university of groningen / faculty of science and engineering / artificial intelligence

The relationship between HRV and Alpha Power

Bachelor's Project Thesis

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Abstract: A part of Major Depressive Disorder (MDD) is Perseverative Cognition (PC): repetitive thinking about stressful past or fearful future events. PC can initiate a peripheral stress response in the body, causing a higher Heart Rate and lower Heart Rate Variability (HRV). HRV measures the intervals between heartbeats and derives from the dynamic control of the Autonomic Nervous System (ANS). Several brain regions are part of the ANS, such as the hippocampus and the amygdala. This study investigated the relationship between HRV, and the most dominant brain activity, alpha power, using electroencephalography (EEG) and electrocardiography (ECG). EEG and ECG signals were acquired simultaneously. Hypothesized was a positive linear relationship between HRV and alpha power. Participants included 23 remitted MDD (RMDD) patients and 23 healthy controls (HC). EEG and ECG signals were recorded during an eyes-closed resting state period. HRV was then calculated using the ECG signal. Results showed no group difference in HRV and a higher alpha power in RMDD subjects than in HC subjects. Moreover, a weak positive correlation was found between HRV and alpha power in both groups. Alpha power was especially active in the parieto-occipital region of the brain, which also showed a weak positive correlation with HRV. This demonstrates that people with RMDD have a higher cognitive load, which can be a predictor of MDD. Future studies should investigate multiple frequency bands to see if any of these bands is a predictor of MDD.

1 Introduction

Major depressive disorder (MDD) is a mental disorder characterized by a depressed mood, diminished interests and low self-esteem. MDD affects approximately one in six adults worldwide, and occurs twice as often in women than in men (Gutiérrez-Rojas et al., 2020; Kupfer et al., 2012; Otte et al., 2016).

Patients who suffer from MDD have reported experiencing fewer positive events than healthy people and are more likely to develop heart disease, obesity, hypertension, and diabetes, among others (Peeters et al., 2003). Furthermore, MDD increases the risk of stroke, cancer, or Alzheimer's disease and is responsible for approximately 10% of worldwide deaths (Lépine & Briley, 2011; Otte et al., 2016).

This study focusses on remitted MDD (RMDD) patients. An MDD patient is in remission when the illness has abated temporarily. This does not imply that the person is free of the illness or that symptoms will stay away (Gesicki & Nelson-Becker, 2018). However, the cognitive functioning of RMDD patients is said to almost be restored to a pre-morbid state. Nevertheless, RMDD patients may still have some cognitive impairments that make them vulnerable to a relapse of the depressive disorder (Hammar & Årdal, 2009; Trivedi, 2006).

Two ways of thinking associated with depression are rumination and worry (Ottaviani, Shahabi, et al., 2015). Rumination and worry are both perseverative and repetitive ways of thinking and critical processes for developing or maintaining MDD (Brosschot et al., 2010; Nolen-Hoeksema, 1991).

However, there is a difference between rumination and worry. Rumination is about past events, whereas worry is about future events (Ottaviani et al., 2016). Nevertheless, both concepts are correlated and share many of the same characteristics (Nolen-Hoeksema et al., 2008). Both ways of thinking, rumination and worry, can be grouped under the collective term perseverative cognition

(PC). PC can be described as repetitive or persistent thinking about past stressful events or feared events in the future (Brosschot et al., 2010; Ottaviani, Medea, et al., 2015).

Several studies have investigated the effect of PC on one's emotional state (Larsen & Christenfeld, 2009; Nolen-Hoeksema et al., 2008; Ottaviani, Medea, et al., 2015; Ottaviani, Shahabi, et al., 2015). All studies found that PC had a negative influence on mood. People reported being more sad, tired, anxious and angry during PC, which is in line with the finding that PC is associated with extending and strengthening depressive moods (Nolen-Hoeksema, 1991). Lastly, multiple studies found that people have an increased recall of negative memories during PC (Cooney et al., 2010; Lyubomirsky et al., 1998)

The influence of PC on brain activity can be measured using electroencephalography (EEG). EEG displays the electric brain activity of an individual during rest and in response to certain stimuli.

Studies have shown that the hypoactivation of the left dorsolateral prefrontal cortex (DLPFC) plays an essential role in PC. Due to the hypoactivation of the DLPFC, the information flow to the temporal brain regions gets restricted (Ferdek et al., 2016; Jin et al., 2019; Putnam & McSweeney, 2008). This connection between the left DLPFC and the temporal brain region is crucial for emotion processing, since the temporal cortex houses the amygdala and hippocampus.

Another brain area involved with PC is the thalamus (Makovac et al., 2020). Multiple nuclei of the thalamus connect to the PFC, such as the dorsal lateral nuclei of the thalamus, which controls input and output to the cingulate gyrus, which is involved in emotion regulation (Lee et al., 2018; Phillips et al., 2021).

PC initiates a 'fight-or-flight' response of the body, which activates a cascade of biological processes (Ottaviani et al., 2016). These processes ultimately result in a peripheral stress response of the body, initiated by a signal of the brain to the autonomic nervous system (ANS). This nervous system is responsible for blood pressure, cortisol levels and heart rate variability (HRV) (Bjorntorp, 2001; Won & Kim, 2016; Yang et al., 2007). Research thereby found that episodes of PC are associated with a higher heart rate (HR) and lower HRV, which is equivalent to less time between heartbeats (Pieper et al., 2007).

The amygdala and hippocampus both play a role in the ANS and consequently in controlling HRV (Ako et al., 2003). The amygdala stimulates the ANS and produces signs of emotional arousal, equivalent to changes in heart rate (Yang et al., 2007). The hippocampus regulates cardiovascular function, mainly the ventral hippocampus was found to increase HR (Ajayi, 2016). HR thereby directly influences HRV, since HRV is inversely proportional to HR (Kazmi et al., 2016).

Several studies used EEG to measure the relationship between HRV and brain activity. However, most of these studies investigated the relation between HRV and emotions or HRV and different stages of sleep, but not between HRV and brain activity during a resting state (Ehrhart et al., 2000; Garcia et al., 2011; Otzenberger et al., 1997). Resting state EEG data can give insight into intrinsic neural activity without a stimulus or task imposed, which is relevant for investigating fundamental brain processes.

Alpha, beta, theta, and delta brain waves are prevalent during rest (Lapomarda et al., 2022; Radi & Nasaruddin, 2022). Nevertheless, very few studies have investigated whether these band frequencies are related to HRV. Therefore, this research focuses on determining the relationship between HRV and alpha power (8-13 Hz) during a resting state in remitted MDD patients. During this resting state, PC will be manipulated using a fantasizing and mindfulness intervention. It is expected that an increase in alpha power leads to an increase in HRV, and thus a positive linear relationship between HRV and alpha power.

2 Methods

2.1 Subjects

This study investigates EEG and HRV data from a research done on understanding the mechanisms of the prevention of depression. In total, 42 subjects completed the experiment. Group 1, the healthy control group (HC), included 23 subjects: 3 males and 20 females. Group 2 included 19 subjects with RMDD: 1 male and 18 females. Remitted MDD (RMDD) patients were selected based on criteria from the Diagnostic Statistical Manual (version 5) and a score on the Inventory of Depressive Symptomatology (IDS), which indicates the presence or absence of clinically relevant depressive symptoms. Table 2.1 displays the demographic data and group measurements of the participants.

2.2 EEG and ECG Data

During the resting state (RS) task, the EEG and ECG signals were measured simultaneously for 5 minutes with closed eyes. During this session, participants had to remain awake and not engage in any particular thought. This task was performed before and after the two interventions: mindfulness and fantasizing. Participants were randomly assigned an order of interventions. This random assignment ensures that any differences between and within the groups are not systematic at the experiment outset. As a result, each participant had to perform in four sessions: two baseline and two after-intervention sessions.

The EEG and ECG signals were recorded via the ActiView 9.02 software, belonging to the BioSemi EEG system (https://www.biosemi.com/). The central electrode (Cz) of the BioSemi head cap was placed on the vertex of the head. In addition to the head cap, eight external electrodes were placed: one at each ear, four eye electrodes, and two ECG electrodes placed in a diagonal line across the heart.

2.3 HRV measurements

HRV values were calculated using the ECG data and the ECG-beats toolbox for MATLAB (Thanapaisal et al., 2020). This toolbox can extract heartbeat peaks and interbeat interval measures from an EEG channel. From these heartbeat peaks, the toolbox can calculate several measures of HRV, such as the Root mean square of successive RR interval differences (RMSSD). The RMSSD is one of the most relevant and accurate measures of HRV over a short period (Shaffer & Ginsberg, 2017).

2.4 Preprocessing

EEG data preprocessing was done using MATLAB 2022b and EEGLAB, a toolbox for MATLAB (Delorme & Makeig, 2004). The EEG data was downsampled to 512 Hz to reduce the computational load, filtered with a FIR filter and segmented into epochs of one minute. Next, the EEG signals are re-referenced, thereby reducing the noise. Artefacts, such as muscular artefacts or head movements, were removed using Independent Component Analysis (ICA).

2.5 Statistical Analyses

The resulting EEG signals and corresponding HRV values were used for statistical analysis. This analysis was done independently for the RMDD patients and the HC participants, using RStudio (RStudio Team, 2020) and MATLAB 2022b.

3 Results

3.1 Main effects of group, session, and time on alpha power and HRV

A three-way ANOVA was run to examine the effect of the group, session, and time on alpha power. There was a significant main effect of the group on alpha power, $F(1, 661) = 13.51$, $p < .001$. No such effect was found between time and alpha power, $F(4, 661) = 0.520$, $p = .721$, or session and alpha power, $F(3, 661) = 0.556$, $p = .644$. Post hoc comparisons using the Tukey HSD test indicated that alpha power was significantly higher for the RMDD group compared to the HC group, $p < 0.001$, $95\%CI = [-2.1408231, -0.9403117]$.

A three-way ANOVA to examine the effect of the group, session, and time on HRV did not show any significant result. Group: $F(1, 661) = 0.013$, $p = .910$; Session: $F(3, 661) = 1.155$, $p = .326$; Time: $F(4, 661) = 1.423$, $p = .225$.

Figure 3.1 shows a summary of the HRV and Alpha Power data in total and per group.

3.2 Mean Alpha Power and HRV

The correlation between alpha power and HRV was calculated using the mean alpha power over all the scalp electrodes. A weak positive correlation was found between this mean alpha power and HRV, $r(132) = .25$, $p < .01$.

Furthermore, the correlation between mean alpha power and HRV was calculated in group 1 and

	Group 1, N = 23		Group 2, N = 19	
	Mean	SD	Mean	SD
Age (years)	34	13	34	11
IDS (PTSS)	5,0	3,2	7,6	4,4
HRV (RMSSD)	41,7	22,5	41,3	20,0
Alpha Power (dB)	2,1	4,3	3,4	4,9

Table 2.1: Demographic data and group measurements of the subjects

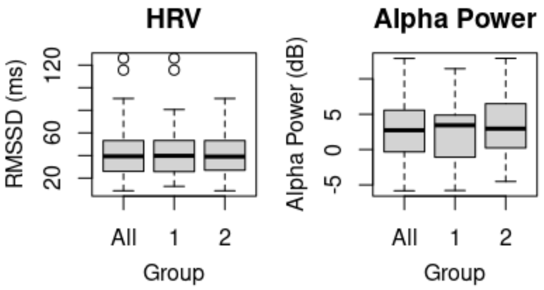


Figure 3.1: Box plot showing the five-number summary of the HRV and Alpha Power data. All: Both groups combined; 1: HC; 2: RMDD

group 2, as to examine whether HRV has a different effect on the brain in RMDD patients than in healthy controls. Results showed a low positive linear correlation between HRV and alpha power in group 1, $r(70) = .23$, $p = .05$ and group 2, $r(60) = .37$, $p < .01$, see figure 3.2.

The correlation within sessions was also calculated to investigate if the relationship between alpha power and HRV is different before and after an intervention. There appeared to be a weak positive linear correlation within these sessions. For the RMDD group, the correlation increased after the intervention, from $r(97) = .30$, $p = .003$ to $r(95) = .33$, $p < .001$. The HC group showed a slight decreased correlation after the intervention, from $r(100) = .28$, $p = .005$ to $r(102) = .26$, $p = .008$.

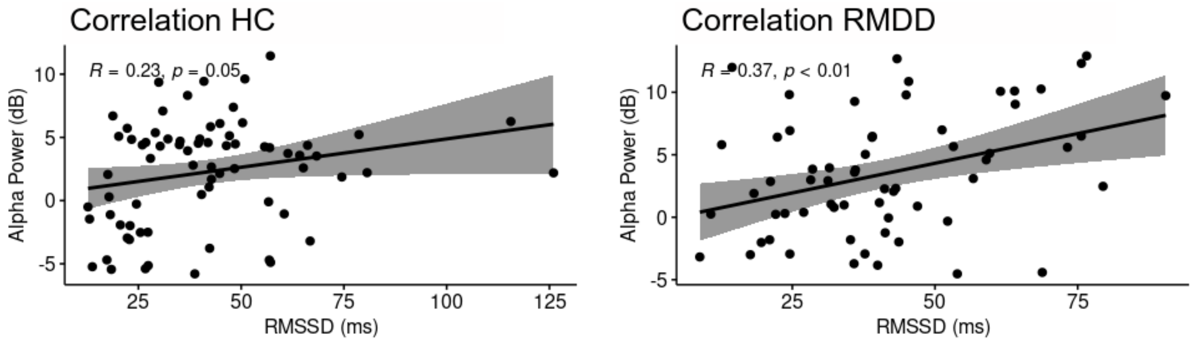
A two-way ANOVA was run to determine the effect of the intervention on alpha power. After adjustment for pre-intervention alpha power, there was no statistical significant difference in post-intervention alpha power between the groups, $F(1, 36) = .002$, $p = .963$. The same was done for HRV. However, no statistical significant difference was found for HRV either, $F(1, 36) = .412$, $p = .525$. Therefore, we can conclude that either the intervention had no effect on alpha power, or the sample size was too small to find an effect.

3.3 Parieto-occipital alpha power and HRV

In addition to the mean alpha power, the correlation between electrodes and HRV was calculated. As displayed in figure 3.3, the highest alpha power was measured in the parieto-occipital regions, corresponding to electrodes P7, P8, PO3, PO4, O1 and O2. These electrodes were found to have a weak positive correlation with HRV (P7: $r(133) = .28$, $p = .001$, P8: $r(133) = .32, p < .001$, PO3: $r(133) = .25$, $p = .003$, PO4: $r(133) = .27$, $p = .001$, O1: $r(133) = .31, p < .001$, O2: $r(133) = .34, p < .001$). Furthermore, a weak positive correlation was found at electrode Oz: $r(133) = .3$, $p < .001$. A possible explanation for these findings is that alpha power in the resting state is highest in the parieto-occipital regions (Mahjoory et al., 2020). This increased alpha power is associated with an increased HRV (Bazanova et al., 2013).

4 Discussion

This study examined the brain-heart interaction in 23 healthy subjects and 19 RMDD subjects during an eyes-closed resting state. EEG and ECG signals were recorded simultaneously during this resting state. The correlations between HRV and EEG alpha band power were calculated in the HC and RMSSD group, as well as in the pre- and post-intervention RS tasks. This correlation was calculated to see if there was a difference in the relationship between the heart and the brain between the two groups, and to see the influence of the intervention on this relationship.



(a) In HC subjects, HRV had a weak positive correlation with alpha power.

(b) In RMDD subjects, HRV had a weak positive correlation with alpha power.

Figure 3.2: Results of the correlation analyses between HRV and EEG in the resting state. The correlation plots with correlation coefficients after false discovery rate (FDR) correction. Each point represents the mean HRV or alpha power measurement over the 5-minute resting state period per participant.

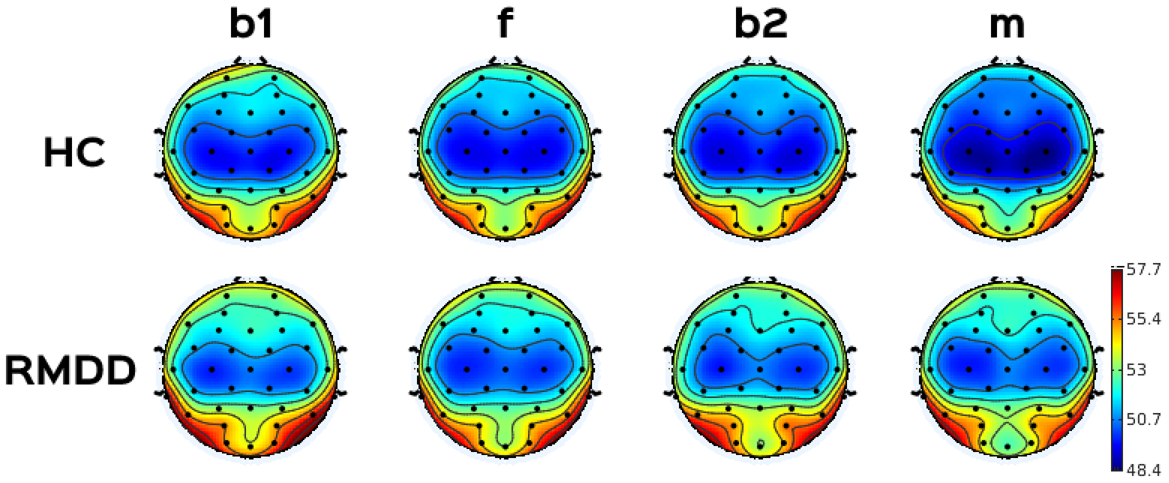


Figure 3.3: Spectrogram showing alpha power per session and group. Electrode placement is according to the 10-20 electrode system. b1: baseline before fantasizing; f: after fantasizing; b2: baseline before mindfulness; m: after mindfulness

The study hypothesized that an increase in alpha power would lead to an increase in HRV, meaning that there would be a positive linear relationship between alpha power and HRV. This hypothesis was based on the findings that the ANS regulates processes such as HRV and that alpha power and ANS activity are positively correlated (Ehrhart et al., 2000; Garcia et al., 2011; Otzenberger et al., 1997; Won & Kim, 2016; Yang et al., 2007). Results show that alpha power in the parieto-occipital brain area and HRV are indeed positively correlated, which is in line with the hypothesis and previous studies (Attar et al., 2021; Bazanova et al., 2013; Kwon et al., 2019).

Two ANOVA tests were done to analyse if there were any group differences and if the intervention had any impact on HRV or alpha power. Results from these tests showed that alpha power was significantly higher in the RMDD group than in the HC group. However, the intervention did not seem to have any effect on HRV nor alpha power.

Unexpectedly, the range of the HRV variables was very large: 6 – 144 ms. A possible explanation for this HRV range could be personal circumstances, like exercise, emotions, nutrition, or sleep (Altini & Plews, 2021; Uusitalo et al., 2007). In addition, several internal systems influence short-term HRV, such as endocrine and respiratory systems (Shaffer & Ginsberg, 2017). Future studies can overcome this problem by calculating HRV related to the personal 24-hour baseline of a participant.

Other explanations could be problems with the ECG recording, such as movement during the test, or electrode placement relative to the body. This last problem could be caused by the size of the chest and the location of the heart within the chest. Problems with the automatic HRV calculation, such as incorrect peak detection, could also have caused wrong outcomes.

Another limitation of this project was the limited time available and the lack of required skills. This time constraint is particularly visible in the EEG data, as artefacts have not been sufficiently removed from the EEG signals, resulting in a more noisy signal. This noise leads to incorrect calculations of the alpha power. For future EEG research, it is necessary to acquire the essential knowledge and skills before the start of the study so that the time constraint does not cause any problems with preprocessing the data.

Furthermore, HRV and alpha power are influenced by mental fatigue caused by the duration of the different sessions (4× a 5-minute resting state session + 2 interventions) (Lagopoulos et al., 2009; Zhao et al., 2012). Based on this influence combined with the insufficient preprocessing, it seems probable that some correlations between EEG and HRV have been impacted negatively. The impact of these factors on the correlations can only be determined by future research with a similar study design. The results can then be compared to the results of this study.

A final limitation of this study is the sample size and data organization. Because the data comes from a related study, it was not always clear whether a participant had participated in all four sessions, since the related study did not have the information and data organization fully in order. In addition, some data files were untraceable or corrupted. By increasing the number of participants and better organizing the data files, more participants could have been included in the analysis of this current study.

Overall, this study is a good first attempt to investigate and elucidate the relationship between HRV and alpha power in RMDD patients. Future study suggestions include investigating if alpha power correlates with indices of HRV, such as LF/HF. The same can be done with indices of alpha power, such as alpha peak frequency or alpha1 (8-10.5 Hz) and alpha2 (10.5-13 Hz). Another suggestion includes looking at the correlation of multiple EEG power bands, to get a more complete image of the relationship between HRV and EEG.

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