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Electrode reduction in EEG sleep research

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1 Abstract

This study aims to determine the power spectral density of the different sleep stages and compare them to the awake state. Specifically, what frequencies differ in sleep stages N1, N2, N3, and REM compared to awake. Afterwards, electrode reduction is done to find the best configuration with respect to the error in power spectral density. To find the power spectral density of the sleep stages, a data-set from Tsukuba Lab is analyzed using the MNE open-source python package. First, the sleep data was categorized, then the power spectral density was found and averaged in the sleep stages. Furthermore, the power spectral densities of non-awake states were compared to the awake state. Lastly four different electrode reduced configurations was tested out and error checked with the original configuration. The results showed a clear difference in power spectral density between sleep stages and a significant difference in the non-awake states compared to the awake state. It also showed that good reduced electrode configurations are dependent on what kind of brain waves is in focus.

These results suggest that EEG is a great tool to find irregularities in sleep, and EEG should be further researched as a tool to find brain diseases under sleep. It is possible to use reduced configurations of electrodes and still get a good results, but it needs to be setup for the specific brain waves in focus. For further research i recommend looking at AI for better results in reduced electrode configurations.

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2 Introduction

2.1 Background and motivation

Electroencephalography (EEG) is a method to record brain signals. The signals are picked up by electrodes (sensors) placed on the head's scalp that record electrical voltages. These signals are then used to reconstruct the brain activity. And by analyzing brain activity, it is possible to identify if a patient has a brain disease. The most common brain disease to detect and investigate with EEG is epilepsy [5]. Other uses for EEG are identifying memory problems such as dementia, head injuries, and brain tumors. EEG is a cheap method to acquire and a good indication of brain activity [6]. It has a high temporal resolution, reaching a sub-millisecond time scale witch is why it's the standard technique in sleep research. Over the last years have computer programs and techniques to reconstruct brain activity improved a lot. This has led to a fast improvement in the field of EEG and is why electrode reduction for sleep analysis is relevant for research now.

EEG was first used on humans in 1924[7]. To this day, EEG is mostly used together with MEG for different brain diseases and especially epilepsy. EEG is categorized in too two categories, high-density EEG and low-density EEG. High-density means more electrodes, and low-density means fewer electrodes. Over 32 electrodes are normally considered high-density, and under 30 is low-density [8]. Using high-density EEG, more information is gained, and therefore, more specific source reconstruction is accomplished. But this comes with the downside that it has a much greater computational cost, and more data analysis and bigger datasets are needed.

2.2 Previous work

We want to reduce the number of electrodes without losing the critical data to get a good source reconstruction and diagnose the patient. This is done before in mobile activity [9] but not in sleep activity. In that study, they tried to find the least electrodes needed for source reconstruction when they had physical tasks. They concluded that 35 electrodes would be sufficient in most tasks. This is what we want to do, but we want to do it in sleeping subjects. Studies on high-density EEG in sleep research have also been done before. The study [10], they found that high-density EEG can be used to study brain functioning in neurological and neurodevelopmental disorders and to evaluate therapeutic approaches. [11] studied brain potentials before rapid eye movements in REM sleep and found activity in emotion, memory, and motor-related brain locations.

2.3 Scope of this report

This report will focus on minimizing the electrodes needed in sleep EEG data. We will start by using a high-density EEG data set and produce the right source reconstruction. Then reduce the number of electrodes but still manage to get the same or close to the exact source reconstruction. This will give us a good indication of how many electrodes are needed to obtain the wanted result. Specifically, starting with source reconstruction with 32 electrodes and getting the power spectral density. Then reduced the electrodes down to 16 and 8 electrodes and getting a new power spectral density. Afterward the error between the reduced configurations and the original 32 electrode configuration will calculated.

2.4 Organization of this report

This report presents method of find the power spectral density of the brain in a sleeping patient. Then reduces the electrodes and finds the error in the reduced configurations compared to the original configuration. Firstly, background theory is presented in chapter 3. Then in chapter 4 the method for going from the raw EEG data to finding the power spectral density is presented. In chapter 5 power spectral density results and the reduced electrode configurations error are presented. Lastly in chapter 6 the results are discussed and a conclusion and future work is talked about.

3 Theory

3.1 Electroencephalogram

An electroencephalogram is a method of recording brain activity. It uses electrodes on the scalp of the head to record electrical voltages. These voltages are small, and when they pass through the scalp, they are reduced even more. It so small voltages that it is hard to differ from noise. It's needed to filter out the noise before the brain activity can be localized. Localization together with the intensity and time-course of the sources is called source reconstruction.

3.2 Data set

This project was supposed to get a data set with HdEEG from Tsukuba University, but due to covid-19, this was not possible. However, they provide a dataset of one participant without sleep annotations. The dataset contains data from 32 channel EEG seen in Figure 3. In addition to the EEG channels, it also contains EOG, a sensor close to the eye for rapid eye movement analysis. And ECG sensor witch is a heart rate sensor. The dataset is 8.3 hours long but has some short periods that contain too much noise for classification. The sampling rate of the data set is 2048Hz witch is much more than needed in this paper. Therefore has the data has been resampled down to 100Hz as the frequency of interest is about 0-30Hz. The classification method used is described more in subsection sleep waves and scoring.

3.3 Sleep

Sleep has four stages. N1, N2, N3, and R. Stages N1 and N2 are often combined under light sleep. Stage N3, commonly known as deep sleep, and R is commonly known as REM sleep, or rapid eye movement sleep. When you sleep, you go through a cycle of all these stages. Normally you start in stage N1, which is the lightest sleep, and easy to wake up from. Then you move to stage N2 after 10-20 minutes, which is a middle stage you need to be in before your body goes to N3 or deep sleep. Deep sleep is where your body is "repairing" the body the most. It is recommended to get about 20% of your sleep in a deep sleep. When your body goes to deep sleep, your brain frequency is the lowest of the four stages, and the amplitude of the brain signals are the highest. The length of N3 is reduced for each cycle you have gone through. From N3, you move back to N2 and then into R. This is a full cycle of sleep and normally takes 1.5 hours. It is in REM sleep you dream, and the R stage gets longer and longer the more cycles you have been through. From R, you go back to N2, and then you move between N2 to N3 to N2 to R. So N2 is a middle stage you need to go into to go from R to N3 or N3 to R. These stages is not distinct entities, and you don't jump for one to another one. You gradually move between them and are they are just a way of differentiating the sleep process.

3.4 Sleep waves and scoring

There are four main waves in sleep, Alpha, Beta, Delta, and Theta. The frequency of the waves classifies them. Beta waves have the fastest frequency between 14 and 30 Hz and are present during wakefulness and drowsiness. It also reemerges during REM sleep. Alpha waves have frequencies between 8 and 13 Hz and are seen during quiet alertness with eyes closed. Theta waves frequencies are between 4 and 8 Hz and are the most common sleep frequency in EEG waves. Delta waves have frequencies between 0.5 and 2 Hz and are most common in a deep sleep. In addition to these waves, sleep spindles and k complexes are used to score the sleep. Sleep spindles originate in the central vertex region and are in the frequency range of 11-16Hz. K complexes are slow and sharp waves that start with a spike in the negative direction before spiking positive. Both sleep spindles and k complexes are an indication of N2 sleep but can be seen in other stages too [1]. Vertex sharp waves are also used to classify sleep. These waves are sharply negative-going bursts that stand out from the background. And lastly, slow waves are high amplitude and low-frequency variants of delta waves. These are the defining characteristics of N3 sleep. An example of the sleep waves can be seen in Figure 1.

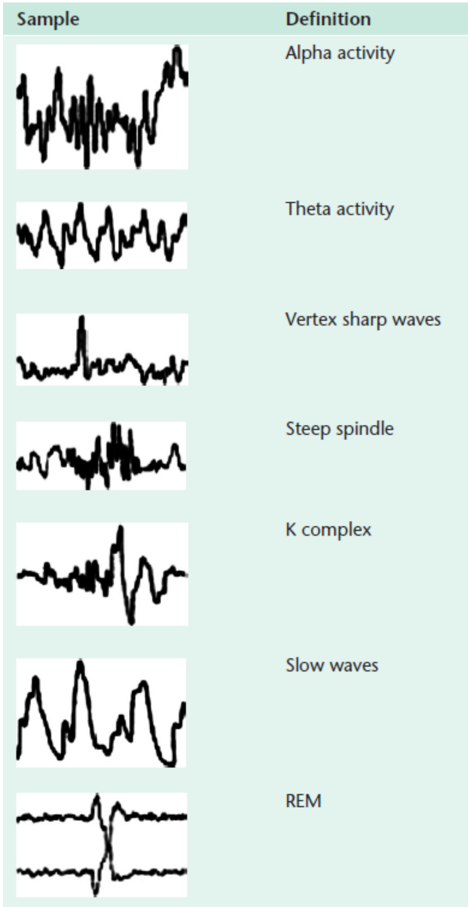

Figure 1: Example of how brain waves look in EEG sensors [1]

Sleep, as mentioned in the sleep subsection, is a cyclic state. This means we can use this knowledge in the scoring. Firstly, the first several minutes of EEG recording will be in an awake state. After the awake state, we know that the subject moves on to state N1. As seen from table 1 N1 are normally 1-5 min long. From N1, the subject can move back to awake, but normally the next stage is N2. The subject will now move between N2 and N3 before going moving from N2 and REM. This cycle can be seen in Figure 2

To classify the sleep with a visual inspection, the brain activity and the time of the sleep cycle are used. The start of the sleep recordings in the awake state. The awake state consists mostly of alpha activity, but when the subject moves, beta activity is also seen. Movement can also cause artifacts shown as spikes in all channels as EEG sensors are susceptible. Stage N1 is characterized by low voltage and fast EEG activity. Theta activity is the dominant wave in this stage but is seen together with low amplitude beta waves. At the end of the N1 sleep stage, Vertex sharp waves may occur, but if sleep spindles or k complexes are observed, the sleep will not be classified N1. Stage N2 is also dominated by theta waves and can have occasional bursts of faster activity. In this stage, K complexes and sleep spindles are typical and normally occur in an episodic fashion. In stage N3 sleep, slow waves with high amplitude are seen. It is also normal for eye movements to cease altogether. In Stage REM, the amplitude of the signals is reduced. It contains a mix of frequencies with theta, alpha, and delta waves. But the Rapid eye movements are the simplest to spot and are seen in the EOG. Physiological activity is also significantly higher, and pulse and blood pressure may increase.

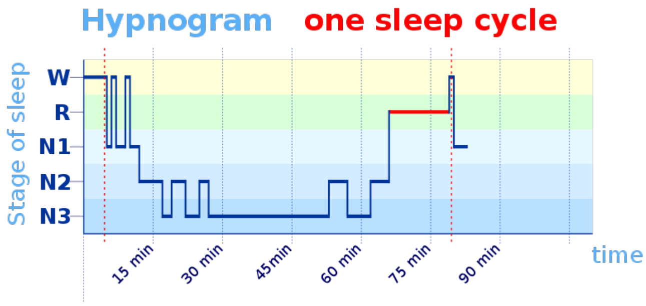

Figure 2: Normal sleep cycle [2]

Sleep Stages	Normal Length
N1	1-5 minutes
N2	10-60 minutes
N3	20-40 minutes
REM	10-60 minutes

Table 1: Table for normal sleep length in sleep stages [4]

3.5 Forward model

In EEG, a forward model is a way of modeling how signals from the brain are detected in the sensors outside the head. The model takes in a signal in the head and predicts what the sensors will detect. This model can be used to simulate what electrodes will detect with different brain activity. To make this forward model, information about the patient's head is needed.

Tree main components are needed to make a forward model, a head model, the sensor positions, and the brain activity. Firstly the head model is described. A head model holds information about how an electric current spreads throughout the head. To find the electric current movements, the electric resistance in the head needs to be found. The electric resistance is different in different elements in the head, so firstly, the head elements' composition is needed. Because humans have different shapes and forms of heads, the head elements' composition is different in every individual. This means that everyone has a unique head model. Usually, to find this model, MRI is used. MRI is an instrument that scans your head and outputs images of how the head is composed. If it's not possible to get an MRI of the patient's head, you can use a template MRI. Template MRI is a standard MRI that is made by averaging a lot of heads, making a model that best fits an average head. In this study, a Template MRI was used.

After the head model is found or a template is used, information about the sensors and the source signal is needed. For the sensors, the position on the surface of the head is needed. And for the source signal, position and amplitude are needed. The sensors are typically placed in the five percent system or the 10-20 system [12]. These systems were made to make it easier to reproduce and analyze EEG data. The electrode position system is typically saved with the dataset. In this study, the forward model was used to calculate the inverse model. The forward model can be used as a tool to test out different brain activities. Using the forward model to simulate brain activity can be compared to a wanted source reconstruction to check if correct.

The forward model is stated as $M = GD + n$. Where M is the matrix of data measurements at different times, D is the matrix of dipole magnitudes at different time instants. G is the lead field that describes the current flow of the electrode through each dipole position know as the gain matrix, and n is the noise. [13]

3.6 Source reconstruction

Source reconstruction is a method using electrode input to estimate brain activity. This is done by using the inverse model. The inverse model is, as the name says, the inverse of the forward model. The input to the inverse model is electrode signals, and the output is brain activity.

The inverse model is stated as $\hat{D} = MG^{-1} + n$. Here is $\hat{D}$ the estimation of the dipole magnitude matrix, M the electrode matrix, G^{-1} the inverse of the gain matrix, and n the noise. This has equation has infinite solutions.

When we have found the inverse model, we use it to calculate the source. The problem with the inverse solution is that the problem doesn't have a unique solution. This means we need to make assumptions to get the best solution. [14] These assumptions can be incorporating different constraints based on a priori information about the desired source or physiological assumptions. It exists many different methods of making source reconstruction. Some examples of these methods are found here [15], but in this project, we will use the minimum norm estimates method. This method solves the infinite solution problem by choosing the solution with the minimum power. The inverse model equation with minimum norm estimates is stated as $\hat{D}_{MNE} = G^T(GG^T + \alpha I_N)^{-1}M$

3.7 Power spectral density

Power spectral density (PSD) is the energy of a signal at different frequencies. In other words, how much power all specifics frequencies in a signal have. This can be found by using the Fast Fourier transform (FFT). FFT is a method the converts a signal from the time-domain to the frequency domain. FFT is calculated using a version of the Discrete Fourier transform. This can be mathematically formulated as $X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N}$, $k = 0, ..., N-1$. Discrete Fourier transform requires $O(N^2)$ operations, and this is why FFT is used. This method takes advantage of repeated calculations in discrete Fourier transform and cuts the operations down to $O(Nlog(N))$.

PSD can be used to analyze the signal and find out what frequencies has the most energy. This is useful in sleep research as the waves' frequency categories the sleep and can be used to find abnormal activity in the brain.

4 Method

4.1 Reading and prepare for classifying

Before classification can be done, the data needs to be pre-processed to get the best results. Reading the dataset is done by using the method `mne.io.read_raw_bdf()`. This method takes in the filename and location of the dataset and makes it accessible by a variable in python. Storing the full dataset in a variable can overload the computer's memory, so to avoid this problem, preload is set to false. Then to set the electrodeposition `raw.set_channel_types` is used. Biosemi32 is the electrodeposition used when recording the dataset in this study, so it's set to that. Biosemi32 is a standard electrode setup and can be seen in the Figure 3. Further, resampling and filtering the data needs to be done. Before we can resample and filter the data, we need it preloaded in the variable. So to avoid the memory problem, the data is cropped into 1000 seconds parts. Then resampling the data to 100 sample points per second (100hz) is done with the method `mne.io.Raw.resample()`. Resampling the data is done to reduce the computational power needed for further analysis of the data. After the resampling, the data is filtered twice. First with highpass and low pass filter then with a notch filter. The highpass and lowpass filter is set to 0.3 − 40Hz. It is in this range the useful information about sleep is and outside is considered noise. The notch filter, also known as a band-stop filter, is used to exclude the frequency 50 Hz because of the voltage where the data are recorded. This is done to avoid a spike of noise in the data set. The data is now ready to be plotted and classified. Plotting the data looks like this Figure 4.

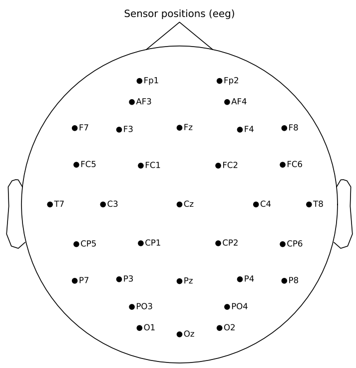

Figure 3: Sensor positons of biosemi32 setup

4.2 Sleep scoring

As the data set is not pre-classified, classification needs to be done. Classification is done by visual inspection in this report. An example of classifying the different sleep stages is shown in Figure 4 to 8. Firstly in Figure 4, low amplitude and fast frequencies can be seen. None of the special waves are present, and mostly alpha and beta waves can be seen. In Figure 5, an example of the N1 sleep stage can be seen. This is close to the awake stage but with some more amplitudes on the signals, and some theta activity can be seen. For N2, N3, and REM, it's much clearer to distinguish visually. As seen in the Figure 6, its more amplitudes on the signals, and a k complex can be seen in the middle of the signal. The Figure 7 contains slow waves and is a clear indication of stage N3. Lastly, stage REM is shown in the Figure 8. Here rapid eye movements are present and most clearly shown in the blue line that is the EOG sensor.

Sleep scoring requires a specific training to adequately identify the characteristics of each stage. Due to missing previous experience of the author in this subject, the scoring was done on a subsection of the data.. Precisely 322 seconds of Awake state, 313 seconds of N1 state, 339 seconds of N2 state, 477 seconds of N3, and 194 seconds of REM sleep. Keeping the length of the sleep stages close to equal to avoid errors in future work with machine learning. In addition to avoid too small samples that may be a bad representation of the average sleep stage.

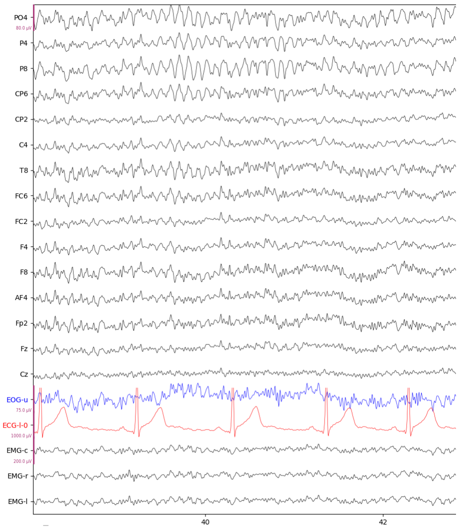

Figure 4: Example of AWAKE raw data

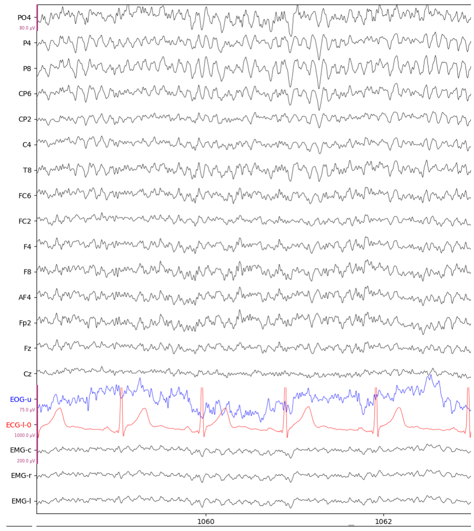

Figure 5: Example of N1 raw data

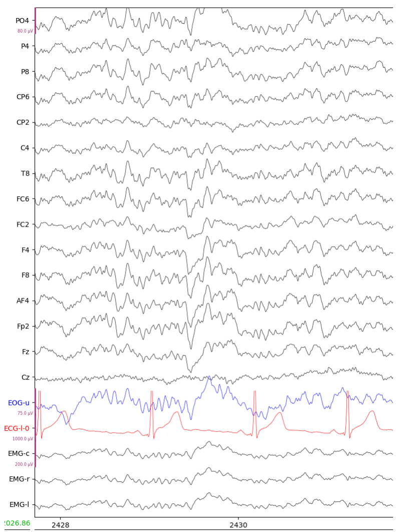

Figure 6: Example of N2 raw data

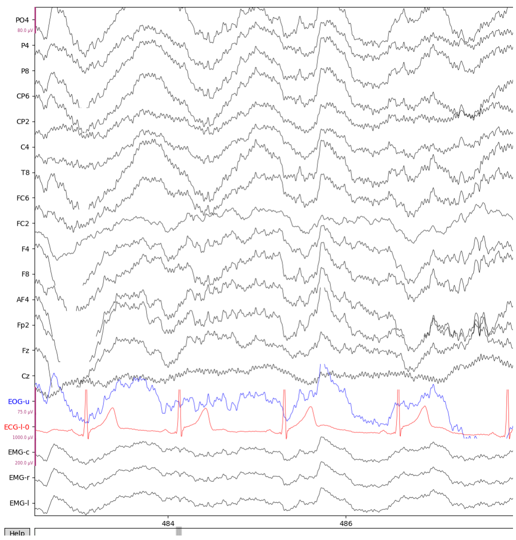

Figure 7: Example of N3 raw data

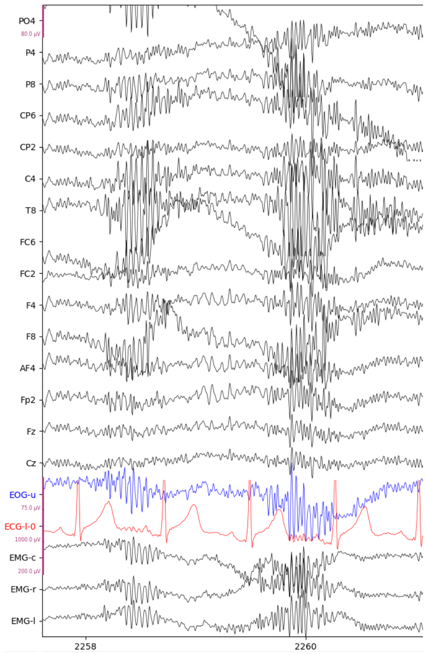

Figure 8: Example of Raw data classified REM

4.3 Computing the models

The head model, forward model, and inverse operator need to be calculated before the power spectral density can be found. In this paper, a template head model is used. The template head model can lead to some errors in further calculations, but an MRI of the patient was not available. The template head model used is the "fsaverage". "Fsaverage" is a model provided by FreeSurferWiki [16]. The model is constructed by using many MRI's to find the average position of components in the head. The head model "fsaverage" with electrodes are plotted in Figure 9. The red points on the scalp of the head are the electrode position set up in the biosemi32 positions. And the yellow points inside the head are the possible brain activity points. After the head model is in place the forward model can be computed. To compute the forward model, the function `mne.make_forward_solution()` is used. This function needs to know the head model and the dataset. It is important to set the "biosemi32" sensor position in the dataset before using this method. This is because the method uses the sensor positions in the calculation of the forward model and the results will not be right without it. After finding the forward model, it is used to find the inverse operator. The inverse operator is calculated by using the function `mne.minimum_norm.make_inverse_operator()`. This function need to know the noise covariance matrix between the electrodes and the forward model. To calculate the noise covariance matrix the method `mne.compute_raw_covariance()` is used. The noise covariance matrix is then used calculate the inverse operator. When the inverse operator is calculated, it is used to find the power spectral density talked about in the next subsection.

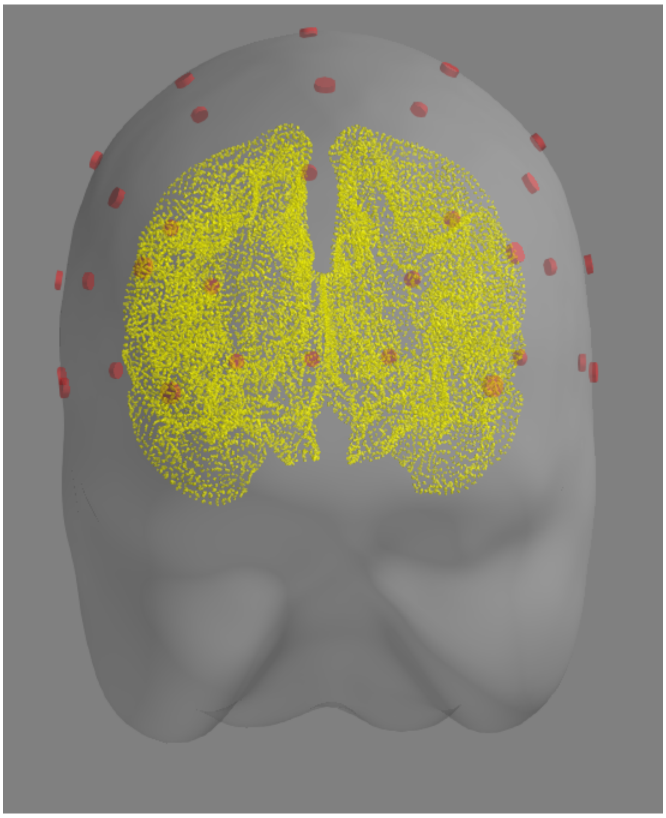

Figure 9: Head model, where red dots are electrode position and yellow dots are posible brain activation points

4.4 Power spectral density

To find the power spectral density(PSD), `mne.minimum_norm.compute_source_psd` was used. This method implements the window function Hann window and a window size of 2048. It also has an overlap of 0.5. Using this method with the head model biosemi32, PSD for 20 484 positions will be calculated. The method is set to find the PSD in all the points in the range between 0 - 50 Hz. This frequency is averaged over the whole sleep stage to find the most common frequency for specific sleep stages. This is then used to compare the sleep stages and for comparing the different electrode configurations. To visualize the PSD and gain an intuition of the brain activity, the brain is plotted and colored according to the activation of different frequencies. An example of this can be seen in the Figure 10. This figure shows 6 brain plots in different frequencies. On the top of the plot is delta frequency is plotted and on the right of the brain is a color map showing what the colors mean. In delta, for example red means activation of 22.5, and blue means activation of 7.5. This shows that delta waves are most active in the front of the head in the awake state in delta waves. The colors are placed so that the middle of the color bar (the value of white) is the mean of brain activity. Whereas the top and bottom of the activity are where the colors are dark red, and dark blue is set to be mean plus or minus half of the mean. This means that the brain can have individual points that have greater value than the max of the color bar, but the important thing is to get an indication of the brain activity.

2

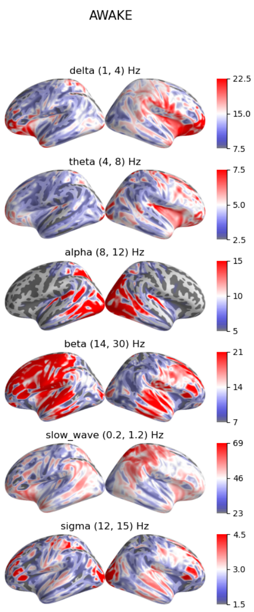

Figure 10: All frequencies of the average of Awake sleep state

4.5 Sleep stages compared to Awake

Comparing sleep stages to the awake stage gives a better indication of the brain activity in the different sleep stages. All the data points from the awake state brain model are subtracted from the other brain models to compare the sleep stages. This means subtracting the 20 484 data points from the awake state of the N1, N2, N3, and REM state. Doing this subtraction, the values will be in reference to the awake state. All values below 0 will have greater activation in the awake state, and all values above 0 will have stronger activation in the non-awake state. An example of this can be seen in the Figure 11. In this figure, red indicates more activation in the N3 than Awake. The figure has set the color bar range from 2 to minus 2 to gain the best visual effect of the differences between awake state and N3 state. In this specific figure, delta waves, beta waves, and slow waves are dominant in N3 over Awake. While sigma waves are dominant in the awake state over N3 and it's a mix in both theta waves and alpha waves.

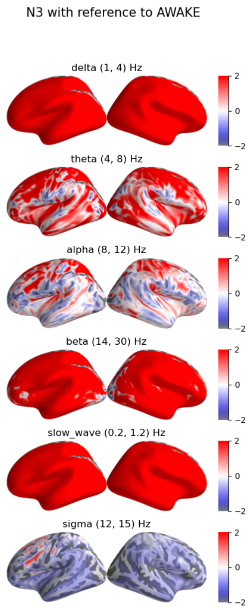

Figure 11: N3 frequencies with a reference to awake state

4.6 Electrode reduction

To find the best possible reduced configuration of electrodes, electrode reduction is done with four different configuration. Two configurations with 8 electrodes and two configurations with 16 electrodes. Electrode reduction is done using the function `mne.raw.pick`. This method takes in an array of channel names and returns the raw data excluding all the data that is not in the channel names picked. The channels picked are shown in the Figures 12 to 15. The configuration shown in Figure 12 and 14 are focused on the center line of the head while the configuration in Figure 13 and 15 are more spread out. These channels are picked to see if the center line of the head is the most critical to create an accurate PSD of the head. With 16 and 8 electrodes it is also possible to see the difference between the original 32 channel electrodes, 16 channel electrodes and 8 channel electrodes. This will give an indication whether the head source reconstructions accuracy is linear in regards to number of electrodes or if its specific parts of the head that is needed more then others.

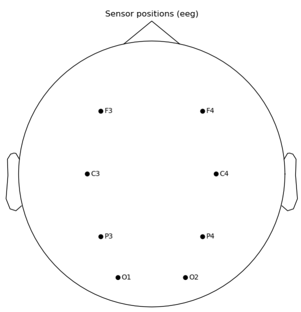

Figure 12: Electrode configuration with 8 electrodes, focused on center line of head

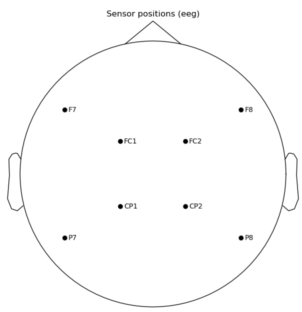

Figure 13: Electrode configuration with 8 electrodes, position as an x

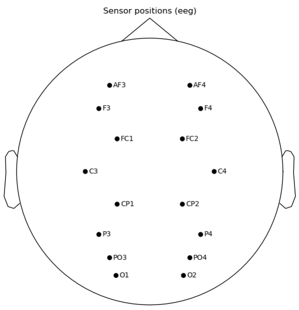

Figure 14: Electrode configuration with 16 electrodes, focused on center line of head

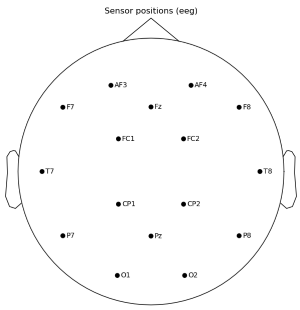

Figure 15: Electrode configuration with 16 electrodes, spread out

4.7 Error measurement

To compare the different reduced electrode configurations the error of the configurations are calculated. The error is calculated by using the 32 electrode configuration as a reference, and mean square error is used for all the 20 484 points in the head model. The error is calculated using the PSD values in the different sleep stages and different frequency ranges. For example the PSD of the beta waves in N3 sleep stage of the 32 electrode configuration is calculated with the PSD of the beta waves in N3 sleep stage in the other 4 electrode configurations. The function $\sum(x-\hat{x})^2$ is used. Here the x is the value of the 32 electrode configuration and $\hat{x}$ is the value of the reduced electrode configuration. Afterwards are the values mapped to values between 0 and 1. This is done to more easily read the tables the values are presented in, and to better compare high and low values with a single number. This is done by dividing all values in the a specific category by the highest value in that category. Making the highest error 1 and all the other errors between 0 and 1.

5 Result

This section shows the results using the method described and describes what can be seen in the results. However, it is not all of the results obtained, just the most important ones that is presented in this section. More result images are shown in the Appendix containing: PSD of sleep stages Section A, PSD of sleep stages with referance to awake Section B, PSD of sleep stages with reduced electrodes Section C .

5.1 PSD of sleep stages Compared to awake stage

This subsection will talk about how the PSD from sleep stages compares to the awake stage. Starting with sleep stage N1. The PSD of the average sleep stage N1 with reference awake state average is presented in Figure 16. The plot shows red for positions in the brain that are motion activated under N1 sleep stage then awake sleep stage. Blue color shows that the brain is more activated in the awake state. In this plot , all frequency ranges except sigma are dominated by red. Almost all points in the brain are more activated in N1 in all frequencies except in sigma.

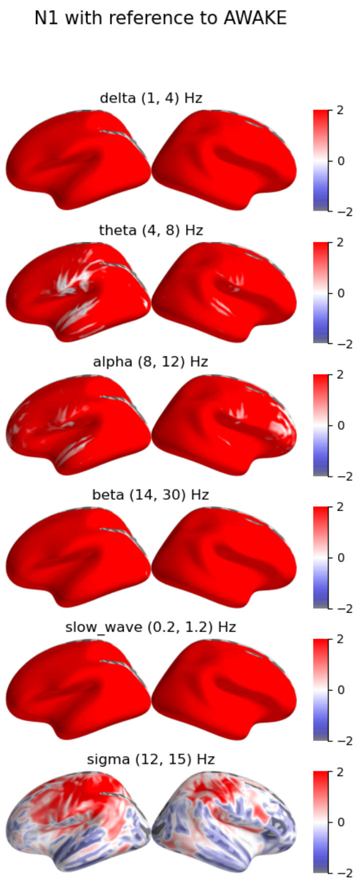

Figure 16: Sleep stage N1 compaired to Awake

Moving on to the N2 sleep stage compared to the awake stage seen in Figure 17. This figure shows that theta and alpha waves are position-specific and not just dominated over the whole brain by either N2 or Awake state. And that N2 has more alpha activity in the back of the head then awake state. Theta has most N2 activity on the top of the head in comparison to the awake state.

The awake state mostly dominates sigma but as the blue color is not dark blue it's a small value difference.

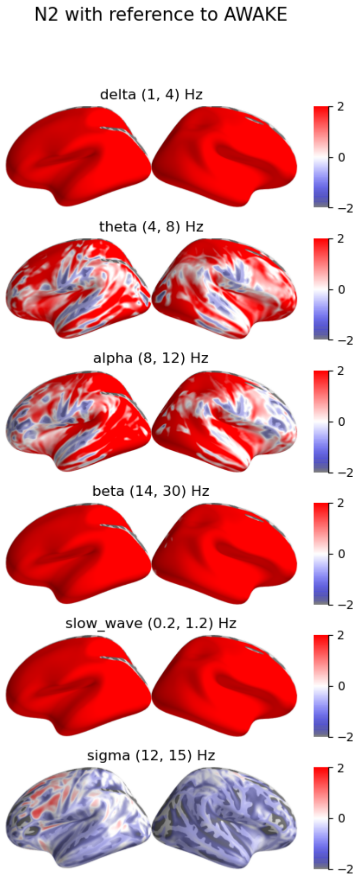

Figure 17: Sleep stage N2 compaired to Awake

Figure 18 shows the N3 sleep stage compared to awake. Here it can be seen that alpha waves are more dominated by the awake state than the N1 and N2 sleep stages were. It can also be seen that it is not completely red in the beta wave part as it was in N1 and N2. But for the delta, slow-wave, and sigma it's almost identical to N1 and N2.

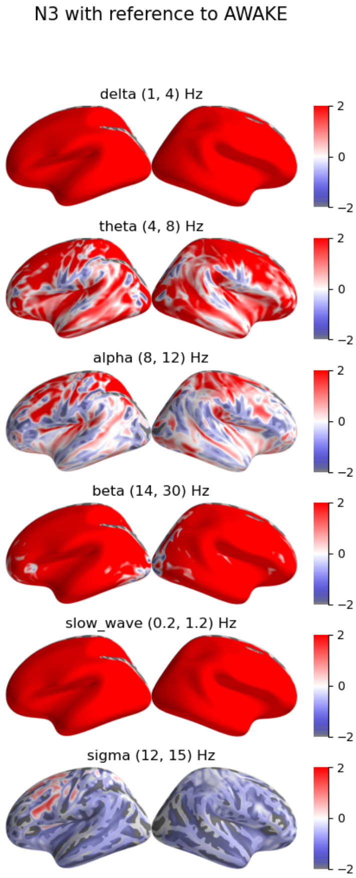

Figure 18: Sleep stage N3 compaired to Awake

Figure 19 shows the REM sleep stage compared to awake. Visually this image is almost identical to the N2 sleep stage compared to awake. Delta, beta, and slow-wave are all dominated by red while sigma is dominated by blue. Theta and alpha are however a mix for most brain activation between REM and awake state.

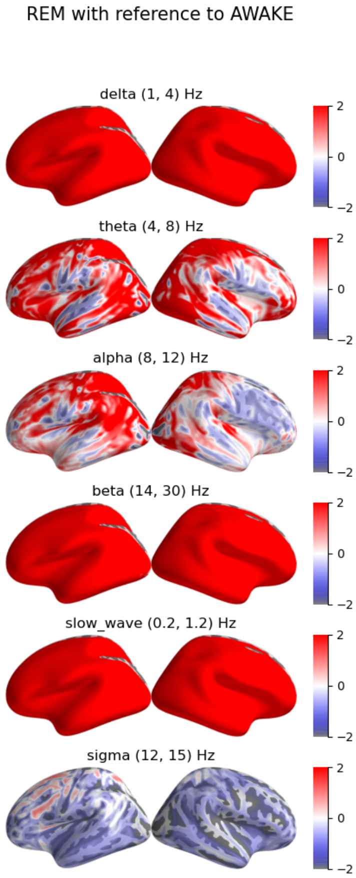

Figure 19: Sleep stage REM compaired to Awake

5.2 Electrode reduction

In this subsection, the visual comparison between 32 electrodes and reduced electrodes will be shown. Starting with Figure 20, that shows PSD of the brain after electrode reduction down to the configuration shown in Figure 12. To get a visual overview of the difference between 8 electrodes in this configuration and 32 electrodes, the figure is placed next to Figure 21 that shows the PSD of the brain with 32 electrodes. Except for the sigma wave, all means shown as the middle point in the color bars are different. In the delta waves, it can be seen that the backside of the head is shown in light blue in the 8 electrode one while it's dark red in the 32 electrodes one. The delta part shows that 32 electrodes have more specific areas of intensive activity while the 8 electrodes have more overall intensity. This can be seen in all the other frequencies except slow-wave witch, which is more spot specific with the 8 electrode setup.

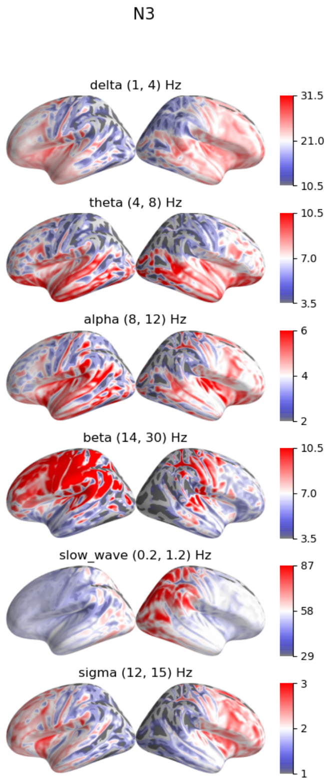

Figure 20: Stage N3 with 8 electrodes center focused

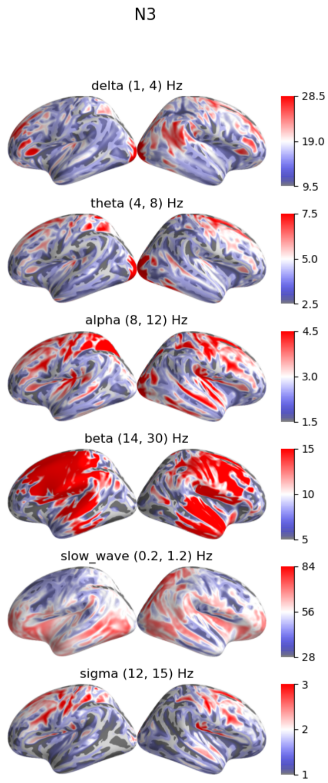

Figure 21: Stage N3 with 32 electrodes

Moving on to 8 electrodes placed in an x pattern as shown in Figure 13. Visual comparison can be done on Figure 22 and Figure 23. Starting with sigma, the color bar shows that the mean with 8 electrodes in x pattern is 1 while it's 8 with 32 electrodes. This shows that it's just half of the activity picked up compared to the 32 electrodes. It has a higher mean in slow-wave but the left side has no red spots showing some inaccuracies. Beta waves have also half the mean at 5 while it's 10 in the 32 electrodes, but the positions of the strongest activation are about the same. Alpha waves have the same mean but the red positions are a little lower than the 32 electrodes one. It's the same for beta waves while delta waves have a difference close to the other 8 electrode setup.

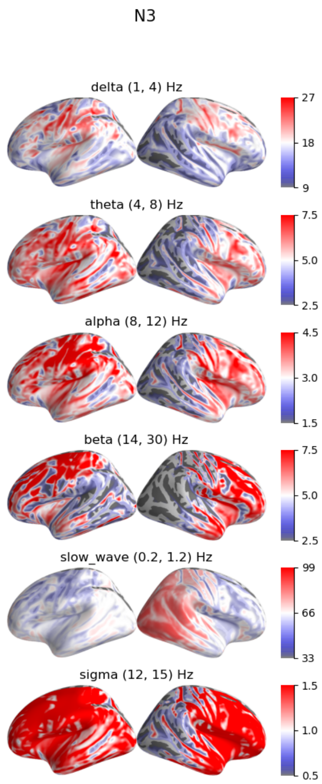

Figure 22: Stage N3 with 8 electrodes in x pattern

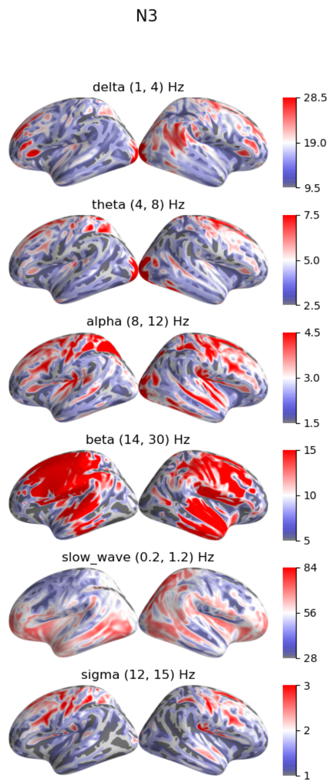

Figure 23: Stage N3 with 32 electrodes

In Figure 24 the brain visualization of 16 electrodes placed shown in Figure 14 is shown. Here are the electrode placed in the centerline. In the delta waves, the strong activation position from 32 electrodes is not shown, rather it is more general strong activation over the whole head. This can be seen in theta waves and alpha waves too. The mean in the delta, theta, alpha is all higher than the means from 32 electrodes. While beta waves, slow waves, and sigma waves are all quite similar to the 32 electrodes. Both in positions and in the mean. Overall, visually it seems that 16 electrodes are an improvement from both of the 8 electrode configurations.

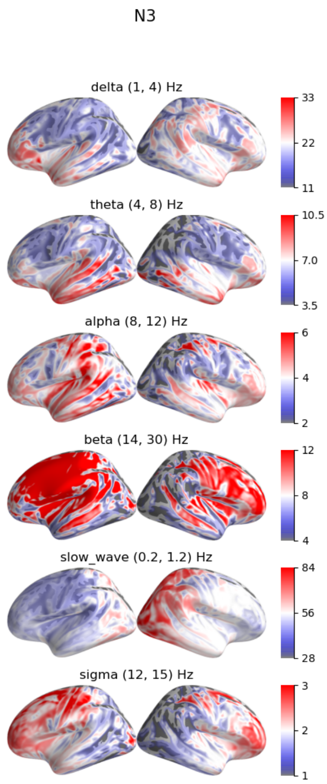

Figure 24: Stage N3 with 16 electrodes center focused

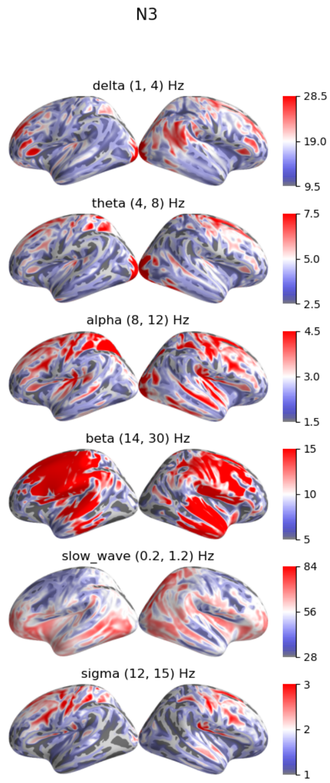

Figure 25: Stage N3 with 32 electrodes

In Figure 26 the brain visualization of 16 electrodes placed shown in Figure 15 is shown. Here are the electrode placed more all over the head. This figure shows that theta waves are quite close to the 32 electrodes. Almost the same mean and the same positions of red that marks the strongest activation. Delta waves have small differences in red position, but not a lot. Alpha waves have small differences in activation places and beta has a 4 point difference in mean. Slow waves have some more activation on the back of the head while sigma is quite similar. Visually this looks better than the centerline 16 electrodes in delta waves, theta wave, and alpha waves while the 16 electrodes with focus on centerline look better in beta waves, slow waves, and sigma waves.

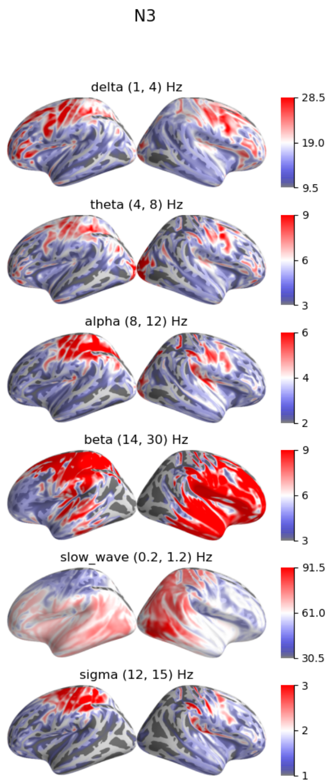

Figure 26: Stage N3 with 16 electrodes spread version

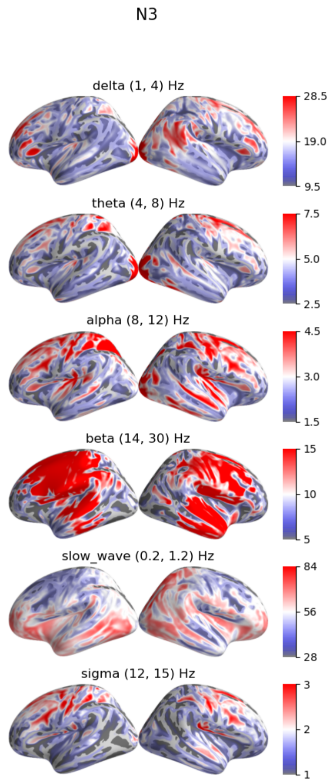

Figure 27: Stage N3 with 32 electrodes

Moving on from visual inspection to the numbers, Table 2 shows errors in delta waves for all four reduced electrode configurations. A zero indicates no error and a one indicates the most error of the four methods. The first column is the 32 electrodes that are always zero as its the reference in this study. The next column shows the 8 electrodes placed in the centerline shown in Figure 12. Then the 16 electrodes placed in the centerline shown in Figure 14. Then the 8 electrodes placed like an x shown in Figure 13. And lastly, the 16 electrodes placed over the hole head shown in Figure 15.

Firstly the Awake state is presented, then N1, N2, N3, and REM. For all five sleep stages, the 8 electrodes placed in the centerline are the worst. 8 electrodes placed in an x shape are the second-worst for all sleep stages and for the 16 electrodes configurations, it is a mix between the different sleep stages.

32	8	16	8x	16x
Delta wave				
Awake state				
0.0	1.0	0.29	0.6	0.31
N1 state				
0.0	1.0	0.5	0.74	0.58
N2 state				
0.0	1.0	0.59	0.75	0.43
N3 state				
0.0	1.0	0.77	0.92	0.64
REM state				
0.0	1.0	0.59	0.94	0.75

Table 2: Electrode reduction error in delta waves

Table 3 shows the errors in the Theta waves in the different sleep stages. Like with the Delta waves 8 electrodes placed in the centerline are the worst. Followed by the 8 electrodes placed in an x shape. But here it is a clear best of the 16 electrodes and that is the 16 electrodes placed spread out over the head. It has less error in all five sleep stages and has the biggest advantage over the other methods in sleep state N3.

32	8	16	8x	16x
Theta wave				
Awake state				
0.0	1.0	0.53	0.67	0.29
N1 state				
0.0	1.0	0.57	0.92	0.45
N2 state				
0.0	1.0	0.46	0.85	0.41
N3 state				
0.0	1.0	0.65	0.63	0.29
REM state				
0.0	1.0	0.53	0.85	0.38

Table 3: Electrode reduction error in Theta waves

Table 4 shows the error in Alpha waves. Here it can be seen that the 8 electrodes with x pattern are worse than the 8 electrodes in the centerline. This holds for all stages except N3. It is also a mix between the 16 electrodes configuration on what is best. The centerline method is best in N1 and N2, while the spread out method is best in Awake, N3, and REM. However, the differences in N3 and REM are quite big and overall, 16 electrodes spread out are the best method for alpha waves.

32	8	16	8x	16x
Alpha wave				
Awake state				
0.0	0.79	0.56	1.0	0.47
N1 state				
0.0	0.67	0.37	1.0	0.44
N2 state				
0.0	0.64	0.36	1.0	0.48
N3 state				
0.0	1.0	0.79	0.72	0.43
REM state				
0.0	0.78	0.65	1.0	0.45

Table 4: Electrode reduction error in Alpha waves

Table 5 shows errors in beta waves. Here it's a little closer between the 8 electrode configuration as the centerline method has the worst error in Awake and REM stages, while the x pattern has the worst in N1, N2, and N3. The same pattern applies to the 16 electrode methods. The biggest difference between the 16 electrodes is in the REM state. Here the 16 electrode centerline method is even worse than the 8 in an x shape method.

32	8	16	8x	16x
Beta wave				
Awake state				
0.0	1.0	0.39	0.76	0.31
N1 state				
0.0	0.97	0.4	1.0	0.56
N2 state				
0.0	0.65	0.37	1.0	0.66
N3 state				
0.0	0.67	0.49	1.0	0.66
REM state				
0.0	1.0	0.97	0.95	0.65

Table 5: Electrode reduction error in Beta waves

Table 6 shows errors in slow waves. All sleep stages except awake have the most errors in 8 electrodes in an x pattern. The other three configurations have quite close errors in N3 and REM state but 16 electrodes with centerline focus have the best in N2. In N1 both the 16 electrode configurations are decidedly better than 8 electrode ones, and in the awake state, the x pattern with 8 electrodes and the spread-out pattern with 16 electrodes is the best. Overall in slow waves are the 16 electrodes with centerline focus the best.

32	8	16	8x	16x
Slow wave				
Awake state				
0.0	1.0	0.44	0.69	0.21
N1 state				
0.0	0.81	0.47	1.0	0.43
N2 state				
0.0	0.58	0.26	1.0	0.51
N3 state				
0.0	0.55	0.48	1.0	0.52
REM state				
0.0	0.56	0.47	1.0	0.62

Table 6: Electrode reduction error in Slow waves

Table 7 shows errors in Sigma waves. Sigma waves have a split of awake and N3 state being the worst in 8 electrodes centerline positions, and N1, N2, and REM the worst in 8 electrodes x positions. The 16 electrode configurations are quite close for the awake, N1, and REM state, while in N2 the center positions are best and in N3 the spread out positions are best. Overall are the 16 electrodes placed along the centerline the best configuration for sigma waves.

32	8	16	8x	16x
Sigma wave				
Awake state				
0.0	1.0	0.35	0.78	0.31
N1 state				
0.0	0.79	0.51	1.0	0.5
N2 state				
0.0	0.84	0.21	1.0	0.71
N3 state				
0.0	1.0	0.85	0.78	0.57
REM state				
0.0	0.59	0.44	1.0	0.43

Table 7: Electrode reduction error in Sigma waves

6 Discussion and conclusion

In this section, the results will be discussed, and a conclusion will be presented. Afterward, future work will be talked about.

6.1 Sleep stages compared to the awake stage

Starting with the N1 stage compared to the awake stage seen in Figure 16, the N1 stage has more activity in all waves except sigma. The brain uses sigma waves when a person is active, and they can be seen in sleep spindles [17]. When a person is in the awake state, it should be seen more sigma waves then in the N1 sleep stage, and this is what is shown. Beta waves should have the most amplitude in drowsy subjects. This means it should be highest in awake and N1 and not in N2, N3. From the first comparison of N1 and awake, the beta stage is completely red, which is a little off in the case of theory. It should be close to white or a little blue as normally beta waves are stronger in awake patients than in sleeping patients. The frequencies' amplitude can vary from patient to patient, and can this can be the case here. Alpha waves are also normally strongest in awake patients and are normally strongest in the occipital head region, which is the back of the head. In this patient, the alpha waves are red, indicating stronger alpha waves in the N1 sleep stage than the awake stage. This can be due to an inaccurate sleep stage rating, or the patient has abnormal brain activity in the sleep stages. It is normal for theta and delta waves to have higher activity in these frequencies the deeper the sleep is. The same concept counts for slow waves but are most clear in N3 sleep.

In the N2 stage compared to the awake stage seen in Figure 17, N2 has more activity in delta beta and slow-wave. Higher delta and slow waves in N2 sleep compared to awake is normal. While beta waves are normally reduced in N2 and N3 sleep stages. As beta waves seem high in all sleep stages compared to awake, there is a possibility that the person has abnormal low beta activity while awake. If the awake state is abnormal, it will affect all other sleep stages compared to the awake stage. There is a mix of positions for theta and alpha where N2 has more activity and where awake has more activity. Alpha should be more active in the awake state than in N2 but as discussed previously, the patient might have abnormal brain activity. Sigma waves in the N2 stage comes from sleep spindles but, normally, sigma waves are more active in the awake state. The Figures for N3 Figure 18 and REM Figure 19 are visually very close to the N2 sleep stage. As slow-wave and delta waves are very active in the N3 stage they are fully red. REM sleep stage can have a mix of all the included frequencies so it's not surprising that it contains much of the same activation as N1-N3.

6.2 Limitations

This project has some limitations that will be mentioned here. Firstly the author had no previous knowledge of EEG or sleep stages. This made the start of the project very time consuming as all the time went to reading articles of EEG and sleep. Secondly the dataset is of one subject only. This leads to special results as people have different brains and there is some variation in brain waves. The data used for PSD is only a subset of the dataset as the annotations was not done for the whole dataset. This increases the chance of special cases of brain waves. Furthermore the head model used in this project was a template head model as MRI of the patient was not available. This leads to some errors in the forward and inverse solution, assuming the patient head is not equal to the template model. Lastly the execution time for the whole script is very long and made it too time consuming to try out more reduced configurations.

6.3 Electrode reduction

From the Tables 2 to 7, it can be seen that different sleep states and different waves affect what electrode positions give the most error. But for all sleep stages and all frequency waves, it is always one of the 16 electrodes that have the smallest error and one of the 8 electrodes that have the biggest error. This comes down to the fact that by reducing the number of electrodes, the information will get lost. This can be seen as an optimization problem where the fewest electrodes that give the least error will be the optimal configuration. And this will be talked about in future work.

Delta waves are prominently in the fronto-central head regions. This is in the middle of the frontal and central region seen in Figure 28. Here are the FC1, FC2, AF3, AF4, and FZ, the closest electrodes. Three of these electrodes are used in 16 electrodes spread, and two of them are used in 16 electrodes centerline. Both of the 16 electrodes have a somewhat small error here, and this comes from non of them having all of the close electrodes, but they have some. In the 8 electrode center line, non of the mentioned electrodes are included. F3 and F4 are quite close to the region of interest, but the errors show that these channels don't pick up delta wave as competently as the five channels mentioned first.

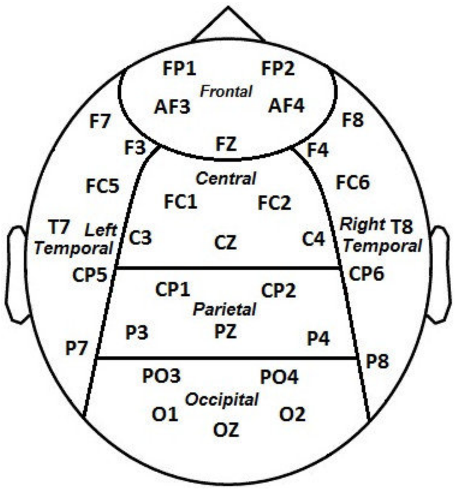

Figure 28: Regions of the scalp, [3]

Moving on to theta waves, these waves are prominently in the fronto-central head region, just like delta waves. This is why they have close to the same error distribution in the different reduced setups.

The alpha waves are dominantly in the occipital head region. This is the back of the head seen in 28. The most important electrodes for alpha waves are PO3, PO4, O1, O2, and OZ. From Table 4 8, electrodes in x pattern are the worst. This comes from the configuration has non of the mentioned electrode positions. The closes electrodes are the P7 and P8, but they are in the right and left temporal. 8 electrodes in the centerline have both O1 and O2 but still have more than half of the error of the 8 electrodes in an x pattern. And is even worse in the N3 state. For the 16 electrodes, the spread out one is the best. This has just the O1, O2 in the occipital region. This is quite interesting as the 16 electrodes with centerline focus have O1, O2, PO3, and PO4. And yet can't do better when it comes to alpha waves. This can be caused by the spread-out pattern having electrodes placed around the target area with P7, PZ, and P8, which the central line focus has not. Overall it's mostly N3, and REM state that the centerline gets a big error in, and this might indicate some special alpha activity in these sleep stages.

Beta waves are most prominent in the frontal and central head regions but move backward in the head as it is fading out. As the waves are more focused on the head's centerline, both the centerline configurations should be good. It can be seen from Table 5 that this holds good for N2 and N3 where both of them are equal or better than the spread out 16 electrode configuration while the 8 electrodes in x pattern are the worst. But for the awake and REM state, the 16 electrodes spread out is best. This may come from the 16 electrodes spread out configuration having the FZ electrodeposition. This is in the perfect position for the strongest beta waves. The biggest difference between the 16 electrodes configuration is in the REM state. Here does the centerline configuration almost as bad as the worst 8 configurations. This might come from a lack of FZ and CZ electrodes.

For slow waves the positions of the starting point varies and they move through out the whole brain like an expanding wave. For this waves the expectations was to see the spread out electrodes having the least error as the waves spreads out over the whole brain. However, this is not the case as it can be seen from Table 6, the 16 electrodes with focus on centerline is the best. This results might come from the fact that the dataset used is quite small and might have biases on positions of the waves. The N3 stage is the one that has the most activity in the slow waves, and are the one that is most important to get low error on. In the N3 stage three of the four configurations are quite close while the 8 electrodes placed in an x pattern has about twice the error as the rest. This indicates that centerline electrodes are important in giving a good representation of slow waves.

Sigma waves are most prominently in the fronto-central head regions which has the most important electrodes AF3, AF4, FZ, FC1, and FC2. This waves are mostly seen in N2 stage with the sleep spindles and in the awake state. In both these to sleep stages, the 16 electrodes with focus on centerline has low error. The 16 electrode spread out has best in the awake state, but high error in the N2 state. This is an indication of the sleep spindles in the N2 sleep stage appear in different locations then the other sigma waves that appears in the awake state. It can also be seen that the 8 electrodes with centerline focus have high error in the N2 stage as well. This means that to get a low error the the N2 sleep spindles a combination of F3, F4 with FC1, FC2, AF3, and AF4 is needed.

6.4 Conclusion

In this paper power spectral density was found in one patient using MNE open source python library. Then the power spectral densities of the different sleep stages was compared to sleep stage awake to better understand the differences in brain waves of the different sleep stages. The comparisons showed that most of the brain waves that are normally stronger in specific sleep stages was stronger in this patient too, while for example beta waves had some abnormal activity in this patient. Furthermore, electrode reduction was done to 4 specific configurations where two of them had 16 electrodes and two of them had 8 electrodes. Then an error comparison between these reduced configurations was done. This showed that for the overall error the 16 electrodes outperformed 8 electrodes ones. However, it also showed that the 8 electrodes ones was equally good for some brain waves and it all came down to what brain waves are in focus and what electrodes are needed for the specific brain waves. To get a good power spectral density with fewer electrodes, the electrode positions need to be in line with where the brain waves are active for the brain waves you want to reconstruct.

6.5 Future work

For future work, AI and optimization can be used to reduced the amount of electrodes while keeping the error low. Many more configurations can be tested and a dataset with more electrodes, for example 256 electrodes can be used as a reference. More patients and more annotated dataset can be used to avoid any errors due to special cases in the patient.

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Appendix

A PSD of sleep stages

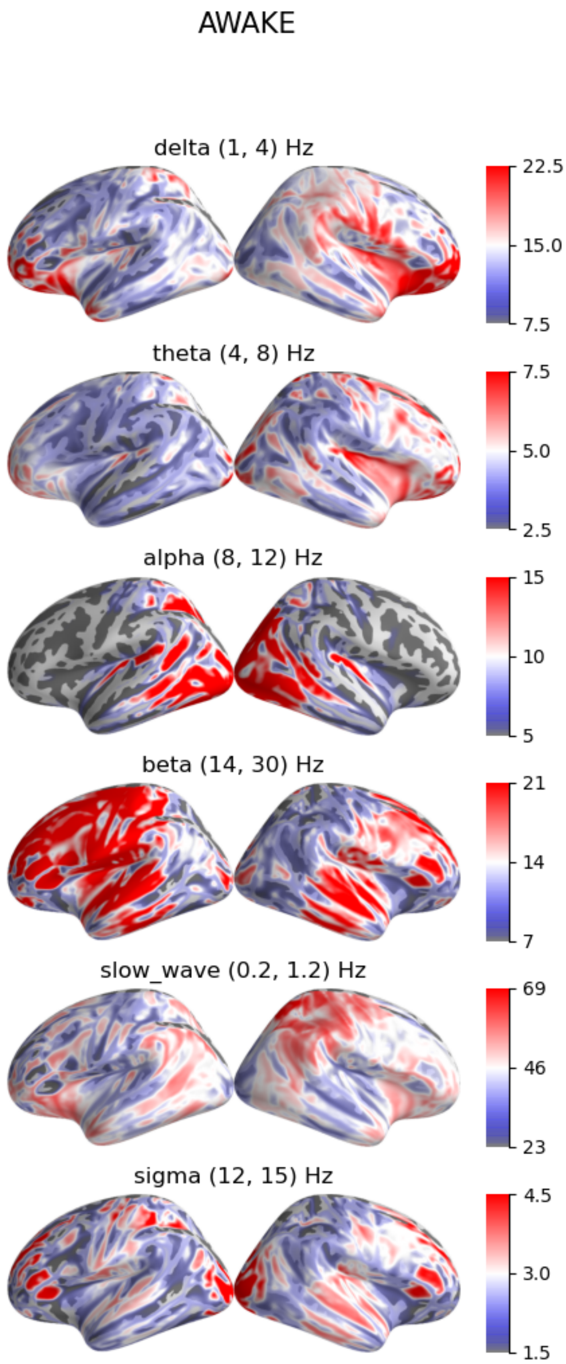

Figure 29: Average of sleep stage Awake

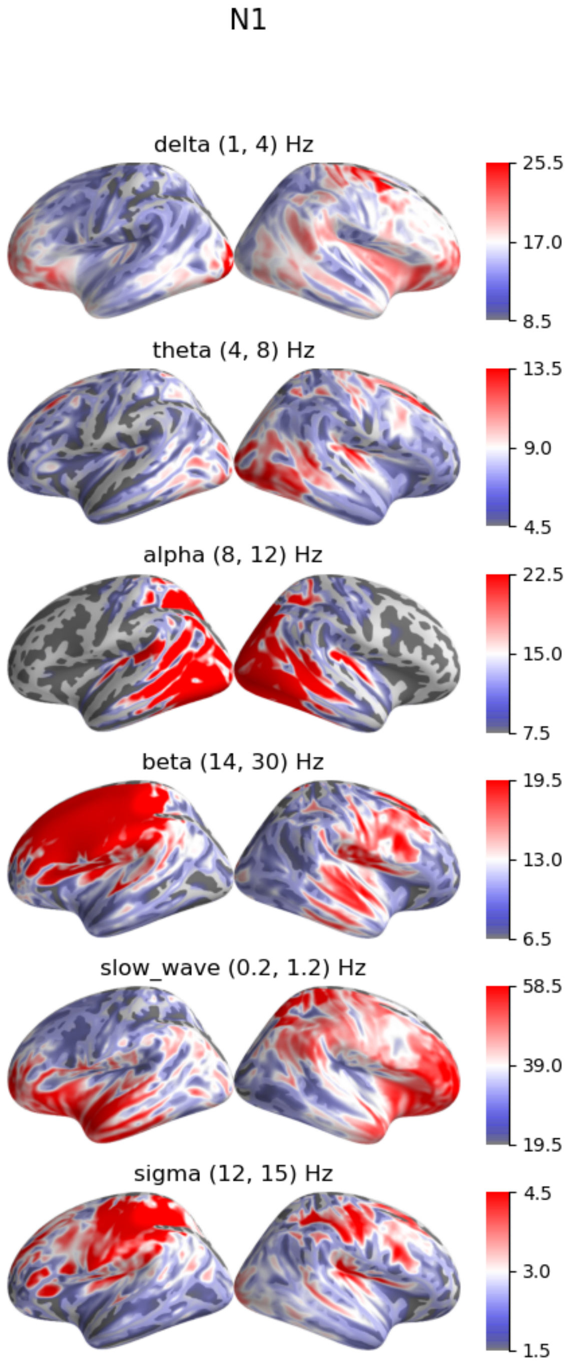

Figure 30: Average of sleep stage N1

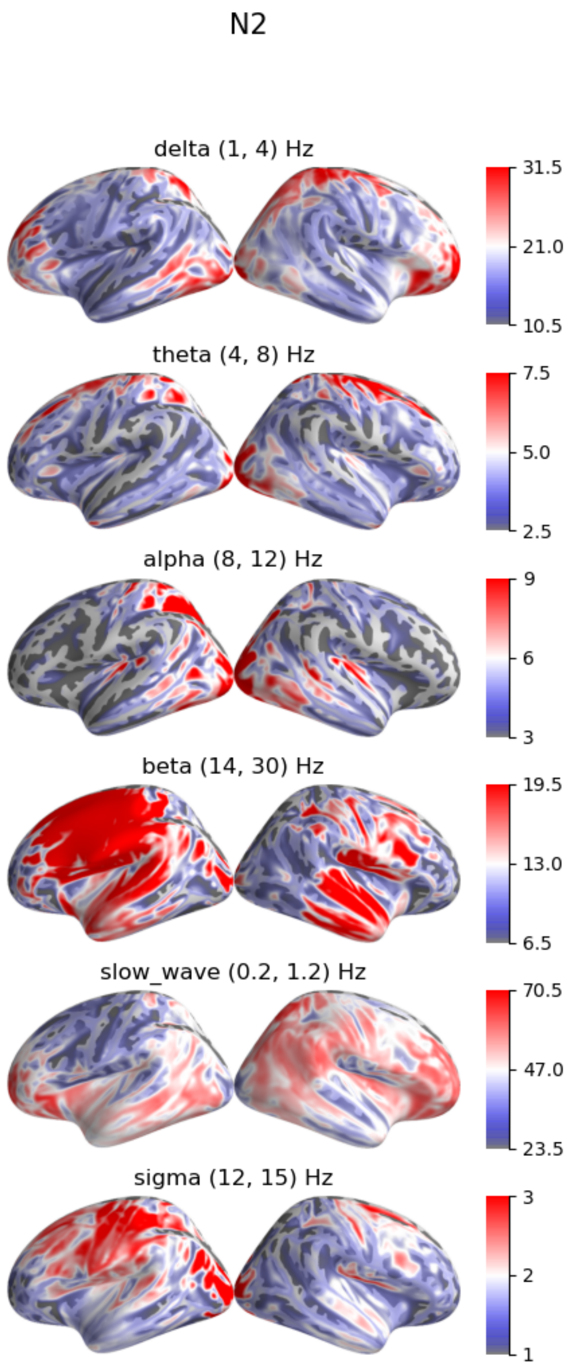

Figure 31: Average of sleep stage N2

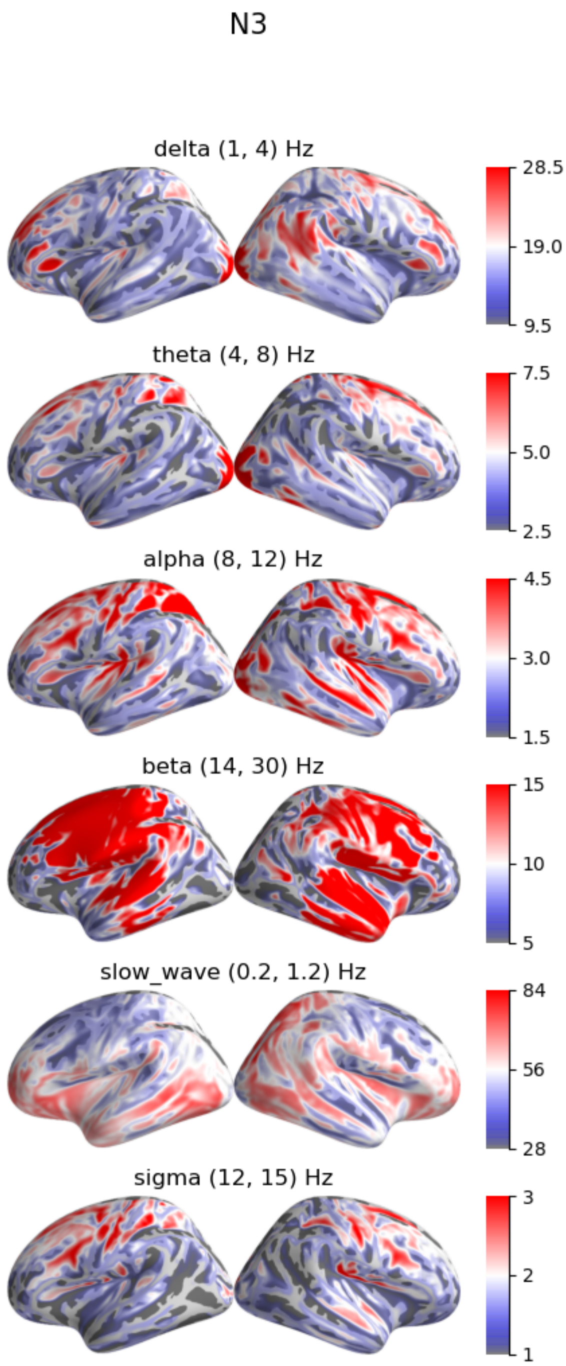

Figure 32: Average of sleep stage N3

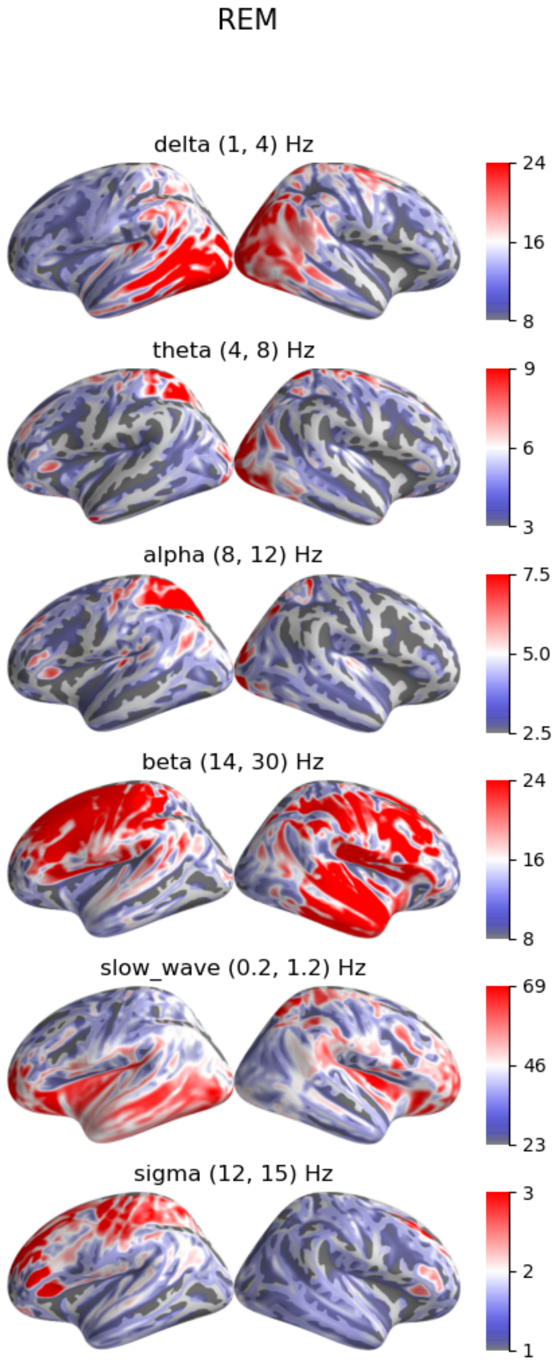

Figure 33: Average of sleep stage REM

B PSD of sleep stages with reference to awake

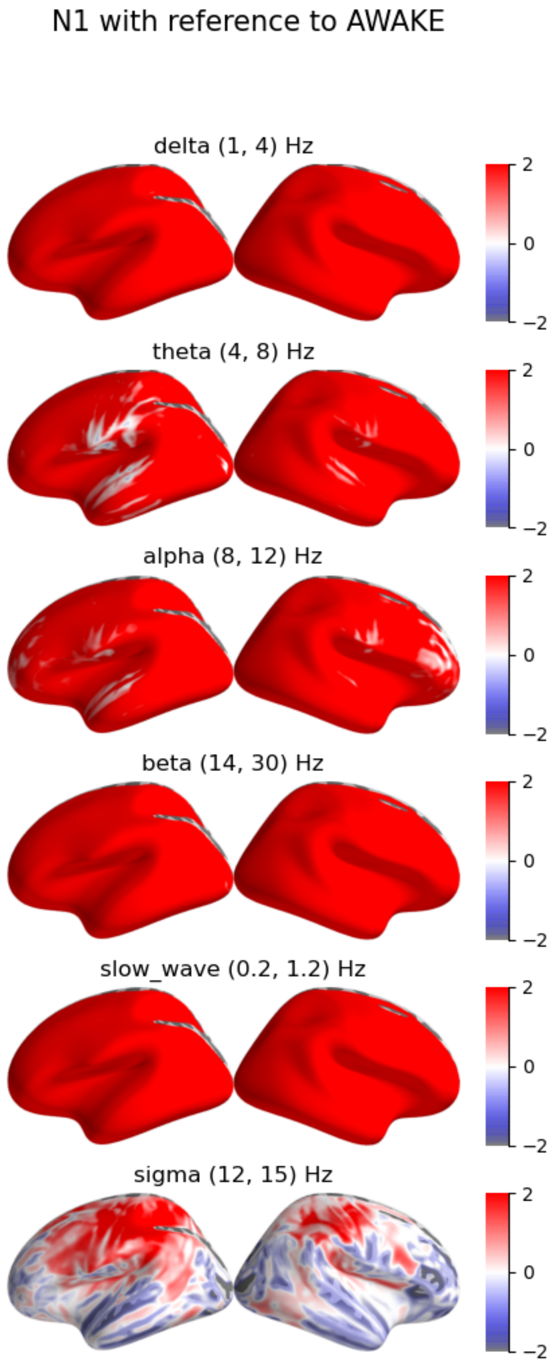

Figure 34: Sleep stage REM with reference to awake state

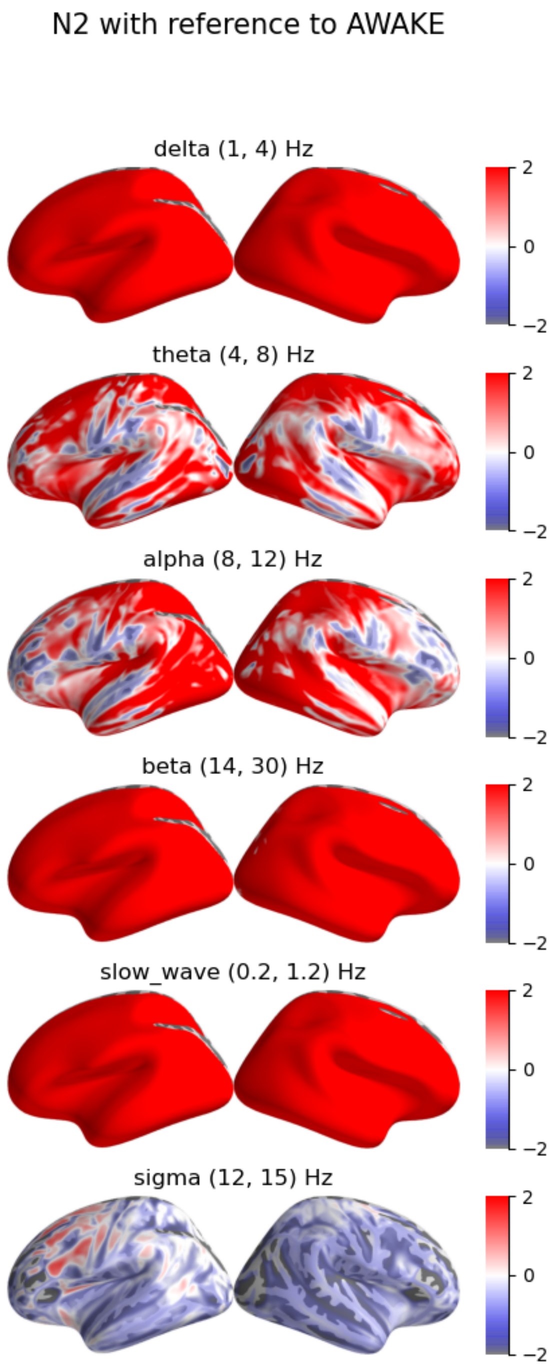

Figure 35: Sleep stage REM with reference to awake state

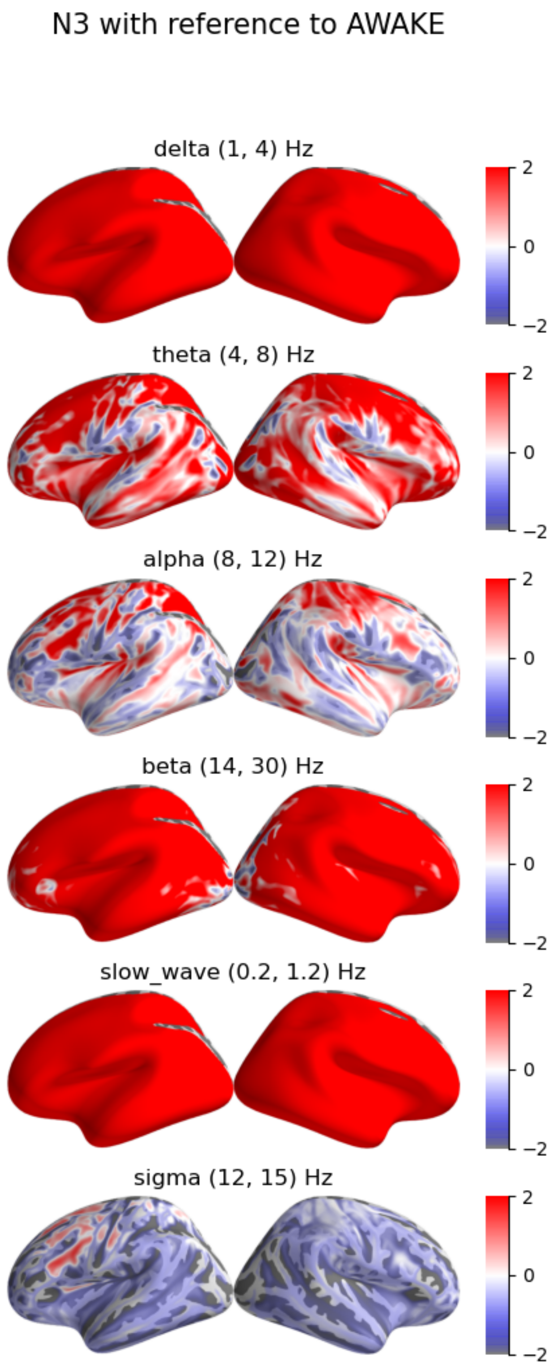

Figure 36: Sleep stage REM with reference to awake state

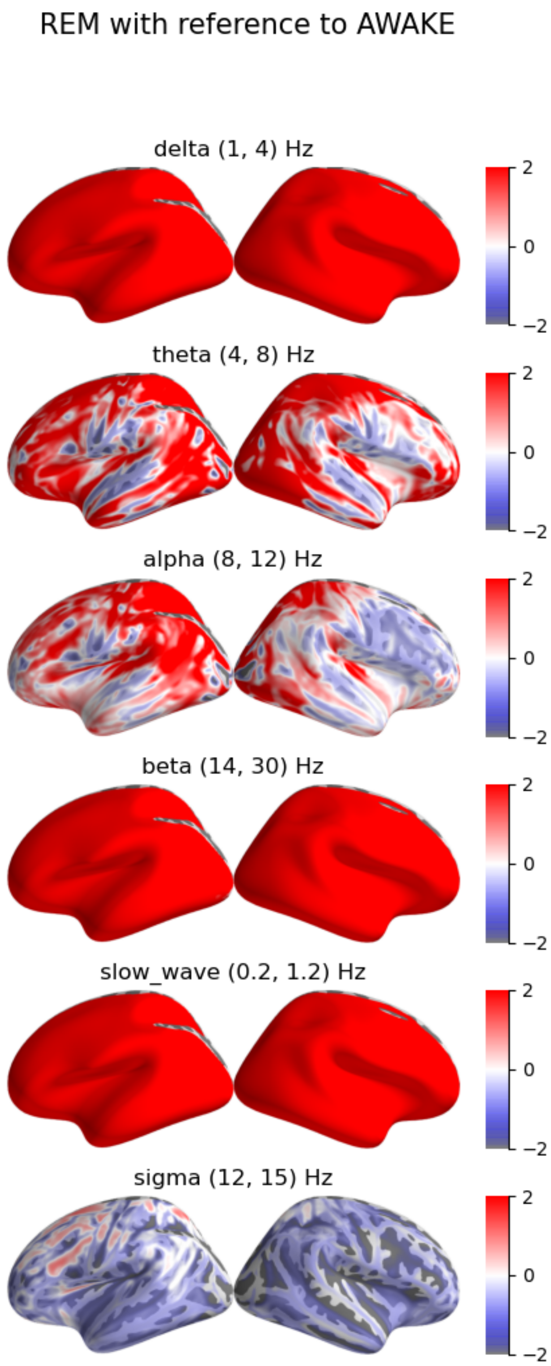

Figure 37: Sleep stage REM with reference to awake state

C PSD of sleep stages with reduced electrodes

C.1 8 channel with focus on centerline

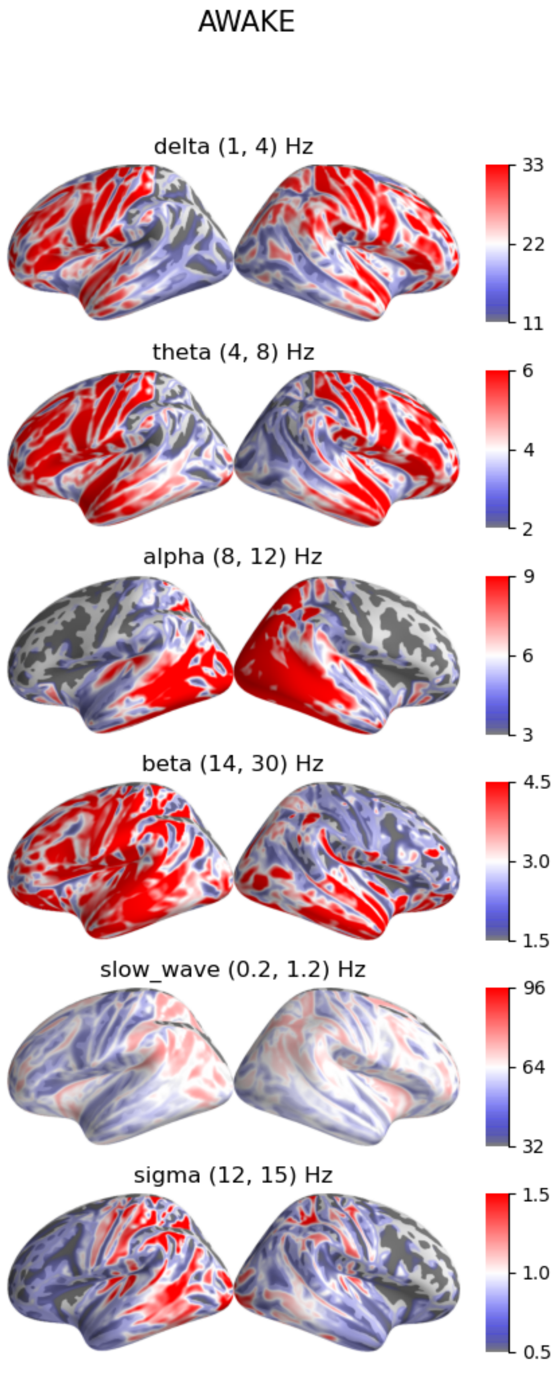

Figure 38: Average of sleep stage Awake with 8 electrodes in centerline

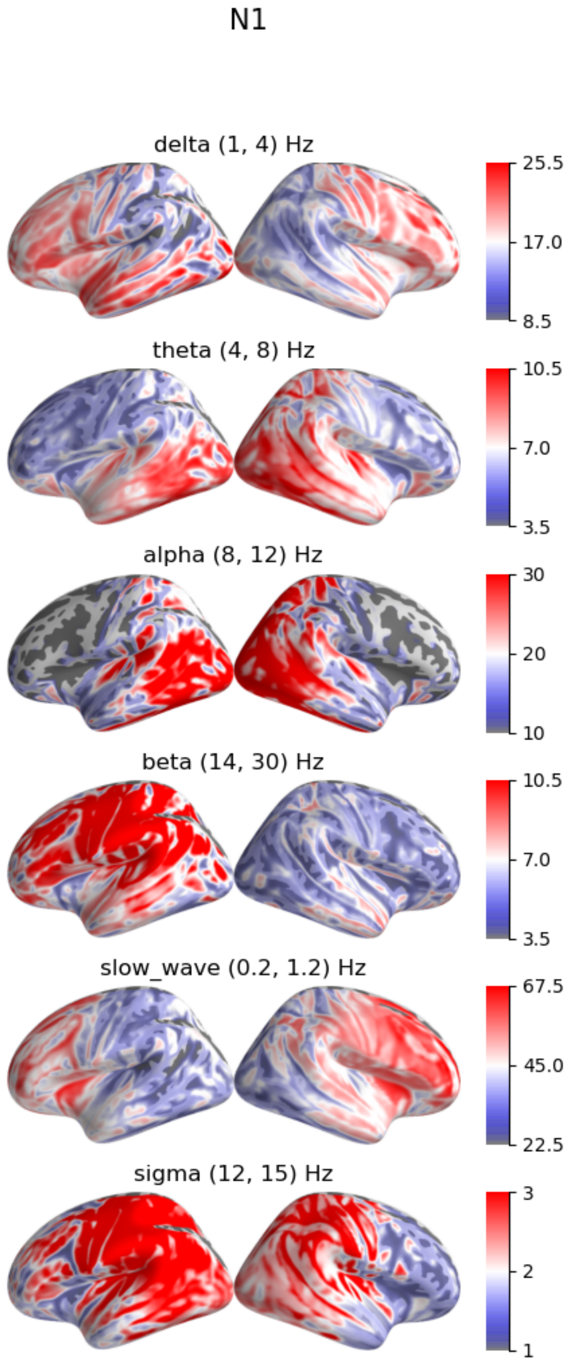

Figure 39: Average of sleep stage N1 with 8 electrodes in centerline

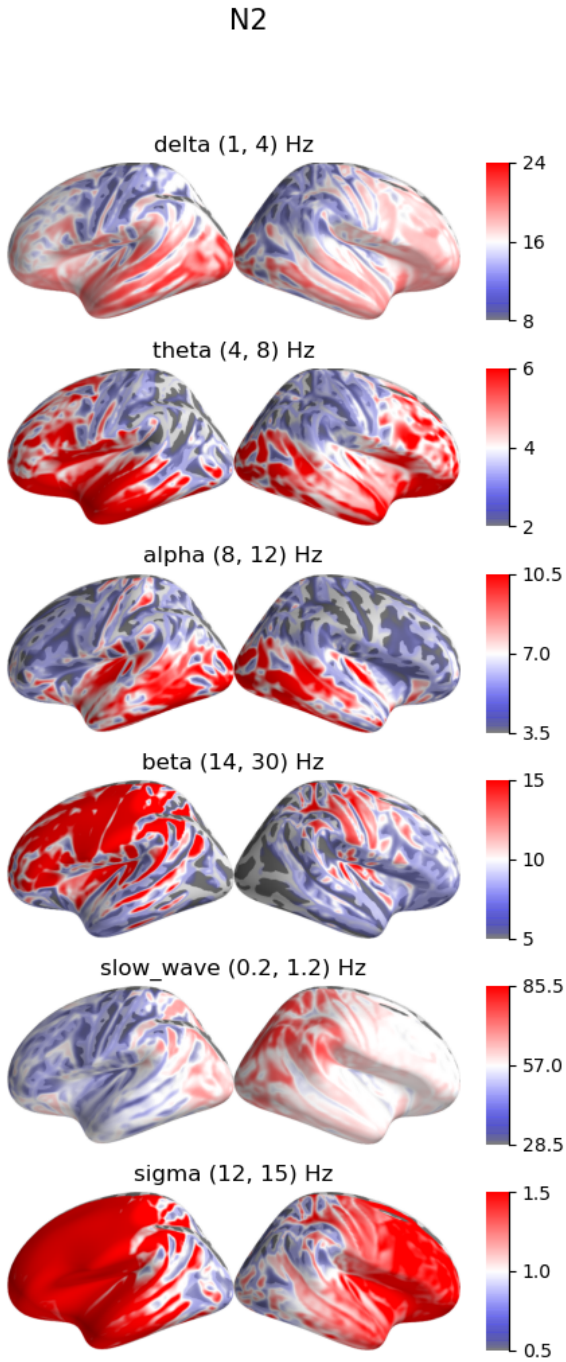

Figure 40: Average of sleep stage N2 with 8 electrodes in centerline

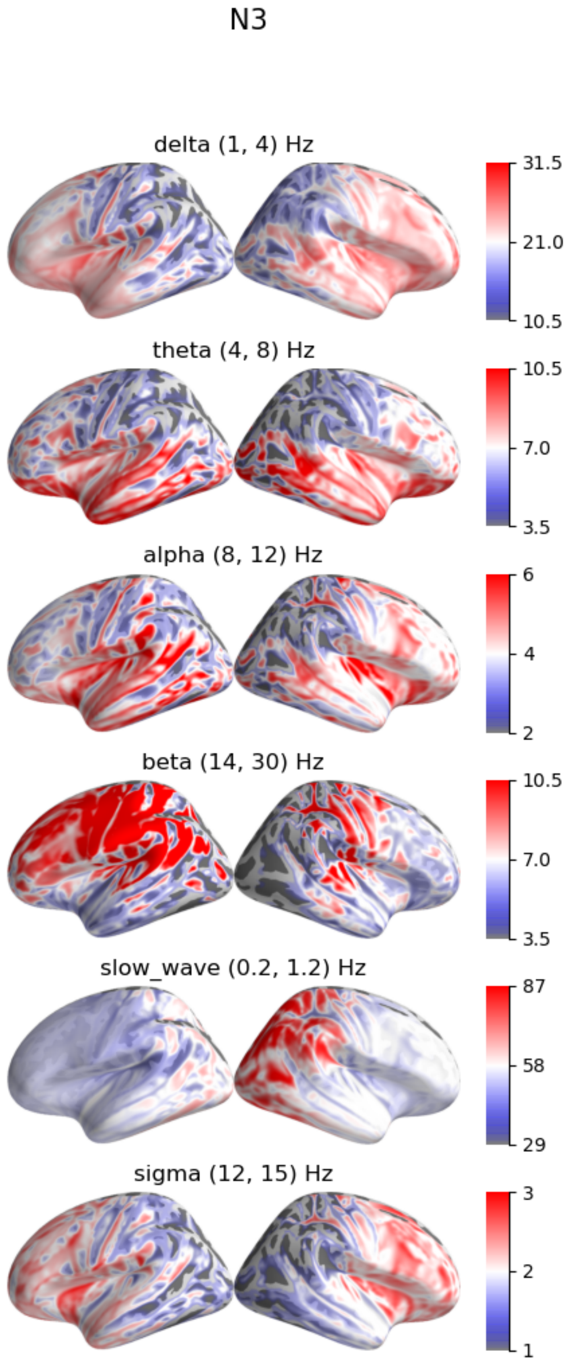

Figure 41: Average of sleep stage N3 with 8 electrodes in centerline

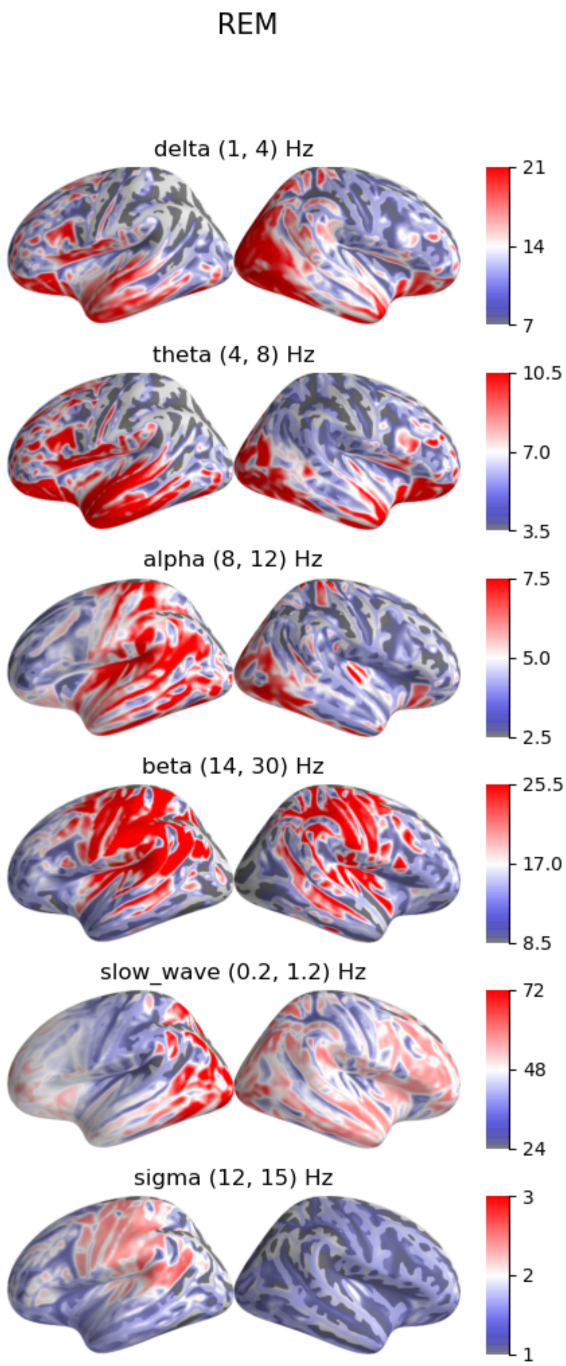

Figure 42: Average of sleep stage REM with 8 electrodes in centerline

C.2 8 channel setup in x pattern

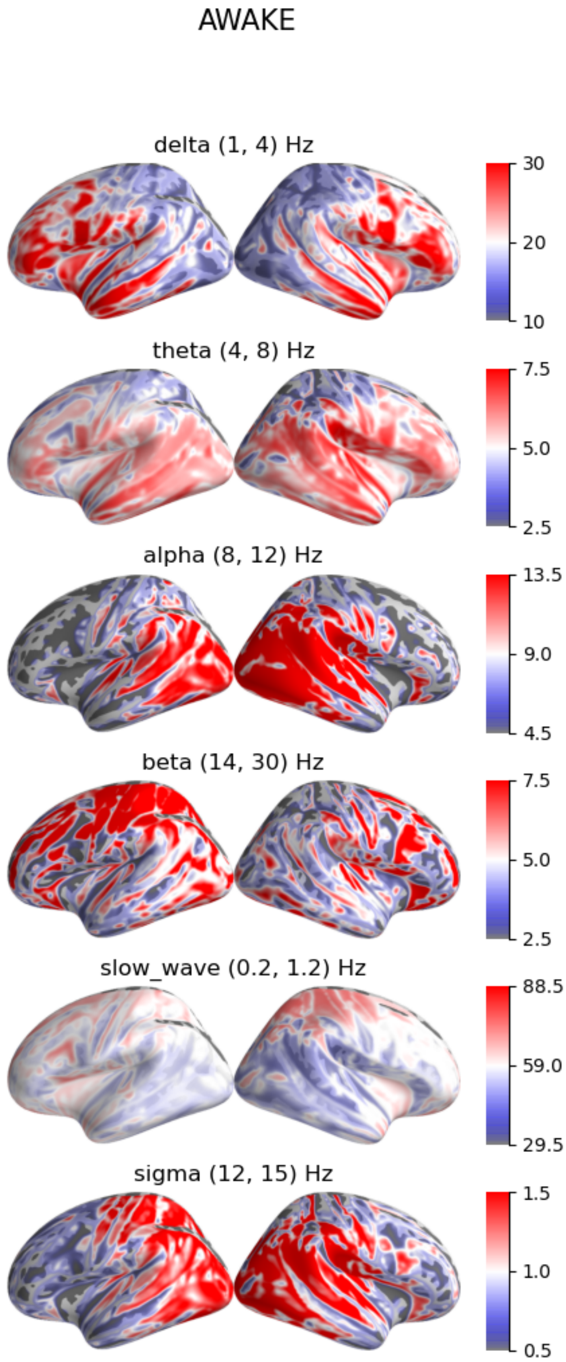

Figure 43: Average of sleep stage Awake with 8 electrodes in x pattern

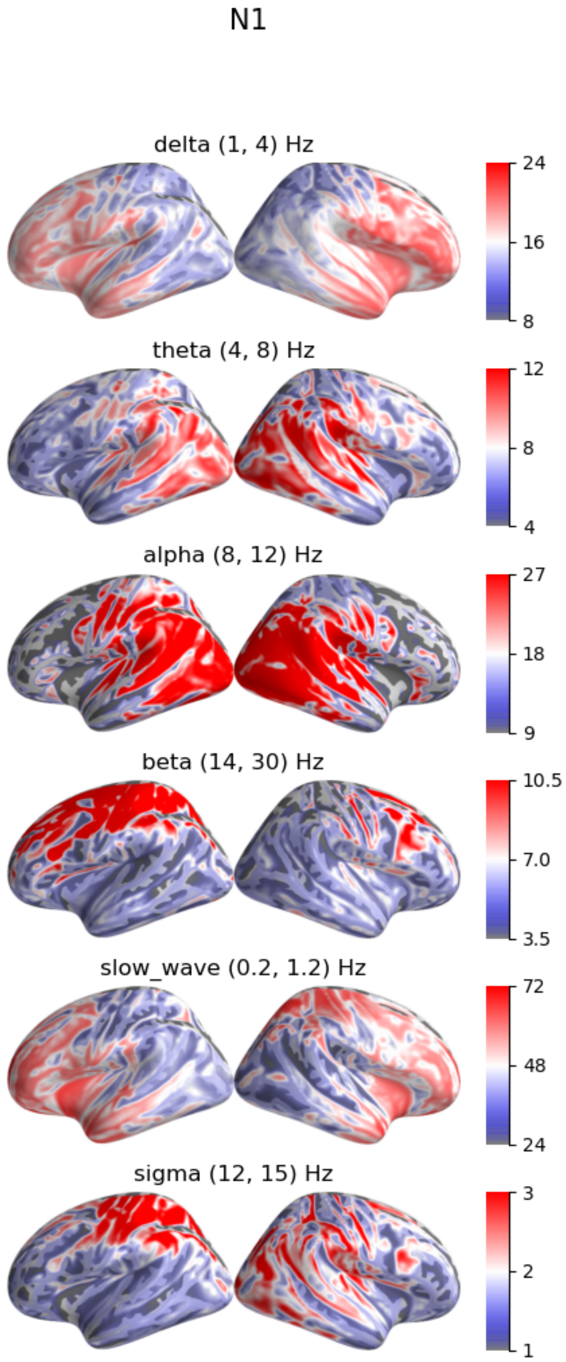

Figure 44: Average of sleep stage N1 with 8 electrodes in x pattern

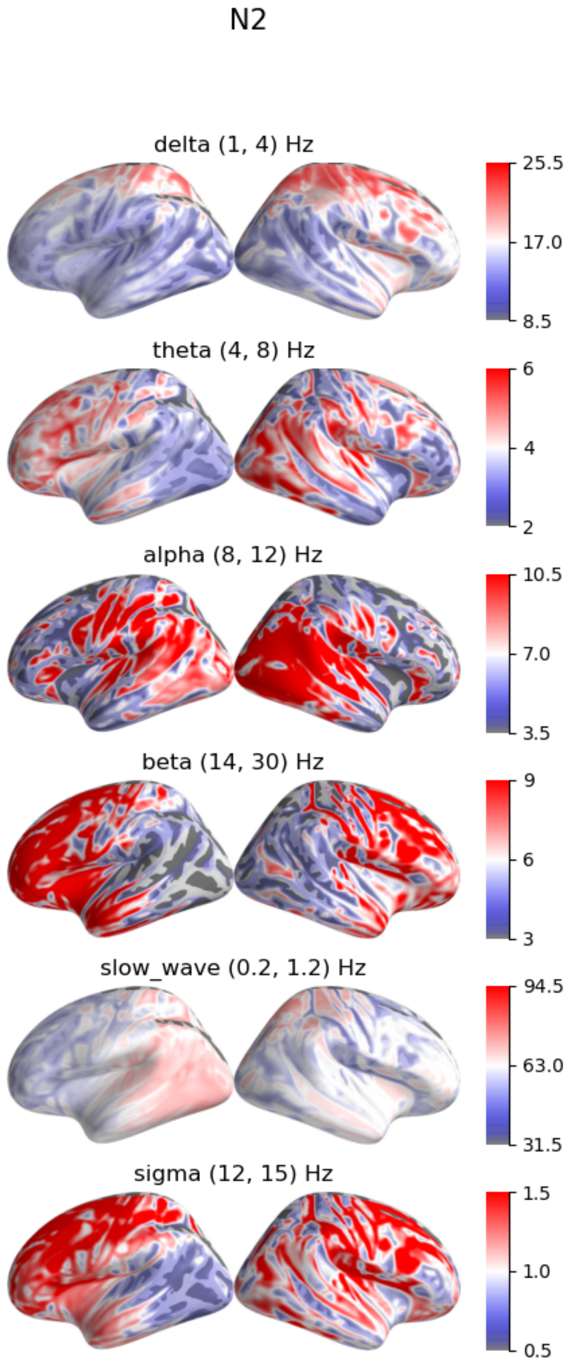

Figure 45: Average of sleep stage N2 with 8 electrodes in x pattern

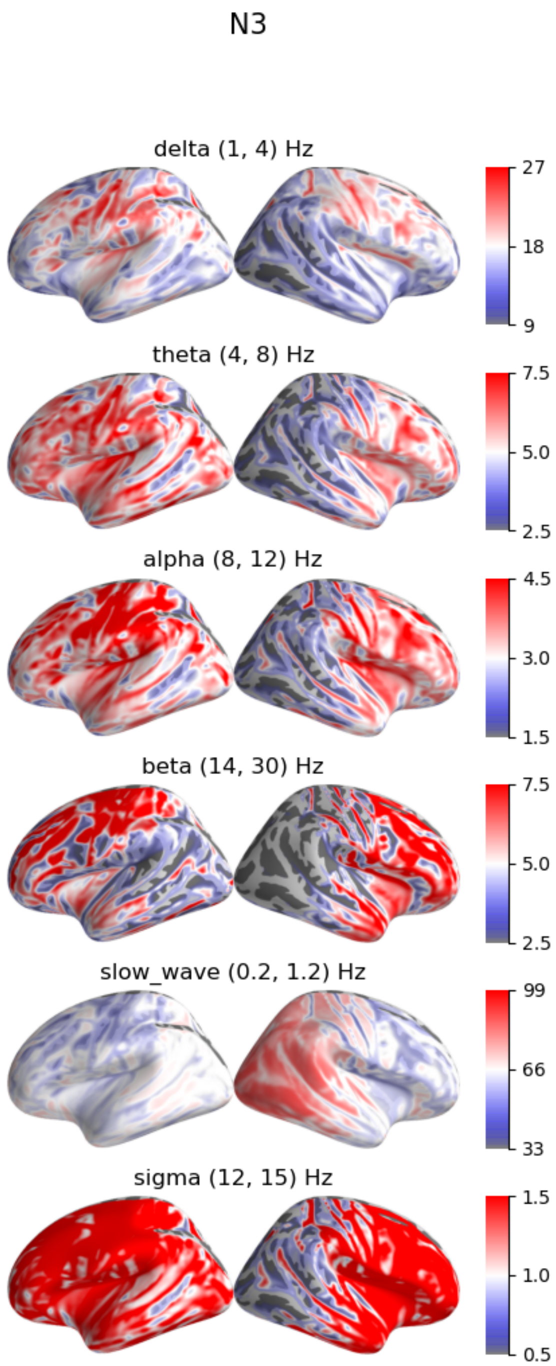

Figure 46: Average of sleep stage N3 with 8 electrodes in x pattern

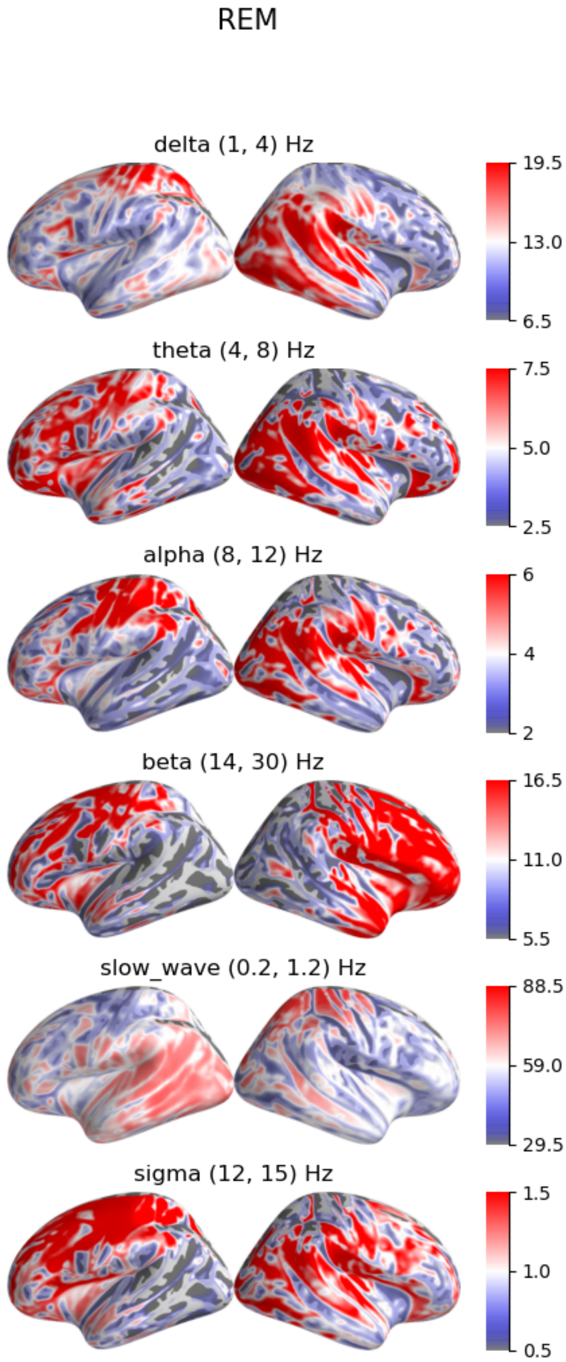

Figure 47: Average of sleep stage REM with 8 electrodes in x pattern

C.3 16 channel with focus on centerline

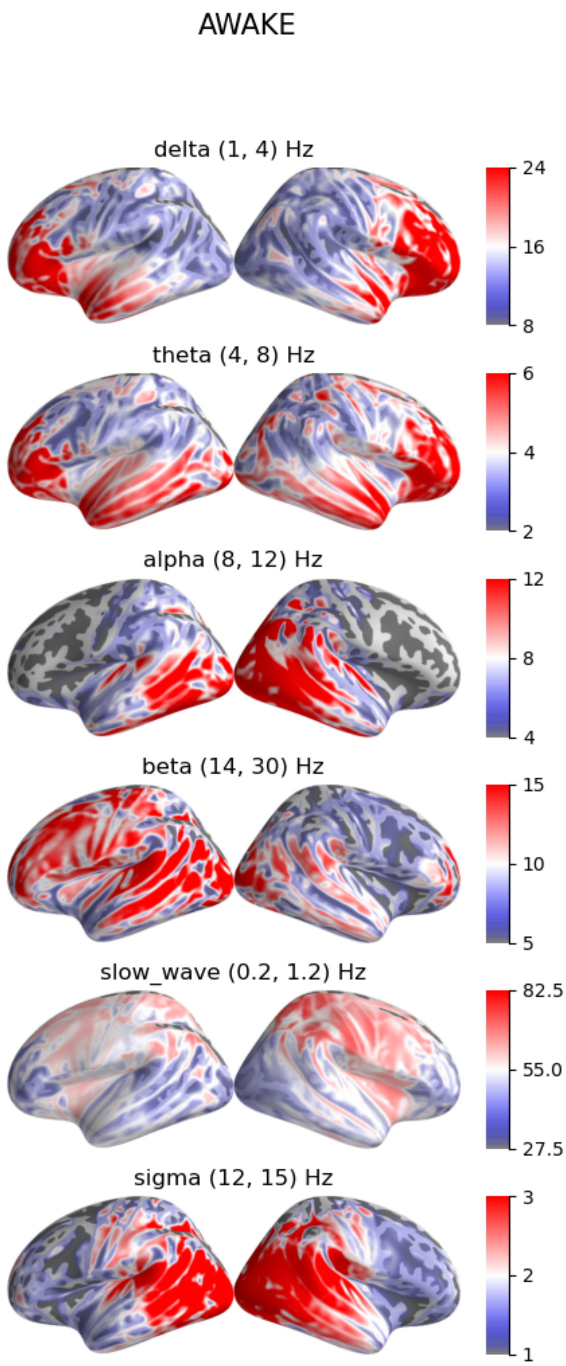

Figure 48: Average of sleep stage Awake with 16 electrodes in centerline

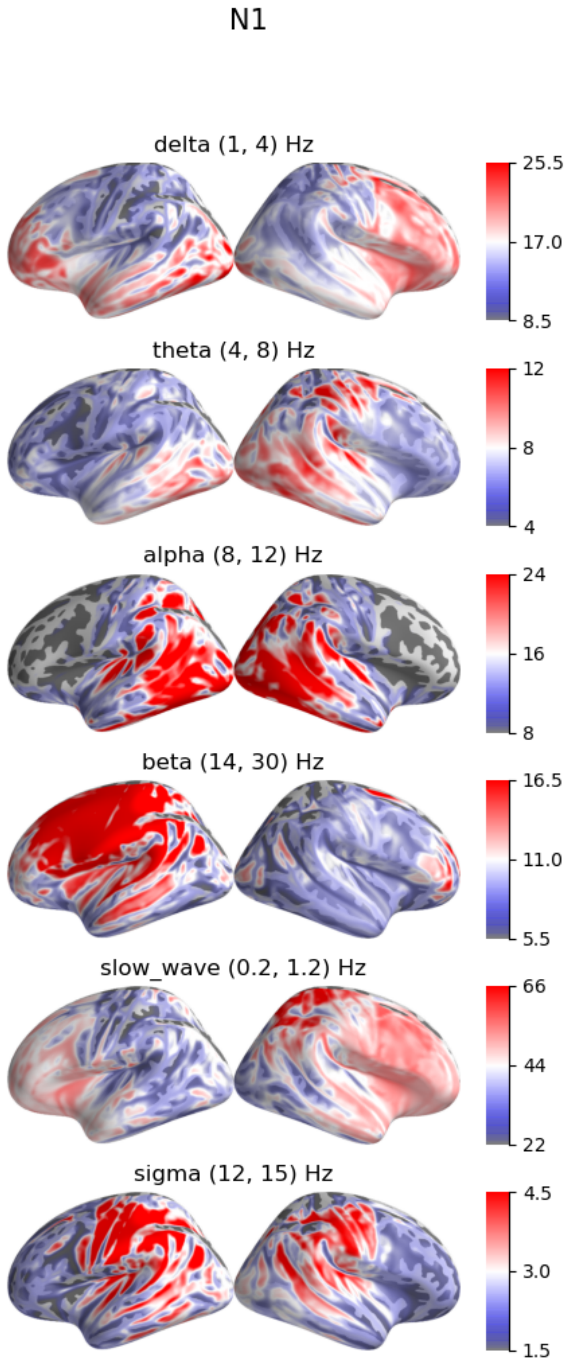

Figure 49: Average of sleep stage N1 with 16 electrodes in centerline

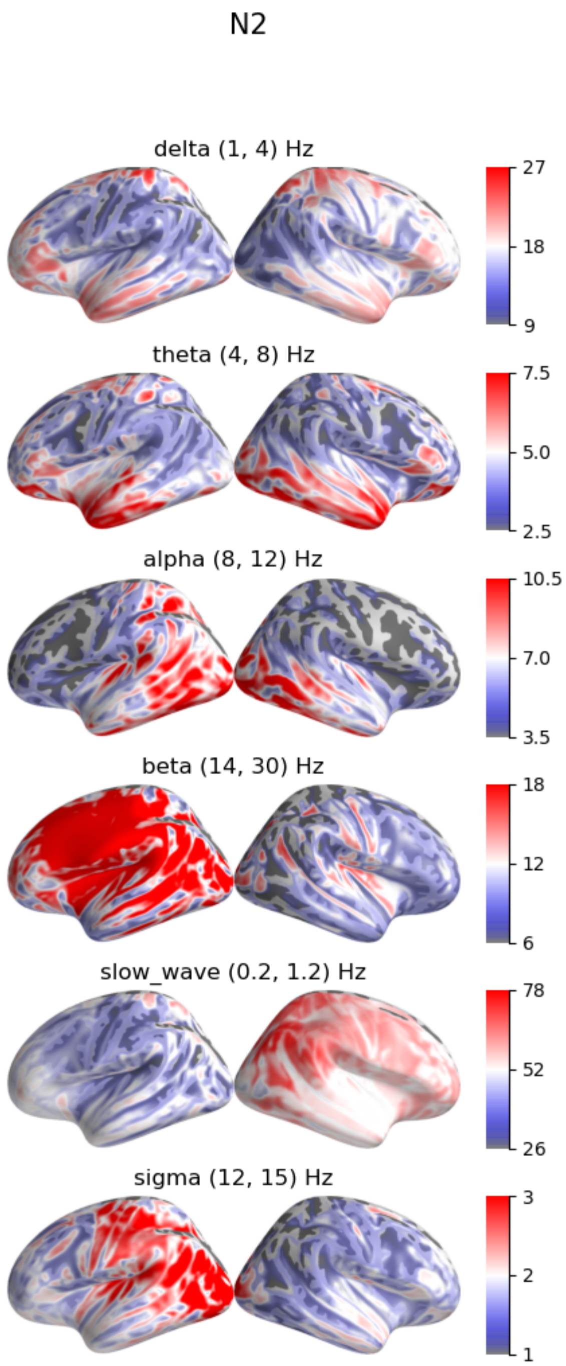

Figure 50: Average of sleep stage N2 with 16 electrodes in centerline

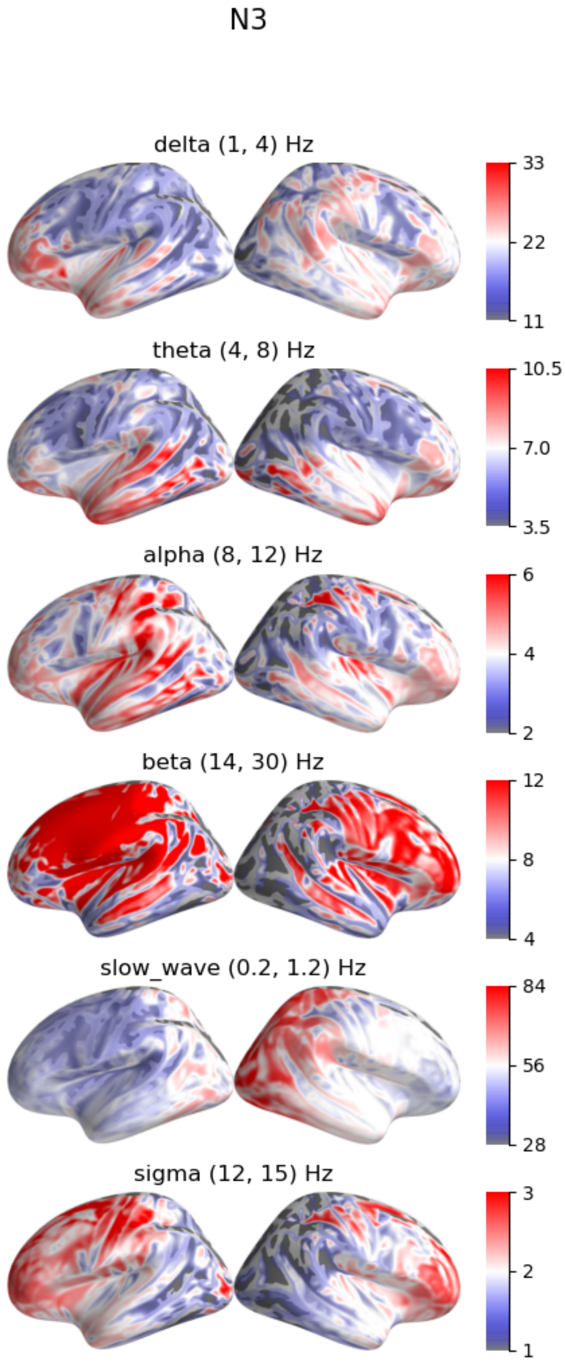

Figure 51: Average of sleep stage N3 with 16 electrodes in centerline

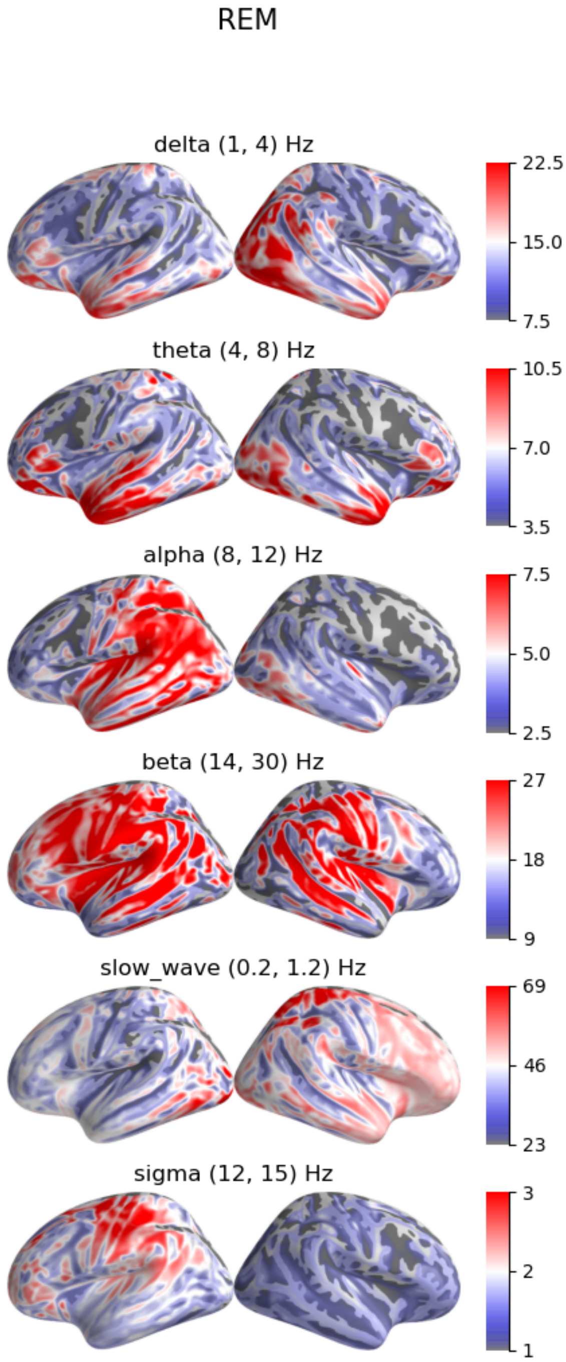

Figure 52: Average of sleep stage REM with 16 electrodes in centerline

C.4 16 channel with spread out

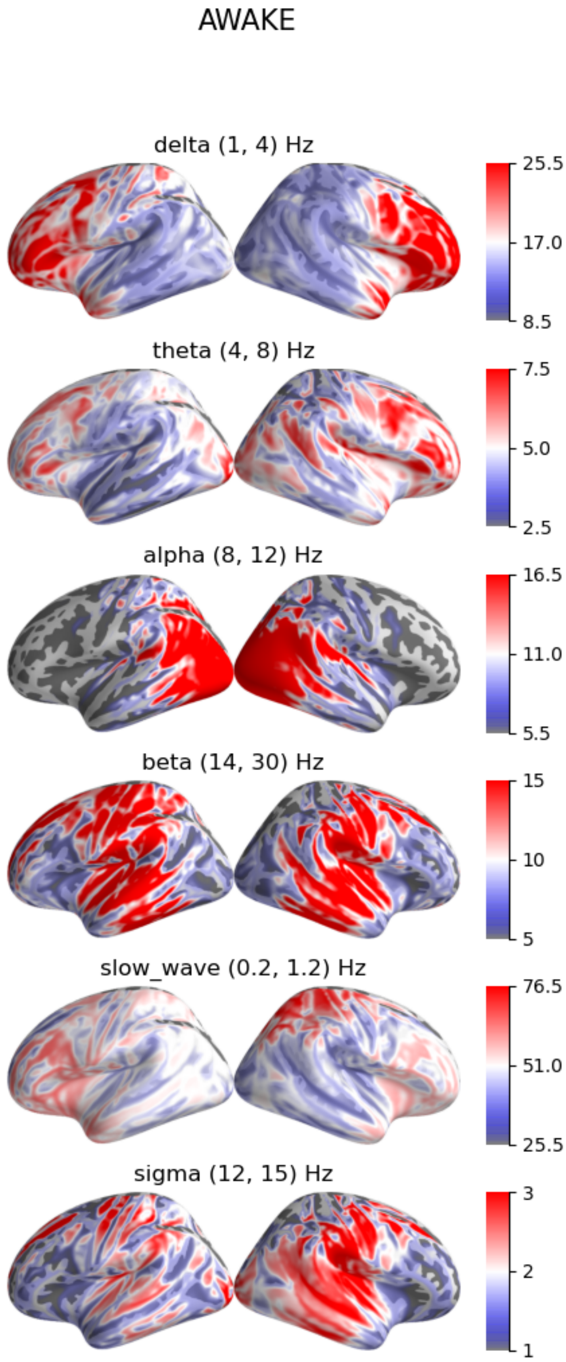

Figure 53: Average of sleep stage Awake with 16 electrodes in x pattern

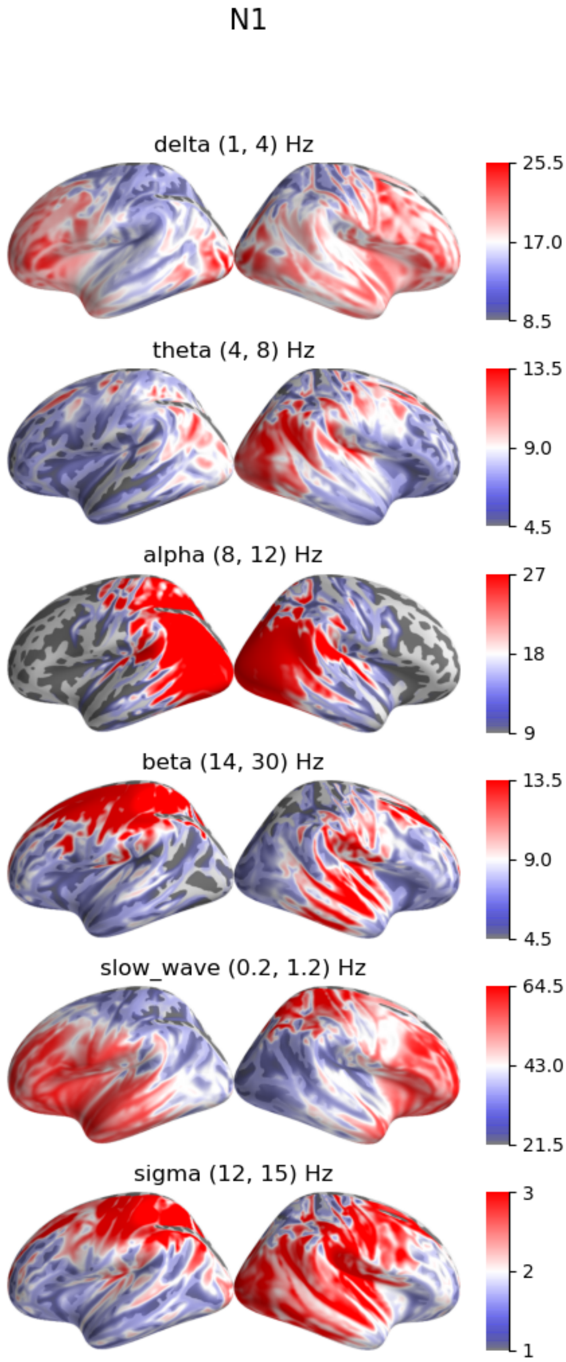

Figure 54: Average of sleep stage N1 with 16 electrodes in x pattern

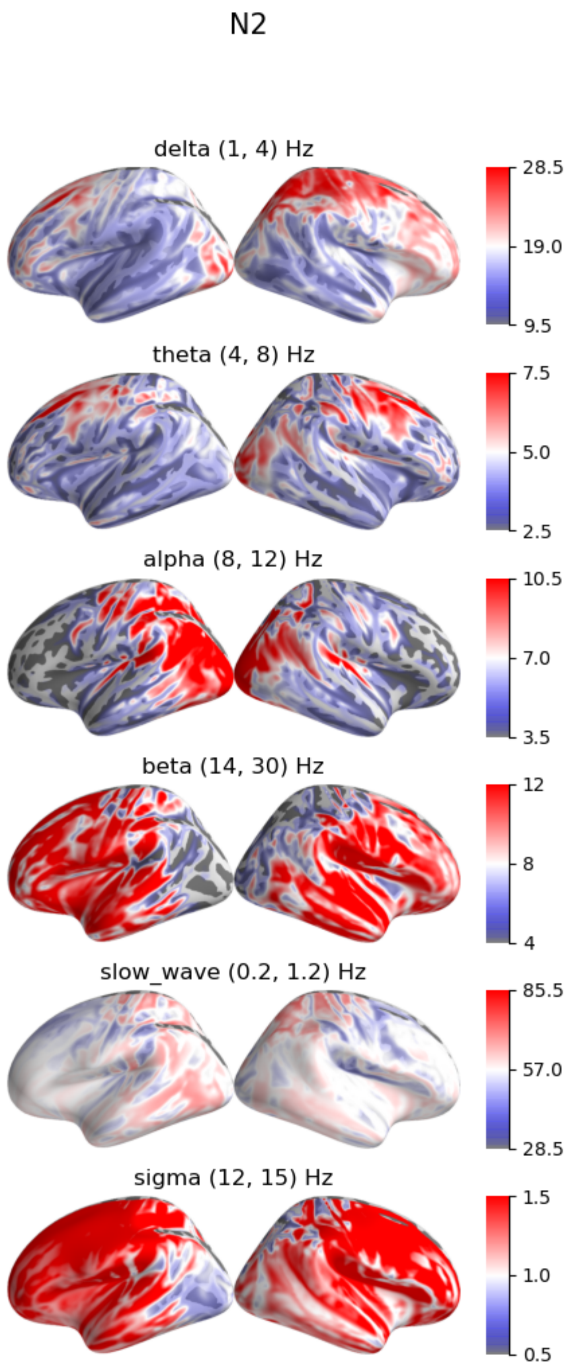

Figure 55: Average of sleep stage N2 with 16 electrodes in x pattern

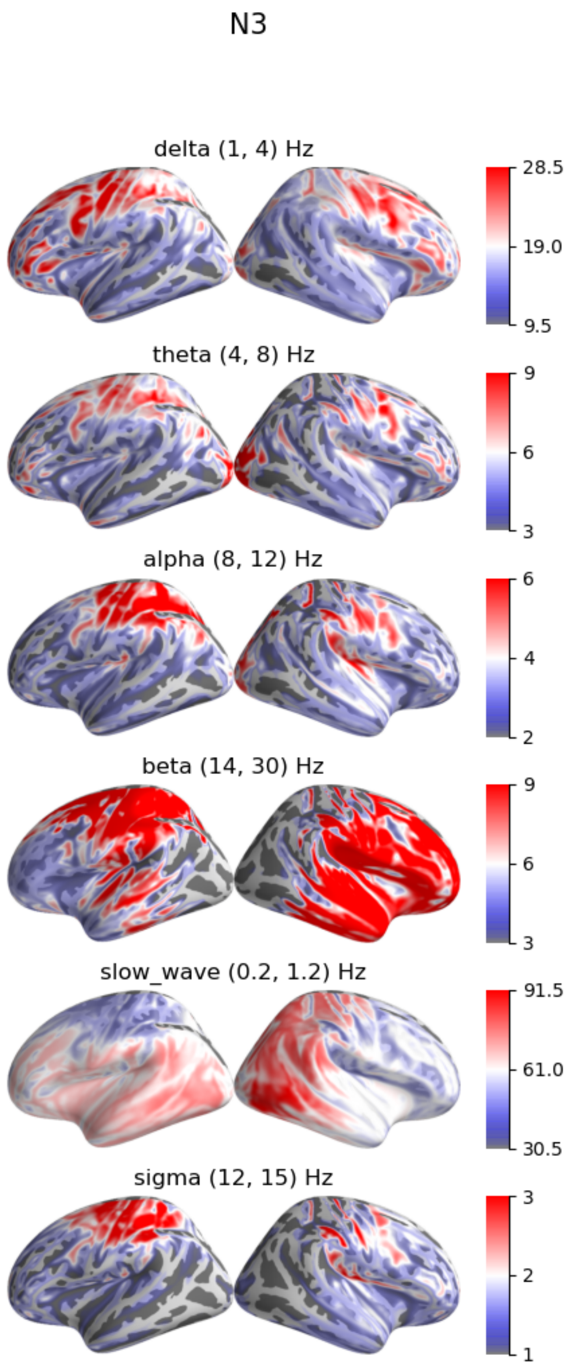

Figure 56: Average of sleep stage N3 with 16 electrodes in x pattern

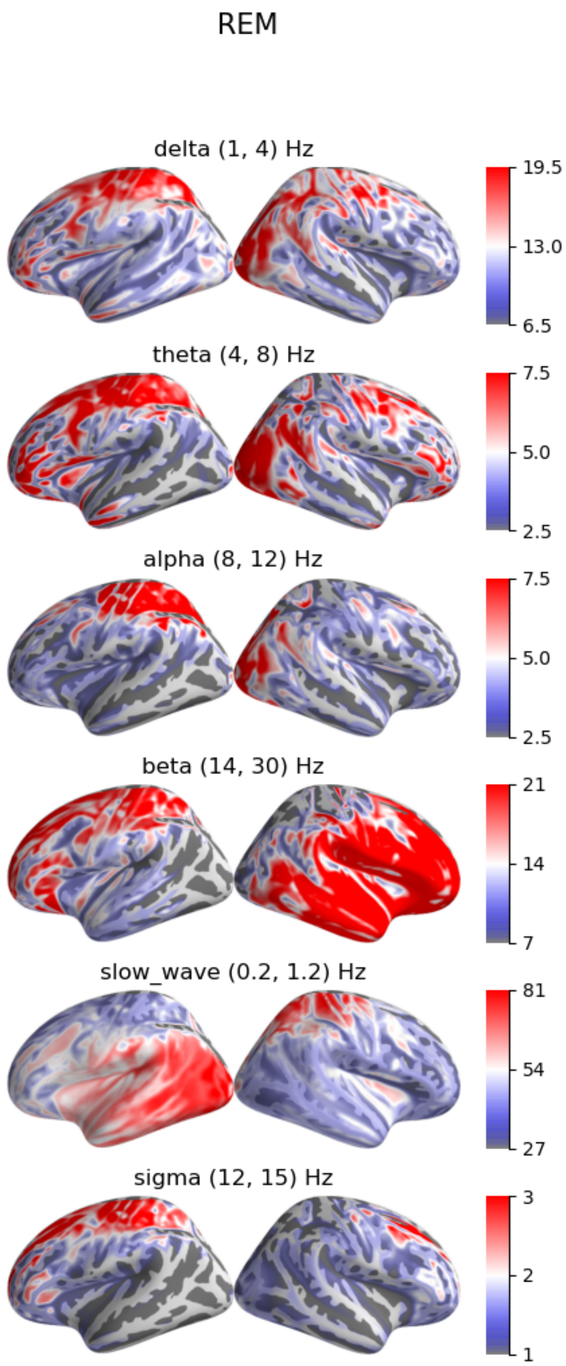

Figure 57: Average of sleep stage REM with 16 electrodes in x pattern