Lab 4. Brain wave measurement and analysis - EEG

1. Objective

- Learn how to measure EEG signals.
- Learn how to recognize and analyze EEG patterns such as Alpha/Beta waves and Alpha block.
- Learn the effects of common EEG artifacts caused by eye blinks, facial muscle contractions, and head movement.
- Learn how to preprocess EEG signal, remove artifacts by applying digital filters, and transform EEG time series to the frequency domain using MATLAB.

2. Backgrounds

2.1. What is an *electroencephalogram* (EEG)?

The living brain produces a continuous output of weak electrical signals, often referred to as brain waves. The recording of these signals, called an *electroencephalogram* (EEG), is the summation of entire postsynaptic potentials of the neurons (including both excitatory and inhibitory) in the cerebral cortex. An *electroencephalograph* is an instrument for recording the electrical activity of the brain with surface electrodes placed along the scalp. Even though the amplitude of signals from the cerebral cortex scale in microvolts, electroencephalograph can accurately detect and record them. The raw signals are initially collected by electrodes that are attached to the surface of the scalp, and amplified to the several millivolt scale. The amplified signals are then measured and recorded. In this lab, we will use *iWorx data recording unit* as an electroencephalograph to perform the entire process of EEG analysis, including data collection, signal amplification, and analog-to-digital conversion.

2.2. EEG patterns and behavioral states

Scalp EEG activity shows oscillations at a variety of frequencies. There are four major EEG frequency patterns (Figure 1): Beta (14-30 Hz), Alpha (8-13 Hz), Theta (4-7 Hz), and Delta (1-3 Hz). In general, the amplitude of the EEG increases as the frequency decreases.

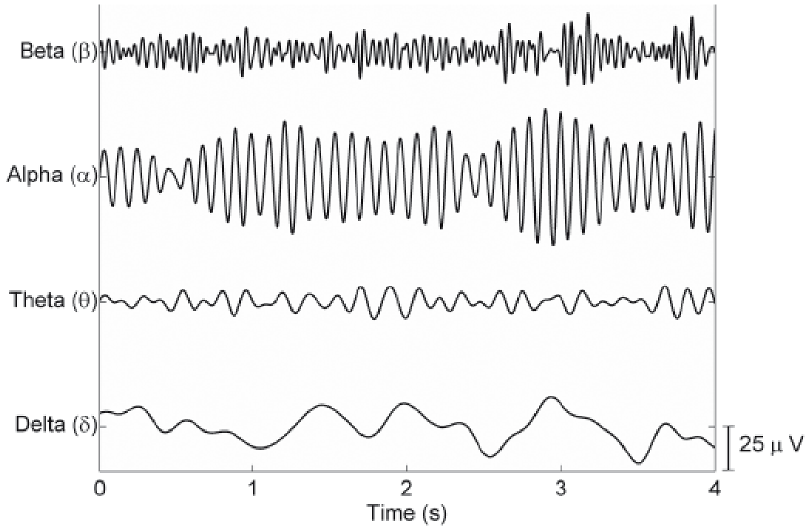


Figure 1. Different types of normal EEG waves (Campisi, Patrizio, Daria La Rocca, and Gaetano Scarano. "EEG for automatic person recognition." Computer 45.7 (2012): 87-89.)

Each of the four EEG frequencies is associated with a different level of arousal of the cerebral cortex. Cortical arousal refers to the firing patterns of the neurons of the cerebral cortex. As the frequency of the EEG pattern decreases, the level of cortical arousal diminishes. As the level of arousal diminishes, the EEG pattern increases in amplitude. Thus, frequency and amplitude are inversely related in the EEG. An EEG with a large amplitude and a low frequency indicates a more synchronized brain wave pattern (groups of cells are acting in concert); whereas an EEG with a low amplitude and a high frequency generally corresponds with a desynchronized brain wave pattern (groups of cells are involved in separate activities). The level of cortical arousal is correlated with various psychological and behavioral states. Some of the behaviors or psychological states often associated with the four prominent EEG frequencies are shown in Table 1.

EEG Pattern	Behavioral/Psychological State
Beta (14-30 Hz)	Awake, alert, focused attention and problem-solving; dream/REM sleep; high level of environmental stimulation (e.g. eyes open).
Alpha (8-13 Hz)	Awake, non-focused, relaxed, drowsy, or non-vigilant; low level of environmental stimulation (e.g. eyes closed).
Theta (4-7 Hz)	Visual imagery, hypnagogic/hypnopompic imagery; light sleep.
Delta (1-3 Hz)	Deep, restful sleep; vague dream states.

Table 1. EEG Patterns and Behavioral States

2.3. EEG spectral analysis

Spectral analysis is one of the standard methods used for quantification of the EEG. The power spectral density (power spectrum) reflects the 'frequency content' of the signal or the distribution of signal power over frequency. Several parameters derived from the power spectrum have been used, including total power, spectral band power, and median and spectral edge frequency. Usually, the power spectrum is analyzed on the basis of broader frequency bands, which represent the sum of the power of several smaller frequency bands (bins).

2.4. Filtering EEG signals

EEG signals from a real experiment include noises coming from the AC power line (external, environmental noise), eye/body movement (physiological noise), etc. To correctly investigate the features of interest, we need to remove those unwanted components from the signal, using a technique called "filtering".

Mathematically, a *signal* is a function $f: \mathbb{R} \to \mathbb{C}$, and a *filter* is a transformation L that sends a signal f to another signal $\tilde{f}$. Filters can be classified by their operations. For example, a low-pass filter passes signals with a frequency lower than a cutoff frequency and removes a higher frequency. High-pass filter and band-pass filter are defined similarly.

Filters of the form $L(f) = g * f$, where $g: \mathbb{R} \to \mathbb{C}$ and $*$ denotes convolution, are particularly useful. If g has finite support, then L is called a *finite impulse response* (FIR) filter; otherwise, it is called an *infinite impulse response* (IIR) filter. For further information, please refer to Supplemental Materials 6.6. Digital Filters with MATLAB by Ricardo A. Losada.

2.5. Fast Fourier Transform (FFT)

To perform a spectral analysis on the frequency bands we targeted, we need to transform our EEG signals from the time domain to the frequency domain. A Fast Fourier transform (FFT) is one of the useful algorithms; computing the discrete Fourier transform (DFT). A signal is decomposed into components of different frequencies and represents which frequency component is dominant in the original signal. Based on the results, we can compare the frequency features of EEG quantitatively.

3. Prelab activity

Please read ***2. Backgrounds*** *and* ***6. Supplemental Materials carefully.*** *Afterward, answer the following questions.*

3.1. Answer the following questions.

A. Which devices are used for imaging neural activity in the human brain? And what is the advantage of EEG compared to other methods?

B. Summarize the 10-20 electrode placement system and recording references.

C. Explain the role of an amplifier and filters including high pass filter, band-pass filter, and low pass filter for EEG measurement.

D. What is the difference between ideal filters and real filters? Why can't we apply ideal filters in real experiments?

E. Explain four typical EEG patterns that are widely detected in human brains (including their frequency range and when they occur).

F. What are the sources of artifacts interrupting EEG analysis? How can we compensate for them?

3.2. Use MATLAB to solve the following tasks and answer the questions.

```
Fs = 1000;          % Sampling frequency
T = 1/Fs;           % Sampling period (s)
L = 1000;           % Length of signal
t = (0:L-1)*T;      % Time vector

Target sinusoidal signal = cos(100πt) + 5cos(300πt) + 10cos(600πt)
```

A. Fast Fourier Transform (FFT) is the algorithm that accelerates the calculation of Fourier transform. Explain what Fourier transform is, and how to use *fft*/*ifft* and *fftshift*/*ifftshift* in Matlab. (hint: You don't need to explain the details of fft algorithm; just suggest simple usage of fft function in MATLAB)

B. Plot the target sinusoidal signal in the time domain (only display graphs from 0 to 100 ms).

C. Plot the spectrum of the target signal in the frequency domain using fft function. (hint: you should take absolute value for spectrum. You need to specify x- and y-axis. Locate frequency=0 in the center)

4. Mainlab activity

4.1. Equipment setup

Equipment Required: PC, iWorx unit, USB or serial cable, AAMI cable and EEG leads, EEG electrodes

1) Connect the iWorx unit to the computer.
2) Select one person from your group to be the subject in this experiment.
3) One electrode will be placed on the backside of the hand (either left or right) and the rest four electrodes will be placed on the head:
4) Remove the plastic disks from the disposable electrodes and apply them to the scrubbed areas. Then, attach the AAMI connector at the end of the gray patient cable to the isolated Channel 1 & 2 inputs of the iWorx unit (Figure 2).
5) Attach the five color-coded electrode cables to the ground and Channels 1 and 2 inputs on the lead pedestal. Refer to Figure 3 and snap the other ends onto the electrodes, so that:

- the "+1" lead (Ch1(+)) is over the left frontal lobe.
- the "-1" lead (Ch1(–)) is on the left mastoid.
- the "+2" lead (Ch2(+)) is over the right frontal lobe.
- the "-2" lead (Ch2(–)) is over the right mastoid.
- the "C" lead (the ground) is on the backside of the hand.

6) Drape the leads for the other electrodes over the subject's shoulder to the lead pedestal, so that it hangs freely down the subject's back and over the chair. There should be no tension on the electrodes.
7) The subject should sit quietly with their hands on the lap.

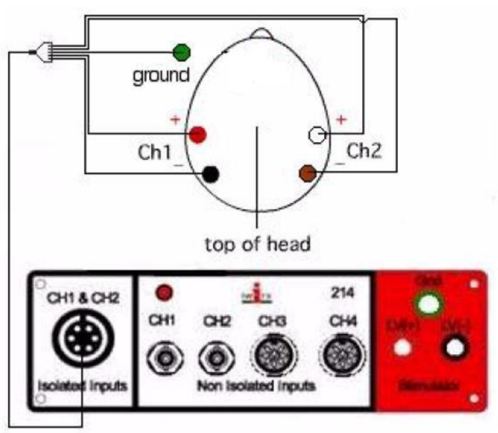


Figure 2. The equipment used to measure the EEG

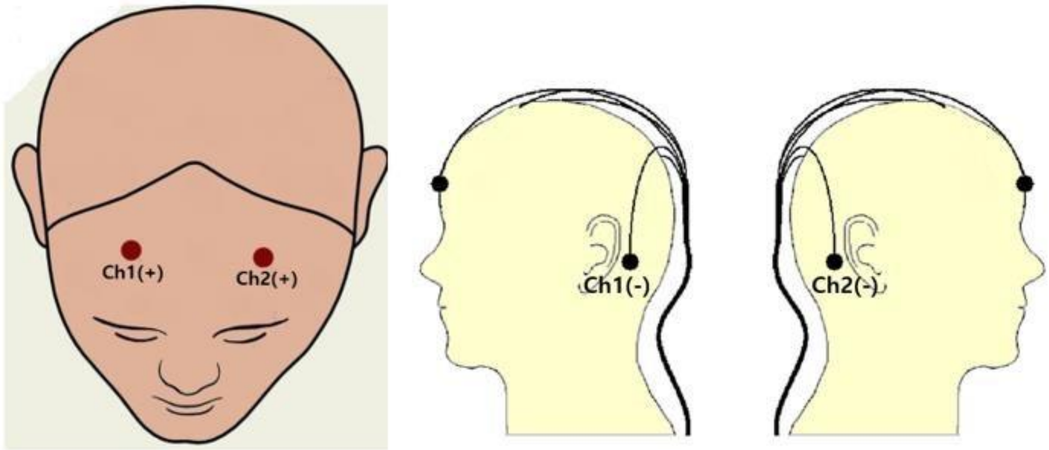


Figure 3. Electrode placement

4.2. Launching the software

1) Click the Windows Start menu, move the cursor to Programs and then to the iWorx folder and select LabScribe; or click on the LabScribe icon on the Desktop.
2) When the program opens, select Load Group from the Settings menu.
3) Click on the Settings menu again and select the EEG Activity settings file.
4) After a short time, LabScribe will appear on the computer screen as configured by the EEG Activity settings.
5) Right-click in the recording area of Channels 1 and 2 and confirm that the Input Mode of each channel is set to 0.3-35 Hz. This setting will filter out frequencies below 0.3 Hz and above 35 Hz, frequencies not generated by the brain.

4.3. Exercise 1: Common EEG Artifacts

1) Ask the subject to sit quietly and not move unless told to do so, and to keep his or her eyes open during this phase of the experiment.
2) Click Start, and then click the AutoScale buttons for all six channels displayed.
3) Over the first 30 seconds of the recording, ask the subject to blink his or her eyes. Before you ask the subject to blink, type “Blink” in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording each time the subject is requested to blink.

4) Over the next 30 seconds of the recording, ask the subject to contract his or her forehead or facial muscles. Before you ask the subject to smile (or frown), type “Smile”(or “Frown”) in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording each time the subject is requested to smile (or frown).
5) Finally, over the last 30 seconds of the recording, ask the subject to rotate (or tilt) her or his head from side to side. Before you ask the subject to rotate their head, type “Rotate”(or “Tilt”) in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording each time the subject is requested to move his or her head.
6) Click Stop to halt recording.
7) Select Save As in the File menu, type a name for the file. Choose a destination on the computer in which to save the file (e.g. the iWorx or class folder). Click the Save button to save the file (*.iwd file). Select Export in the File menu and export the file as the text (.txt) file.

4.4. Exercise 2: Alpha and Beta EEG Patterns

1) Inform the subject that he or she needs to avoid any movement other than opening or closing his or her eyes. The subject will be asked repeatedly to open and close his or her eyes during this exercise.
2) During this exercise, you will also need to enter two comments to indicate:
   - the section of the recording when the eyes are open
   - the section of the recording when the eyes are closed
3) Click Start, and then click the AutoScale buttons for all six channels.
4) The subject should have his or her eyes open at the beginning of the recording. Type “Open” in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording. Record for 20 seconds.
5) While the subject has his or her eyes open, type “Close” in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording as you instruct the subject to close his or her eyes. Record the subject’s EEG pattern with his or her eyes closed for additional 20 seconds.
6) Continue to record the subject’s EEG pattern for total of 2 minutes as the subject alternates having his or her eyes open or closed for alternating 20 second periods. Annotate the recording with comments each time the subject opens or closes his or her eyes.
7) Click Stop to halt recording.
8) Select Save As in the File menu, type a name for the file. Choose a destination on the computer in which to save the file (e.g. the iWorx or class folder). Click the Save button to save the file (*.iwd file). Select Export in the File menu and export the file as the text (.txt) file.

4.5. Exercise 3: The Alpha Block

1) Before beginning this exercise, inform the subject of the experimental conditions:

- The subject should sit quietly with his or her eyes closed throughout the recording period.

- Following a quiet period when the subject's resting EEG pattern is established, the subject will be given a mental arithmetic problem to solve.

- The subject should understand that the correct answer is not important, and should work on the problem until an answer is found.

- When the subject has completed the problem, he or she should say the answer out loud, and then resume sitting quietly with no particular mental focus.

- The person operating the computer will enter appropriate comments on the recording to indicate the beginning of the quiet period, the time at which the question was asked, the time when the subject speaks the answer, and the time when the recording ended.

2) Click Start. Click the AutoScale buttons for Channels 1 and 2. Type the letter "R" (for Resting) in the comment line to the right of the Mark button. Press the Enter key on the keyboard to mark the recording. Make a recording of at least 30 seconds of Alpha EEG while the subject is sitting quietly with his or her eyes closed.
3) Type "P1" (for Problem 1) in the comment line to the right of the Mark button. Ask the subject to solve a mental arithmetic problem such as "multiply 46 by 28" or "divide 157 by 16." The problem should be delivered to the subject quickly. Press the Enter key on the keyboard to mark the recording as soon as the problem is first given to the subject.
4) Type "EP1" (for End of Problem 1) in the comment line to the right of the Mark button. When the subject finishes the problem and announces the answer out loud, press the Enter key on the keyboard to indicate the end of the problem-solving period.
5) Repeat this procedure (Steps 2, 3, and 4) one more time, using a different mental arithmetic problem labeled as "P2".
6) Click Stop to halt recording.
7) Select Save As in the File menu, type a name for the file. Choose a destination on the computer in which to save the file (e.g. the iWorx or class folder). Click the Save button to save the file (*.iwd file). Select Export in the File menu and export the file as the text (.txt) file.

4.6. Commercial device for EEG measurement: NeuroSky.

Figure 4. Sample screen from NeuroSky program

1) Download Brainwave Visualizer application (Figure 4.) at AppStore, and obtain brain wave signal using NeuroSky equipment.
2) Select one of the activities from NeuroSky store, and play it.

4.7. Data analysis using MATLAB

Execute the MATLAB and do the following steps using the results from Exercise 1, 2, and 3. In case of Exercise 1, you do not need to perform the spectral analysis. Refer to Figure 5, 6, and 7 for the entire process and example signals.

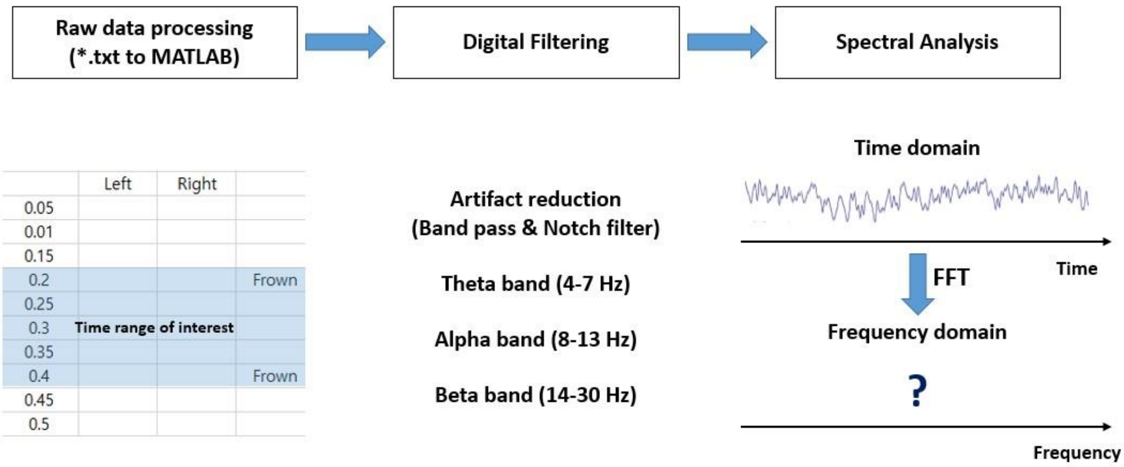


Figure 5. Entire EEG analysis process

1) Raw data processing

- Read the text file (*.txt) and convert into an array.
- Verify the marks entered during the experiments and leave only the target of analyses.
- Verify each column and load the raw EEG data of each hemisphere.

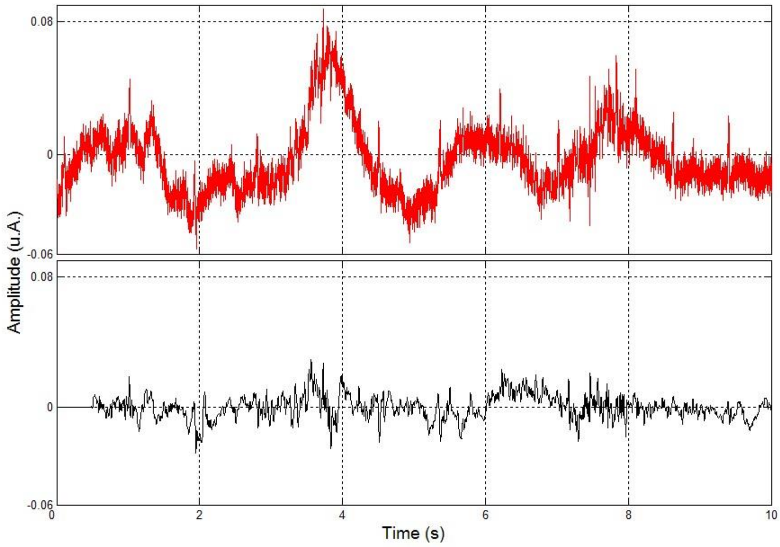


Figure 6. Example of filtering and artifact removal (Top: raw signal, bottom: filtered signal)

2) Digital filtering

- Apply the digital filters to remove artifacts. You may define your own filter rather than using predefined function.

- Apply the digital filters to obtain Alpha, Beta, and Theta band from the original time series.

- From the original array, load the Alpha and Beta data of each hemisphere.

- Compare the results obtained above.

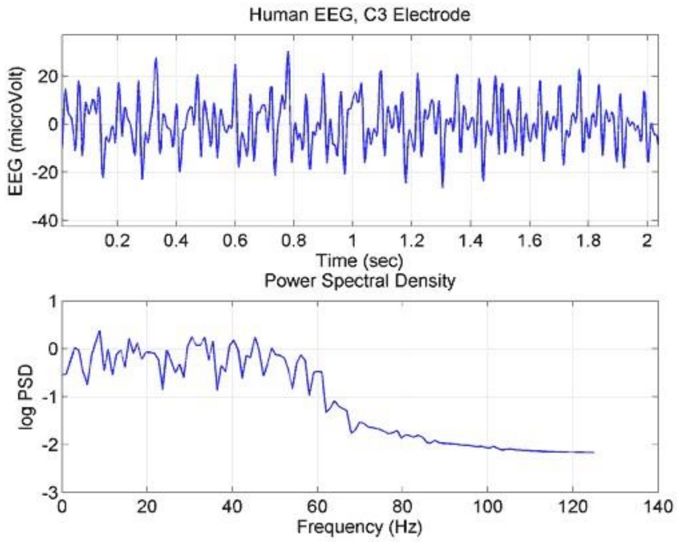
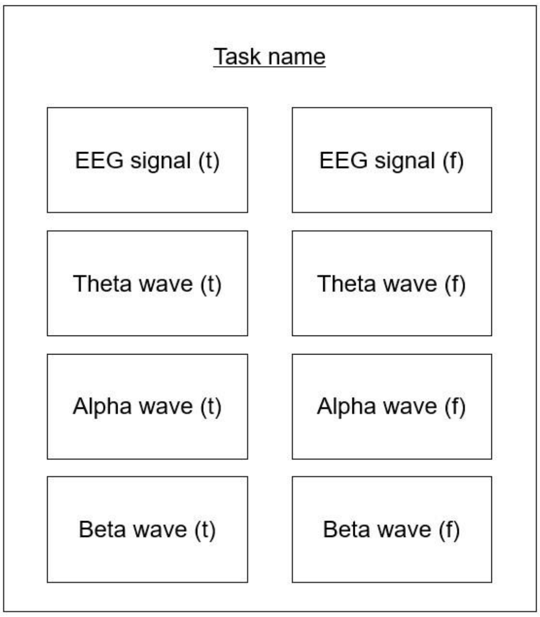


Figure 7. Example of spectral analysis (Top: raw signal, bottom: transformed signal)

3) Spectral analysis

- Transform the data obtained in Exercises 2 and 3 into the frequency domain using the MATLAB *fft* function. (You should consider <u>*Nyquist Theorem*</u> for spectrum)

- Plot both (time and frequency) domains for each EEG data. You may use MATLAB functions such as *subplot*, *xlim*, and *sgtitle*.



- From the data of both domains, find the relationship between behavioral data and EEG data.

Mainlab Questions

All of questions below should be answered in the final report, in addition to MATLAB analysis results from ***4.7. Data analysis using MATLAB.***

Demo questions:

1) *What is the filter setting of your amplifier?*
2) *What is the sampling frequency that you used for digitization of EEG signal?*
3) *How many channels were used for the data acquisition?*
4) *Where is the source of the EEG data that we acquired?*
5) *Why should we record the resting state?*

4.3. Exercise 1: Common EEG Artifacts

Q. Compare the amplitudes of EEG in the following cases and describe the reason:

(1) eye open vs. blink, (2) smile vs. frown, (3) rotate vs. tilt.

4.4. Exercise 2: Alpha and Beta EEG Patterns

Q. Compare the Alpha and Beta pattern in the following cases and describe the reason: when eyes are (1) open or (2) closed.

4.5. Exercise 3: The Alpha Block

Q. Compare the Alpha and Beta pattern between the resting state and concentrating state (i.e., when you were doing the calculation).

4.6. Commercial device for EEG measurement: NeuroSky.

Q. Compare the characteristics of brain waves obtained from iWorx and NeuroSky. How are they different? Why?

Q. Let's reverse-engineer the program. How does this software work? Which component of the EEG did they use for the activity?

Q. Can you implement a similar system based on the iWorx EEG data? If you cannot, why?

Q. How can you improve this device (Neurosky)?

5. References

[1] The iWorx 214 LabScribe Tutorial

[2] C Ramon, Teaching Medical Instrumentation at the University of Washington, *MathWorks*

[3] M Teplan, Fundamentals of EEG measurement, *Measurement Science Review*, 2002

[4] O Dressler et al., Awareness and the EEG power spectrum: analysis of frequencies, *British Journal of Anaesthesia*, 2004

[5] MAG Correa and EL Leber, Chapter 8: Noise Removal from EEG Signals in Polisomnographic Records Applying Adaptive Filters in Cascade, Adaptive Filtering Applications, 2011

6. Supplemental Materials

6.1. Introduction to EEG by Jeremy Moeller (Upload date: 2014.8.25)

(https://youtu.be/XMizSSOejg0)

6.2. Technical Issues in EEG by Jeremy Moeller (Upload date: 2015.6.8)

(https://youtu.be/KrJaJDMBo54)

6.3. Fast Fourier Transform from MATLAB

(https://kr.mathworks.com/help/matlab/ref/fft.html?lang=en)

6.4. fftshift from MATLAB

(https://kr.mathworks.com/help/matlab/ref/fftshift.html?lang=en)

6.5. Low-pass filter from Wikipedia

(https://en.wikipedia.org/wiki/Low-pass_filter#Ideal_and_real_filters)

6.6. Digital Filters with MATLAB by Ricardo A.Losada (Upload date: 2008.5.18) page 9~14

(https://www.mathworks.com/tagteam/82961_digfilt.pdf)