, and found no significant relationship between theta band power and PEP ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold).

Lower alpha band 1 and PEP

As shown in Figure 6a, there is a significant relationship between lower alpha band 1 and PEP ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold). The topographies in Figure 6a show the relationship between lower alpha band 1 power and PEP for all subjects across all channels. The distribution of significance is mostly in the central channels. The topography on the bottom indicates p-values > .05 thresholded to zero, as represented by the dark blue color.

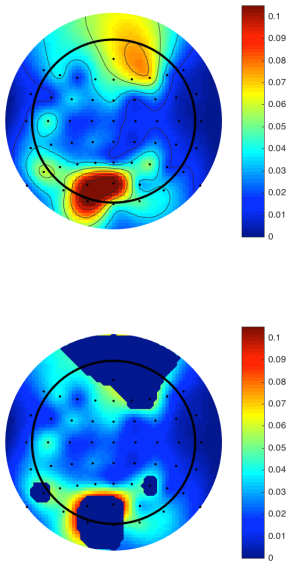


Figure 6a: P-values for the relationship between lower alpha band 1 power and PEP

As seen in Figure 6b, there is a negative relationship between lower alpha band 1 power and PEP. As the amount of PEP increased (x-axis), the amount of lower alpha band 1 power decreased (y-axis). This indicates that as lower alpha band 1 power increased, there was a larger influence of the sympathetic nervous system. This relationship was significant in all channels except O1, a posterior channel.

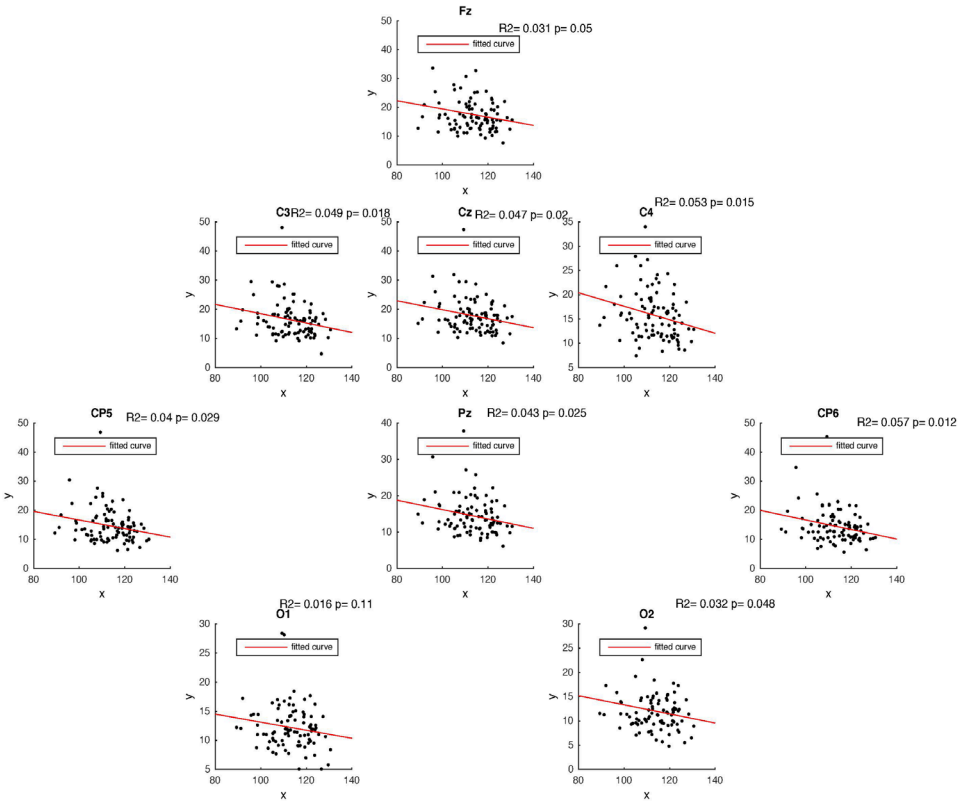


Figure 6b: Scatter plots of relationship between lower alpha band 1 power and PEP with adjusted R^2 and p-values as annotations

Lower alpha band 2 and PEP

As shown in Figure 7a, there was a significant relationship between PEP and lower alpha band 2 ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold). The topographies in Figure 7a show the relationship between lower alpha band 2 power and PEP for all subjects across all channels. Statistically significant association between PEP and lower alpha band 2 power was observed in the frontal and central channels. The posterior channels have no significant relationship between lower alpha band 2 power and PEP. The topography on the bottom indicates p-values > .05 thresholded to zero, as represented by the dark blue color.

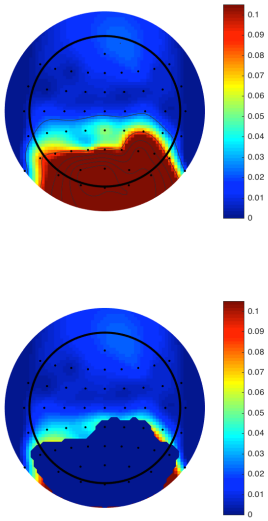


Figure 7a: P-values for the relationship between lower alpha band 2 power and PEP

As seen in Figure 7b, there is a negative relationship between lower alpha band 2 power and PEP. As PEP increases (x-axis), lower alpha band power decreases (y-axis). This indicates that as lower alpha band 2 power increases, the influence of the sympathetic nervous system increases. This relationship is significant in all channels except O1, O2, and Pz, which are posterior channels.

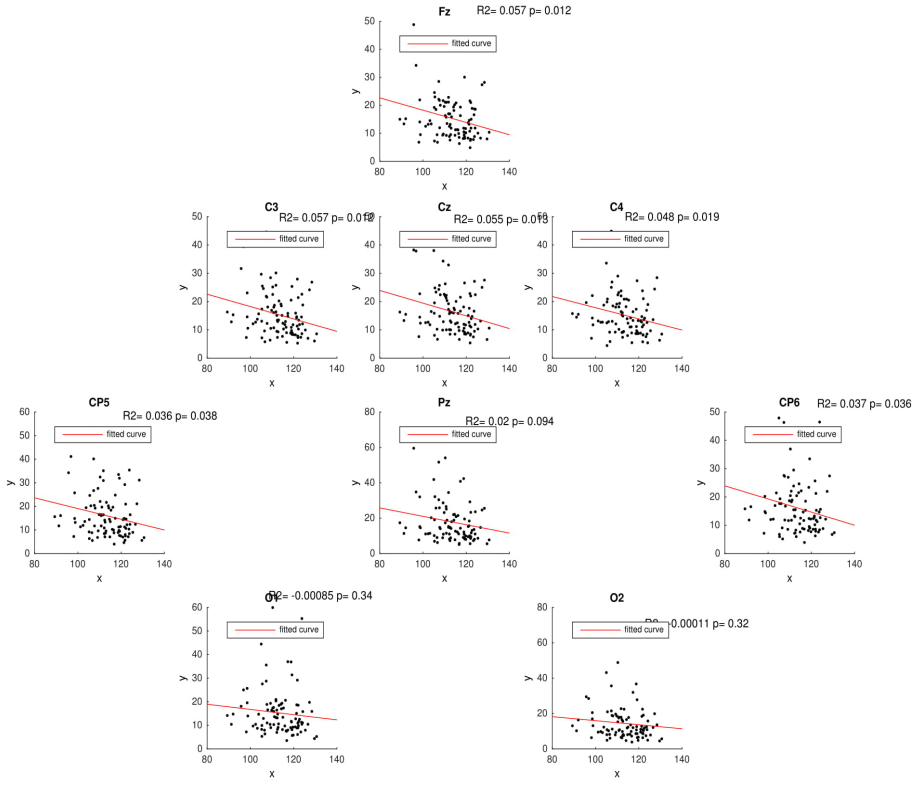


Figure 7b: Scatter plots of relationship between lower alpha band 2 power and PEP with adjusted R^2 and p-values as annotations

Beta Band

We tested the relationship between the beta band and PEP, and found no significant relationship between beta band power and PEP ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold).

Summary

In summary, there was a significant relationship between delta, lower alpha 1, and lower alpha 2 to PEP, indicated by the asterisk ($p < .05$, uncorrected for multiple comparisons cluster threshold at 4 neighboring electrodes). For HRV, there were no significant relationships found for any of the frequency bands.

PEP	HRV
Delta Band*	Delta Band
Theta Band	Theta Band
Lower Alpha Band 1*	Lower Alpha Band 1
Lower Alpha Band 2*	Lower Alpha Band 2
Upper Alpha Band	Upper Alpha Band
Beta Band	Beta Band

Table 1: Summary of relationships between the relative frequency bands and PEP/HRV ($R(94) > 0.2$, $p < 0.05$ with 4 channel cluster threshold).

Discussion

This study is the first report of a relationship between ongoing EEG oscillations and pre-ejection period activity in a controlled resting baseline condition that was constant across participants. This baseline condition is commonly used in studies utilizing cardiac measures of autonomic function, yet the relationship to the autonomic measures and ongoing oscillations has not been addressed.

Main Findings

The main findings from this research are a significant negative relationship between lower alpha band 1 and PEP, a significant negative relationship between lower alpha band 2 and PEP, and a significant positive relationship between delta and PEP. For lower alpha band 1 and 2, as alpha power increased, the amount of PEP decreased. This was the opposite of the hypothesis, as I thought there would be a positive relationship between alpha power and PEP. This was anticipated because alpha power is associated with being in a state of relaxation, and thus would likely have less sympathetic nervous system input since the parasympathetic nervous system is the portion of the ANS associated with relaxation (Teplan, 2002; Moore, 2015;Porges, 1995).

Effects of task-positive and task-negative states on brain oscillations

One potential reason there could have been differences between the results I found and what I researched in the literature is the fact that my test was during a baseline state only, and had no task associated with it, perhaps indicating a state closer

to the default-made network that the brain operates in during task-negative events (Nishida et al., 2015).

In a review by Nishida et al. (2015), they describe how there are different brain networks that are active during various brain states. For resting state alone, there are over 12 known networks, but most of these are active during task-positive events (Nishida et al., 2015). One of the most widely studied resting state networks is the default-mode network (DMN), since it is associated with being active during task-negative events (Nishida et al., 2015). The DMN is most active during activities such as wandering of the mind, which could have occurred while the subjects watched the baseline video (Nishida et al., 2015). Since it is deactivated during tasks, it seems reasonable that this network was active during my experiment compared to task-positive networks. Alternatively, since the subjects still had to attend to the video, there is the possibility that this was enough of a task to decrease the involvement of the default-mode network. While I considered it to be a task-negative event, I did not want to rule out the possibility that it could be task-positive, since the subjects were not simply thinking to themselves. Due to that, I tried to find previous research relating physiological state to brain state in both task-positive and resting state network.

Effects of attention on alpha

For task-positive experiments, previous research has indicated that slower frequencies of alpha, such as lower alpha band 1 and 2, reflect attention demands, whereas the higher frequencies of alpha, such as upper alpha, tend to be related to semantic memory processing (Klimesch, 1999). Specifically, the low frequencies of alpha that are generated from the frontal areas of the brain tend to be decreased with

controlled attention (Smith & Gevins, 2004). However, the relationship between attention and alpha can be different in other attentive states such as meditation (Takahashi et al., 2005). Since meditation involves attention to internal processes in mind and body versus attention to external events, I focused on a review of tasks that exemplified external attention. In my experiment, the significant relationship seen between lower alpha band 1 and lower alpha band 2 and PEP was generated mostly in the central and frontal regions of the brain. This was also unexpected, since alpha power tends to be associated with the posterior regions of the brain (Teplan, 2002). There are various cognitive functions of the different alpha bands related to phasic versus tonic attention. Klimesch et al. (1998) found that there were distinct processes that attenuated lower alpha 1, lower alpha 2 and upper alpha. Lower alpha 1 was attenuated by a warning signal, which Klimesch et al. (1998) determined to be related to phasic changes attention. These phasic changes are characterized by quick alterations that cause immediate alertness, such as a warning signal. For lower alpha 2, this was slowly attenuated by the expectancy of the targets to appear in the experiment. Unlike lower alpha 1, lower alpha 2 had a more gradual decrease in the amount of alpha power in this band as the expectancy of the target to appear increased, reflecting a more tonic alertness. Finally, the upper band of alpha was attenuated by the targets themselves appearing and the subject being required to count the targets. These results indicate that alpha does not reflect a unitary brain state.

The findings of Klimesch et al. (1998) can help explain why there was a significant relationship between lower alpha band 1 and lower alpha band 2 with PEP. Since lower alpha band 1 is attenuated by phasic changes in attention, this could mean

that as phasic attention in my experiment increased, lower alpha band 1 power decreased. Similarly, since lower alpha band 2 is attenuated by tonic attention, this could mean in my experiment that as tonic attention increased, lower alpha band 2 power decreased. Relating this attention increase (reflecting lower alpha) to the engagement of the sympathetic nervous system, this could mean with more sympathetic input, individuals have less controlled attention, as they are in a more reactive state. This interpretation is supported by the finding that individuals who have decreased HRV have less of an ability to inhibit the sympathetic nervous system, and thus the input from the sympathetic nervous system increases (Thayer & Lane, 2000). As a result, these individuals have less attention control (Thayer & Lane, 2000). This directly relates to the results I found, since when there was more SNS input, there was a higher power of alpha band 1 and alpha band 2. Since alpha bands 1 and 2 are attenuated by attention, this should mean that individuals who had the highest alpha band 1 and 2 power had the least amount of attention control. Along with this, research has found that individuals who have anxiety disorders tend to have a decreased ability to inhibit the SNS (Thayer & Lane, 2000). Due to this, I explored what research has been done regarding anxiety and brain waves.

Anxiety as a link to the relationship between the SNS and alpha power

A study by Knyazev et al. (2004) may offer further evidence for the link between the increase in alpha power in lower alpha band 2 to increasing SNS activity during baseline state. Within their study, Knyazev et al. (2004) found that during a baseline state, a measure of anxiety (self-report scale) was positively correlated with alpha power 2. While the baseline portion relates most directly to my research, they also

found that there was a positive correlation across all conditions of the experiment with alpha power 2 and trait anxiety, manifest anxiety, and state anxiety. This provides evidence that the link between lower alpha band 2 and anxiety are true for both task-positive and task-negative events. The article proposes to view the increase in alpha power in anxious individuals through the lens of the behavior inhibition system (BIS). When this system is active, the mind is constantly scanning the environment for potential threat. BIS is involved in risk evaluation of these threats and subsequent avoidance actions, and is thought to control anxiety (Brenner, Beauchaine, & Sylvers, 2005). Knyazev et al. (2004) framed their findings by stating that it is possible individuals with higher alpha are more prepared to react in avoidance to a threat in the environment.

This idea ties back into the polyvagal theory, that an individual's brain is constantly assessing their environment for whether it is safe or not (Porges, 2007). Anxious individuals would be constantly in the state of expecting a threat. Individuals are much more likely to have sympathetic nervous system activation when anxious (Kreibig, 2010). This correlates with the idea proposed by Thayer and Lane (2000) that individuals with less ability to inhibit their SNS are not able to properly assess their environmental situation, and control their attention demands. This could explain why there was a relationship between the sympathetic nervous system (PEP) and increased alpha power 2 in normal individuals at rest. Individuals with the highest alpha power 2 had the most amount of SNS input (shorter PEP), perhaps because they had the least amount of attention control. That would mean that the individuals with the highest amounts of alpha power 2 and lowest amounts of PEP (high amounts of SNS influence)

could potentially be considered more anxious individuals during this baseline task, while individuals on the other side of the scale would be more relaxed.

Knyazev et al. (2004) only found this relationship for lower alpha band 2, not lower alpha band 1 or upper alpha. Since I did see a relationship between lower alpha band 1 and the sympathetic nervous system, but Kyazev et al. found no relationship between lower alpha band 1 and anxiety, it is possible lower alpha band 2 is the alpha band most closely related to the behavior inhibition system, since this modulates anxiety.

Negative relationship between delta power and anxiety

Knyazev et al. (2004) also found a negative correlation between delta power and anxiety during baseline state, and across the conditions of the experiment. This relates to the findings of my experiment as well, as there was a negative relationship between delta power and the amount of SNS influence (indexed by PEP). In a previous study, Knyazev et al. (2003) also found that delta had a negative relationship to the BIS system, while alpha had a positive relationship to BIS. Considering these findings, this means that higher delta power is negatively associated with being in a state of anxiety. Since less anxious individuals are more likely to have less sympathetic nervous system input, this should mean that delta power would be negatively related to sympathetic nervous system activity. This agrees with the results I found, as individuals who had the highest delta power had the highest amount of PEP, indicating lower SNS activation.

Limitations & Future Directions

This study demonstrated a relationship between ongoing oscillations (delta and alpha) and PEP in a task that would be easily reproducible across studies, but I am limited in terms of the ability to generalize to other brain states. Future studies should test this relationship in both resting state and task-positive states. This could determine whether there is a difference between the default-mode network and task-positive networks of the brain under different conditions of sympathetic arousal. For example, analyzing the differences between resting state and a task-positive state across individuals. This could help further explain the relationship between the alpha bands and PEP, and whether this relationship during a resting state is maintained during a task-positive event.

Pre-ejection period activity represents an objective measure of physiological state, however, its relationship to self-report measures of anxiety or stress in not clear. Future studies that include self-report measures will be useful to determine whether the individuals who had increased reported anxiety also were the individuals that had the strongest negative relationship between lower alpha band 2 and PEP.

Additional analyses could also be informative. For example, to analyze not only the individual differences between the interactions of the heart and the brain, but also to explore the relationship between right-sided lateralization of alpha band 1 and PEP, since I saw some right-sided lateralization in alpha band 1. There has been some evidence that there is increased right frontal lateralization of alpha power in anxious individuals (Mathersul, Williams, Hopkinson, & Kemp, 2008). As my results showed

right frontal lateralization in lower alpha band 1 topography more so than alpha band 2, this relationship between lower alpha band 1 and anxiety could be explored further.

Another future direction could be to analyze the ratio of HRV to PEP and its relationship to the three alpha bands. Since the sympathetic nervous system and parasympathetic nervous system modulate each other and are not independent of each other, it could be beneficial to explore how the ratio of their values relates to the various EEG brain oscillations.

Importance of this research

It is important to further understand human physiology and the basis of our stress response. The fact that different forms of attention and memory attenuate the three alpha bands indicates that perhaps each alpha band has a unique relationship to the autonomic nervous system as well. The relationship between the three alpha bands and the autonomic nervous system is an area that could be useful to explore, as previously alpha has been treated as a broad frequency range of 8-13 Hz. Separating alpha into different bands could clarify previous findings, as perhaps only certain activities influence one type of alpha band, instead of the broad frequency as a whole. Along with this, analyzing both the sympathetic nervous system and parasympathetic nervous system through separate measures in future studies is extremely important, as it appears there are differences in what EEG frequency bands have a significant relationship to each part of the autonomic nervous system.

Potential to use this relationship to diagnose and treat mental disorders

Understanding this relationship between the heart and the brain is important because it allows us to further understand human physiology, and how this relationship could be altered by various stress disorders. Already, there has been some indication that the default mode network is altered by various mental disorders (Broyd et al., 2009). If we were able to understand what this relationship between the heart and the brain looks like at rest, and then compare that to what it this relationship looks like in individuals who have various mental disorders, this could be an important biomarker for diagnosis and treatment. As of right now, the alterations in either cardiac physiology or EEG brain waves are not enough to definitively diagnose and treat individuals with mental disorders. Alterations have been found, such as how individuals with anxiety tend to have more right sided alpha lateralization, but these are not enough to diagnose someone with anxiety. If we were able to better measure the interaction between the heart and the brain, and have more definitive ideas of what this relationship is at rest, then one day it could be possible to use as a diagnostic tool or as a tool to make a differential diagnosis. Taking this even further, future research could look at what treatments strategies work best for specific types of variations in this relationship. This is why it is very important to continue to research and understand what the relationship between the heart and the brain looks like in a normal individual and patients to come up with integrative methods that analyze both the sympathetic nervous system and parasympathetic nervous system.

Concluding remarks

This experiment has built a foundation for the understanding the relationship between the EEG brain waves and the autonomic nervous system at rest, pointing to the importance of additional studies investigating the role of the autonomic nervous system in brain function, emotion, and cognition.

Bibliography

Beissner, F., Meissner, K., Bär, K.-J., & Napadow, V. (2013). The autonomic brain: an activation likelihood estimation meta-analysis for central processing of autonomic function. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *33*(25), 10503–11. http://doi.org/10.1523/JNEUROSCI.1103-13.2013

Berntson, G. G., Lozano, D. L., Chen, Y. J., & Cacioppo, J. T. (2004). Where to Q in PEP. *Psychophysiology*, *41*(2), 333-337. doi: 10.1111/j.1469-8986.2004.00156.x

Brenner, S. L., Beauchaine, T. P., & Sylvers, P. D. (2005). A comparison of psychophysiological and self-report measures of BAS and BIS activation. *Psychophysiology*, *42*(1), 108–115. http://doi.org/10.1111/j.1469-8986.2005.00261.x

Broyd, S. J., Demanuele, C., Debener, S., Helps, S. K., James, C. J., & Sonuga-Barke, E. J. S. (2009). Default-mode brain dysfunction in mental disorders: A systematic review. *Neuroscience & Biobehavioral Reviews*, *33*(3), 279–296. http://doi.org/10.1016/j.neubiorev.2008.09.002

Buckley, U., & Shivkumar, K. (2016). Stress-induced cardiac arrhythmias: The heart–brain interaction. *Trends in Cardiovascular Medicine*, *26*(1), 78–80. http://doi.org/10.1016/J.TCM.2015.05.001

Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2001). Age and sex effects in the EEG: development of the normal child. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *112*(5), 806–14. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11336896

Doehner, W., Ural, D., Haeusler, K. G., Čelutkienė, J., Bestetti, R., Cavusoglu, Y., … Ruschitzka, F. (2018). Heart and brain interaction in patients with heart failure: overview and proposal for a taxonomy. A position paper from the Study Group on Heart and Brain Interaction of the Heart Failure Association. *European Journal of Heart Failure*, *20*(2), 199–215. http://doi.org/10.1002/ejhf.1100

Dorrance, A. M., & Fink, G. (2015). Effects of Stroke on the Autonomic Nervous System. In *Comprehensive Physiology* (Vol. 5, pp. 1241–1263). Hoboken, NJ, USA: John Wiley & Sons, Inc. http://doi.org/10.1002/cphy.c140016

Duggento, A., Bianciardi, M., Passamonti, L., Wald, L. L., Guerrisi, M., Barbieri, R., & Toschi, N. (2016). Globally conditioned Granger causality in brain-brain and brain-heart interactions: a combined heart rate variability/ultra-high-field (7 T) functional magnetic resonance imaging study. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *374*(2067), 20150185. http://doi.org/10.1098/rsta.2015.0185

Hall, J. E. (2016a). Cardiac Muscle; The Heart as a Pump and Function of the Heart Valves. In, *Guyton and Hall Textbook of Medical Physiology* (13th ed., pp. 120-121). Philadelphia, PA: Elsevier.

Hall, J. E. (2016b). Nervous Regulation of the Circulation and Rapid Control of Arterial Pressure. In, *Guyton and Hall Textbook of Medical Physiology* (13th ed., pp. 216-221). Philadelphia, PA: Elsevier.

Hall, J. E. (2016c). Organization of the Nervous System, Basic Functions of Synapses, and Neurotransmitters. In, *Guyton and Hall Textbook of Medical Physiology* (13th ed., pp. 588-590). Philadelphia, PA: Elsevier.

Hall, J. E. (2016d). The Autonomic Nervous System and the Adrenal Medulla. In, Guyton and Hall Textbook of Medical Physiology (13th ed., pp. 781-783). Philadelphia, PA: Elsevier.

Harmony, T. (2013). The functional significance of delta oscillations in cognitive processing. Frontiers in Integrative Neuroscience, 7, 83. http://doi.org/10.3389/fnint.2013.00083

Karns, C.M., Giuliano, R. J., Pakulak, E., Bell, T. Petersen, S., Skowron, E., & Neville, H. J. (2015). Autonomic and neural mechanisms supporting inhibitory control in a stop-signal task. *Pyschophysiology,* 52.

Keil, F. C. (2014). The Biology of Development. In A. Javsicas (Ed.), *Developmental Psychology: The Growth of Mind and Behavior* (1st ed., pp. 59-60). New York, NY: W.W. Norton & Company.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews*, *29*, 169–195. Retrieved from https://ac-els-cdn-com.libproxy.uoregon.edu/S0165017398000563/1-s2.0-S0165017398000563-main.pdf?_tid=fd5962b0-5d15-4952-9fe6-5f1de64a1b6a&acdnat=1523829882_074246e15e61e1a45f71195d70e55314

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience Letters*, *244*(2), 73–76. http://doi.org/10.1016/S0304-3940(98)00122-0

Knyazev, G. G., Savostyanov, A. N., & Levin, E. A. (2004). Alpha oscillations as a correlate of trait anxiety. *International Journal of Psychophysiology*, *53*(2), 147–160. http://doi.org/10.1016/j.ijpsycho.2004.03.001

Knyazev, G. G., Slobodskaya, H. R., Safronova, M. V., Sorokin, O. V., Goodman, R., & Wilson, G. D. (2003). Personality, psychopathology and brain oscillations. *Personality and Individual Differences*, *35*(6), 1331–1349. http://doi.org/10.1016/S0191-8869(02)00353-7

Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biological Psychology*, *84*(3), 394–421. http://doi.org/10.1016/J.BIOPSYCHO.2010.03.010

Kubota, Y., Sato, W., Toichi, M., Murai, T., Okada, T., Hayashi, A., & Sengoku, A. (2001). Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. *Cognitive Brain Research*, *11*(2), 281–287. http://doi.org/10.1016/S0926-6410(00)00086-0

Lozano, D. L., Norman, G., Knox, D., Wood, B. L., Miller, B. D., Emery, C. F., & Berntson, G. G. (2007). Where to B in dZ/dt. *Psychophysiology*, *44*(1), 113–9. http://doi.org/10.1111/j.1469-8986.2006.00468.x

Mathersul, D., Williams, L. M., Hopkinson, P. J., & Kemp, A. H. (2008). Investigating models of affect: Relationships among EEG alpha asymmetry, depression, and anxiety. *Emotion*, *8*(4), 560–572. http://doi.org/10.1037/a0012811

Montano, N., Porta, A., Cogliati, C., Costantino, G., Tobaldini, E., Casali, K. R., & Iellamo, F. (2009). Heart rate variability explored in the frequency domain: A tool to investigate the link between heart and behavior. *Neuroscience & Biobehavioral Reviews*, *33*(2), 71–80. http://doi.org/10.1016/J.NEUBIOREV.2008.07.006

Moore, Keith L., A. M. R. Agur, and Dalley, A.F. (2015). Introduction to Clinical Anatomy. In, *Essential Clinical Anatomy* (5th ed., pp. 28-38). Baltimore, MD: Lippincott Williams & Wilkins. Print.

Newlin, D. B., & Levenson, R. W. (1979). Pre-ejection period: measuring beta-adrenergic influences upon the heart. *Psychophysiology*, *16*(6), 546–53. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/229507

Nishida, K., Razavi, N., Jann, K., Yoshimura, M., Dierks, T., Kinoshita, T., & Koenig, T. (2015). Integrating Different Aspects of Resting Brain Activity: A Review of Electroencephalographic Signatures in Resting State Networks Derived from Functional Magnetic Resonance Imaging. *Neuropsychobiology*, *71*(1), 6–16. http://doi.org/10.1159/000363342

Porges, S. W. (1995). Cardiac vagal tone: A physiological index of stress. *Neuroscience & Biobehavioral Reviews*, *19*(2), 225–233. http://doi.org/10.1016/0149-7634(94)00066-A

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology*, *74*(2), 116–43. http://doi.org/10.1016/j.biopsycho.2006.06.009

Smith, M. E., & Gevins, A. (2004). Attention and Brain Activity While Watching Television: Components of Viewer Engagement. Media Psychology, 6(3), 285–305. http://doi.org/10.1207/s1532785xmep0603_3

Stevens, C., & Bavelier, D. (2012). The role of selective attention on academic foundations: A cognitive neuroscience perspective. *Developmental Cognitive Neuroscience*, *2*, S30–S48. http://doi.org/10.1016/J.DCN.2011.11.001

Subhani, A. R., Xia Likun, X., & Malik, A. S. (2012). Association of Autonomic Nervous System and EEG Scalp Potential During Playing 2D Grand Turismo 5. In 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (Vol. 2012, pp. 3420–3423). IEEE. http://doi.org/10.1109/EMBC.2012.6346700

Takahashi, T., Murata, T., Hamada, T., Omori, M., Kosaka, H., Kikuchi, M., … Wada, Y. (2005). Changes in EEG and autonomic nervous activity during meditation and their association with personality traits. *International Journal of Psychophysiology*, *55*(2), 199–207. http://doi.org/10.1016/J.IJPSYCHO.2004.07.004

Teplan, M. (2002). FUNDAMENTALS OF EEG MEASUREMENT. *MEASUREMENT SCIENCE REVIEW*, *2*(2). Retrieved from http://www.edumed.org.br/cursos/neurociencia/MethodsEEGMeasurement.pdf

Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, *36*(2), 747–756. http://doi.org/10.1016/J.NEUBIOREV.2011.11.009

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*(3), 201–16. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11163422

Tresilian, J. (2012). Neuromechanical Foundations. In, *Sensorimotor Control and Learning: An Introduction to the Behavioral Neuroscience of Action* (pp. 40-65). Basingstoke, England: Palgrave Macmillan.

Triggiani, A. I., Valenzano, A., Del Percio, C., Marzano, N., Soricelli, A., Petito, A., … Babiloni, C. (2016). Resting state Rolandic mu rhythms are related to activity of sympathetic component of autonomic nervous system in healthy humans. *International Journal of Psychophysiology*, *103*, 79–87. http://doi.org/10.1016/J.IJPSYCHO.2015.02.009

Valenza, G., Duggento, A., Passamonti, L., Diciotti, S., Tessa, C., Barbieri, R., & Toschi, N. (2017). Resting-state brain correlates of instantaneous autonomic outflow. In *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (Vol. 2017, pp. 3325–3328). IEEE. http://doi.org/10.1109/EMBC.2017.8037568

Valenza, G., Toschi, N., & Barbieri, R. (2016). Uncovering brain-heart information through advanced signal and image processing. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *374*(2067), 20160020. http://doi.org/10.1098/rsta.2016.0020

van der Wall, E. E., & van Gilst, W. H. (2013). Neurocardiology: close interaction between heart and brain. *Netherlands Heart Journal : Monthly Journal of the Netherlands Society of Cardiology and the Netherlands Heart Foundation*, *21*(2), 51–2. http://doi.org/10.1007/s12471-012-0369-4