

A Comparative Study of Alpha Frequency Analysis between Medical and Consumer-grade Electroencephalography Devices on the Measurement of Male Healthy Subjects

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Abstract The relatively high cost of medical-grade electroencephalography (EEG) devices has pushed the production of low-cost wireless consumer-grade devices. Therefore, it is essential to assess the performance of wireless consumer devices to determine whether they are sufficient for medical purposes. This research assessed consumer-grade EEG (C-EEG) recording quality by quantitatively comparing the consumer-grade EEG with a medical-grade EEG device (M-EEG). Recording data from C-EEG and M-EEG were obtained from 20 male subjects in age 19-23 years old. Recording for both devices was done sequentially with similar methods of recording. Upon EEG recording, the subject is asked to sit in a chair facing the screen. EEG recording was performed when the subject was asked to open and close their eyes for 30 seconds each. Subsequently, subjects took a verbal memory test. This research compared the following parameters: power spectral density (PSD), full width at half max (FWHM) from PSD, and individual peak alpha frequency (IPAF) shift. P-value, standard error, mean absolute percentage error (MAPE) and mean squared error (MSE) were also obtained based on mentioned parameters. Based on the IPAF shift, it was concluded that C-EEG could read EEG signals against time well. Based on PSD and FWHM results, it was concluded that the C-EEG could not read EEG signal amplitudes well compared to the M-EEG device. The results of this research are important as a benchmark for carrying out further research using EEG, both medical and consumer-grade.

Keywords: Electroencephalography, Medical-grade, Consumer-grade, Power spectral density, Alpha frequency.

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Introduction

Electroencephalography (EEG) is a commonly used method for brain electrical activity studies because of its simplicity, but rich information is given. EEG is an electrical activity recording technique that places electrodes on the head scalp. This technique produces a graphical representation of the voltage difference between two cerebral regions plotted against time. The EEG signals are produced by an electrical field that is generated from the fluctuations in the brain electrical activity in a large population caused by spatial accumulation from post-synaptic potential. Electric current from the brain penetrates the skin, skull, and other layers so that the electrodes receive it. This signal is then amplified, digitized, and saved in a computer [1–3].

Despite its importance, medical EEG devices are relatively high cost. This condition has pushed companies to develop the production of cheap consumer EEG devices. For comparison, the price of C-EEG on the market currently ranges from USD 99-1700, while for M-EEG, the price ranges from USD 2000-25000. To maintain the production of consumer EEG devices with good quality and low cost, it is essential to assess the performance of wireless consumer devices to determine whether they are sufficient for medical purposes. Thus, this paper aims to assess consumer-grade EEG recording quality by comparing the recordings with the recordings of medical-grade EEG devices [4,5].

EEG device (also known as an electroencephalograph) is a system that acquires analog signal from recording subjects, then converts it into digital representation [3]. EEG device mainly consists of a headbox and an amplifier. Electrodes are attached to the head following the 10-20 System of Electrode Placement rules. The 10-20 system is standard for placing electrodes on a subject's scalp in EEG research.

The EEG devices can be grouped into medical and consumer EEG devices [6]. An EEG device can be classified as medical if specific requirements are met. For example, the Standard American Clinical Neurophysiology Society (ACNS) requires a medical device to have at least 21 electrodes connected to an amplifier by cable with a minimum of 16 electrodes taking measurements simultaneously [7]. Some consumer EEG devices eliminate cable usage and substitute it with wireless transmission to accomplish practicality. Based on Abhang, the substitution from cable to wireless communication decreases the accuracy of the recordings and instead increases sensitivity to noise [8]. Research by Duvinage showed that wireless EEG devices have a lower signal-to-noise ratio (SNR) than medical EEG devices, which means they capture more unwanted noise [6].

This research is focused on using spectral analysis and the Welch periodogram to assess the quality of recordings from wireless consumer and medical EEG devices. Spectral analysis is a statistical signal analysis technique in the frequency domain widely used in EEG analysis [9]. EEG recordings present results in the time domain; therefore, converting them into the frequency domain is first required. This conversion then displays the signal's power in the frequency spectrum, known as power spectral density (PSD). This PSD will be the quantity to be analysed in this study.

Materials and Methods

Participants

This experiment was conducted on 20 healthy male subjects within the age range of 19-23 years old. Participants were ensured never to have a brain disease, damage, or disabilities. Before the experiment started, participants were asked to complete a questionnaire regarding their medical records. All participants were explained the research objectives and techniques. After that, all participants signed an informed consent sheet before entering the data acquisition stage.

Experimental Devices

Two EEG devices were used in this study. Medical-grade EEG uses cables, while consumer-grade EEG is wireless. Both data have specifications which can be seen in Table 1.

Table 1. Comparison of medical-grade and consumer-grade EEG device specifications

| | Medical-grade EEG (M-EEG) | Consumer-grade EEG (C-EEG) |
|----------------------|--|--|
| Number of electrodes | 19 (+2 references) | 14 (+2 references) |
| Electrodes | FP1, FP2, FZ, F3, F4, F7, F8, T7, T8, CZ, C3, C4, PZ, P3, P4, P7, P8, O1, O2 | AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2 |
| Configuration | IS 10-20 | IS 10-20 |
| Connectivity | Cable | Wireless with Bluetooth |
| Sampling rate | 500 Hz | 128 Hz |
| Dynamic range | 350 mV | 8.4 mV |

Data Acquisition

The experiment for both devices was done on the same day for each participant. The EEG measurement space is set between the subject position, screen, and EEG device as shown in Figure 1. This setting is done to avoid signal interference. Measurement space validation has been carried out in previous studies

[10,11]. The investigation for consumer-grade EEG was done before the experiment for medical-grade EEG. This order is based on technical matters that have been tested before the main experiment. The use of C-EEG is more practical than M-EEG, both in terms of the electrode cap, electrode gel, and the length of installation time. When the order of use is reversed, it increases the delay time in switching from M-EEG to C-EEG. This makes the participant tired and unable to focus on following data recording with C-EEG. When recording, participants were asked to sit on a chair. The participants were asked to close their eyes without sleeping and then open them while staring at the cross symbol displayed on a screen. Both conditions were done in 30 seconds each. Taking 30 seconds in the relaxation condition (both eyes open and eyes closed) was based on initial observations of the subject during the preliminary experiment. The transition time from the instructions given to the relaxation state takes 5-10 seconds. Therefore, 30 seconds are taken, so that later only the middle 10 seconds of data will be taken for processing. Subsequently, participants took a verbal memory test.

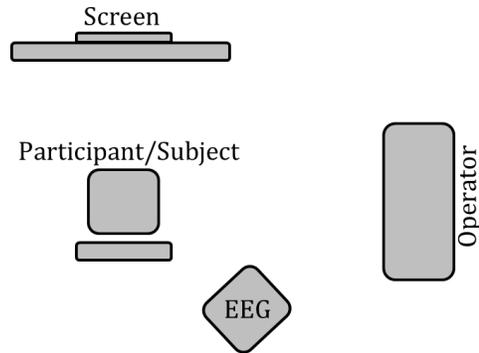


Figure 1. Layout of the experimental room for data acquisition [10]

Participants had a memorizing period of 30 seconds on the verbal memory test. In this period, a list of categorized words and the categories were displayed on the screen. After 30 seconds, the display was replaced by the verbal memory test questions number 1, number 2, and number 3 sequentially. Figure 2 shows an example of the content of a verbal memory test given to a subject. Participants were asked not to move any body parts except blinking and breathing on the test. Participants answered all questions verbally. After question number 3 was responded to, participants were again asked to stare at the cross symbol for 30 seconds. This final period was named the relaxation period.

| | |
|--|--|
| <p>FLOWER: Chrysolite, Frangipani, Tulip, Rafflesia</p> <p>TOOLS: Secateur, Broom, Wok, Hoe</p> <p>ART: Puppet, Quintet, Angklung, Orchestra</p> <p>ANIMAL: Lion, Iguana, Deer, Moose</p> <p>FRUIT: Kiwi, Jackfruit, Guava, Pomegranate</p> | <p>Q1. A word that starts with the letter A is a...</p> <p>A. Flower B. Tools C. Art D. Animal E. Fruit</p> <p>Q2. A word that starts with the letter S is a...</p> <p>A. Flower B. Tools C. Art D. Animal E. Fruit</p> <p>Q3. A word that begins with the letter A and ends with the letter T is a...</p> <p>A. Flower B. Tools C. Art D. Animal E. Fruit</p> |
|--|--|

Figure 2. Examples of "a list of categorized words and the categories" (left) and "verbal memory test questions" (right)

All the obtained data from the experiment was in the .edf file in the time domain. The raw data was then segmented and labeled based on the recording periods. "Resting eyes closed" and "Resting eyes opened" were the labels assigned to the first 30 seconds eyes closed and 30 seconds eyes opened conditions, respectively. "Q1", "Q2", and "Q3" were the labels for the state when the participant answered each question. The time for each question is taken from 1 second before participants answered up to 1 second after participants answered. Finally, "Relaxation" was the label for the 30 seconds relaxation

period. The results were labeled based on the device: M-EEG for the results from medical-grade EEG recordings and C-EEG for the results from consumer-grade EEG recordings.

Data Processing and Analysis

The data acquired from the EEG recordings were pre-processed by data centering and filtering. The data-centering process was carried out by converting changes in the data to the average value into relative changes to the null value. Thus, if the data has changed above the average value, the changes were considered positive. Meanwhile, the changes were considered negative if the data changed below the average value. After the data centering, data were filtered within the alpha frequency range. The alpha wave frequency range was selected because the subject was conditioned to relax during the recording. Bandpass filtering procedure was conducted to the signal on the range of 8 Hz to 13 Hz. Brain wave alpha frequency is 8-13 Hz, so 8 Hz and 13 Hz were used as the low and high cutoff values, respectively [12]. This resulted in the EEG signal only without blinks (mostly below 0.5 Hz). This filtering process was also beneficial for removing noise caused by signal drift and electric interference.

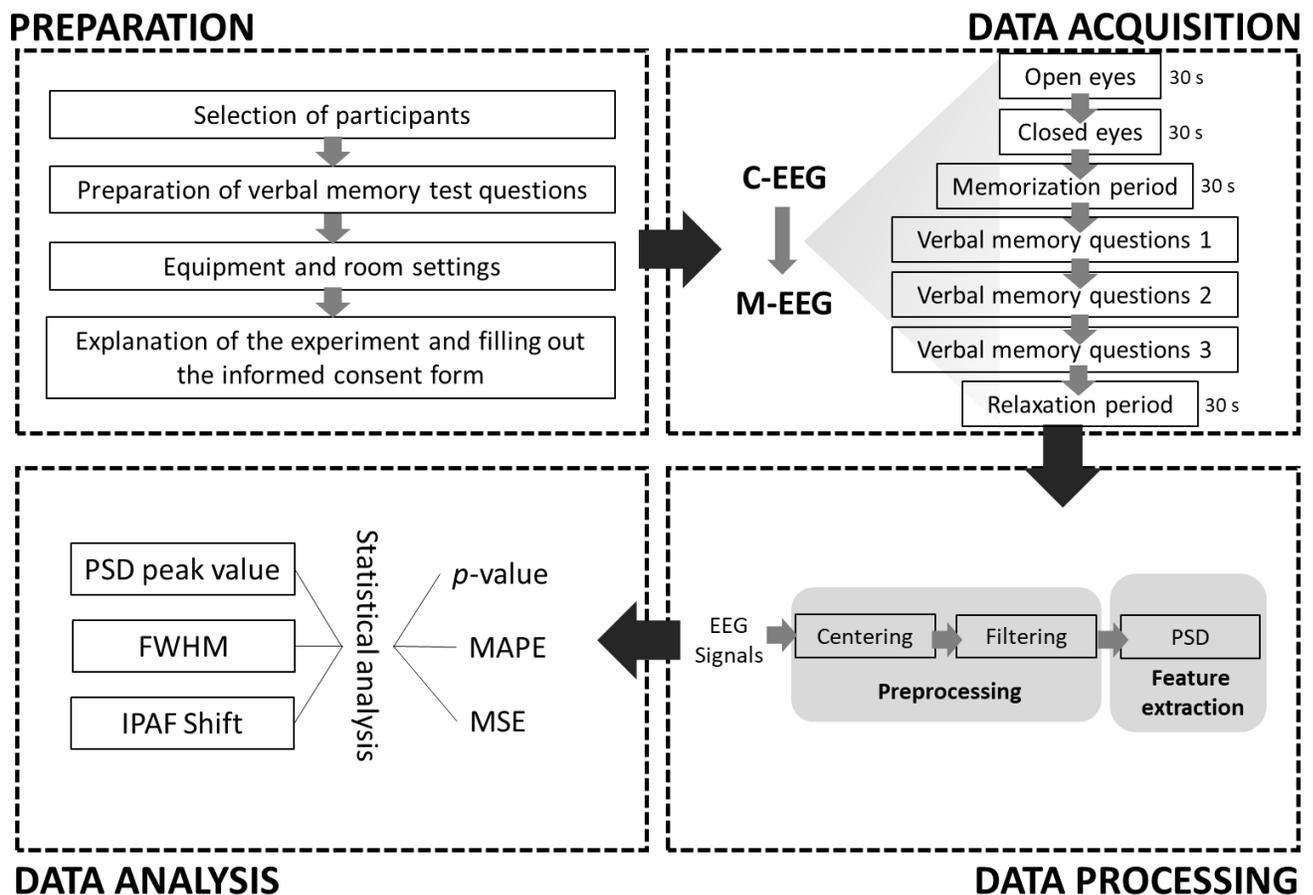


Figure 3. The overall experimental design of the study is divided into four major parts: preparation, data acquisition, data processing, and data analysis.

After the data goes through pre-processing, there is one parameter that can be calculated, namely the signal to noise ratio (SNR). SNR can be defined as the size or level of the desired signal compared to its noise. In the case of using EEG, the highest possible SNR is expected to be obtained because the noise is in the same voltage range as the desired signal.

From the data that had gone through the pre-process, power spectral density (PSD) was estimated using the Welch method. The primary procedure from this method is dividing the signal in the time domain into several segments that overlap at the ends. The segmented signals are then computed using discrete

Fourier transform (DFT) or fast Fourier transform (FFT). Each of the conversion results was averaged [13]. For every data $x(n)$, the Welch periodogram at every frequency f , with a sampling rate of f_s , can be written as

$$P_k(f) = \frac{1}{LU} \left| \sum_{n=0}^{L-1} x_k(n)w(n)e^{-i2\pi\frac{f}{f_s}n} \right|^2, \quad k = 0, 1, \dots, K \quad (1)$$

with L as the amount of data, K as the number of segments, $w(n)$ as data segmentation (known as the window) used, and $U(f)$ as a normalization factor

$$U = \frac{1}{L} \sum_{n=0}^{L-1} w^2(n) \quad (2)$$

For the data segmentation, the windowing process using Hamming window was done for every electrode. Hamming window is expressed as

$$w(n) = 0.54 - 0.46 \cos \left[\left(\frac{2\pi}{L-1} \right) n \right] \quad (3)$$

with L is the amount of data initially in time series, and $n = 1, 2, \dots, N - 1$ [8].

The output of the Welch method is then the average of the periodogram in equation (1),

$$P_{xx}(f) = \frac{1}{K} \sum_{k=0}^{K-1} P_k(f) \quad (4)$$

The obtained PSD can then be analysed for various parameters. Several parameters were then measured based on the PSD curve obtained: PSD peak value, PSD full width at half maximum (FWHM), and individual peak alpha frequency (IPAF) shift. The FWHM can be described as the length between two points at the curve when the amplitude is at half maximum [14]. In the context of PSD, FWHM represents the frequency resolution of the PSD curve. The smaller the FWHM of a PSD curve, the higher the frequency resolution. The higher the frequency resolution, the less interference can be captured by the EEG spectra [15].

EEG waves are classified into five frequency bands: delta, theta, alpha, beta, and gamma. These frequency bands usually become dominant depending on the condition and behaviour of individuals [16]. This research only includes the alpha frequency band, as the study only focuses on relaxed conditions and cognitive tests. The most dominant frequency of the EEG wave in the alpha frequency band is known by the term individual peak alpha frequency (IPAF). IPAF is usually associated with individual cognitive performance, like attention and memory [17]. Klimesch's (1993) experiment showed that when personal attention and memory demands increase, the IPAF shifts from its value when the individual is at rest [18]. IPAF can be determined based on the inspection of the PSD curve. When a single spectral peak is found at the alpha frequency band, that frequency peak is then defined as the IPAF.

The results are compared only for electrodes that both devices have (F3, F4, F7, F8, T7, T8, P7, P8, O1, and O2). PSD peak value and PSD FWHM were measured for resting eyes closed and opened conditions. Meanwhile, the IPAF shift was calculated based on the differences (delta) of IPAF in Q1, Q2, Q3, and relaxation to the IPAF in resting eyes closed. The value for every parameter was averaged for every brain lobe; therefore, the values for every parameter for frontal (F3, F4, F7, F8), temporal (T7, T8), parietal (P7, P8), and occipital (O1, O2) lobes were obtained.

As the quantitative comparisons, statistical hypothesis tests and goodness-of-fit tests were done to the values for every parameter from all samples. The student t-test was done on the data, and then the p-values for both systems were obtained. The null hypothesis H_0 used in this experiment assumed that C-EEG was better than M-EEG or equal; meanwhile, the alternate hypothesis H_1 assumed that the quality of C-EEG was below M-EEG. The result from M-EEG and C-EEG are expressed as x_1 and x_2 , respectively, with each average as μ_1 and μ_2 , each standard deviation as σ_1 and σ_2 , and the amount of data as N . The result of the t-test is

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\sigma_1}{N} + \frac{\sigma_2}{N}}} \tag{5}$$

with

$$\sigma_{1,2} = \sqrt{\frac{\sum_{i=1}^N (x_{1,2i} - \mu_{1,2})^2}{N - 1}} \tag{6}$$

From the t-test result, the p-value could then be obtained. The significance level used in this research is 0.05. The goodness-of-fit test done in this experiment was the standard error (SE), mean absolute percentage error (MAPE), and mean squared error (MSE). SE was done to estimate how large the sample average could vary from the population's average. SE is expressed as

$$SE_{1,2} = \frac{\sigma_{1,2}}{\sqrt{N}} \tag{7}$$

MAPE and MSE were done to measure how significant the error from measurements by C-EEG was against M-EEG. MAPE is expressed as

$$MAPE = \frac{100\%}{N} \sum_{i=1}^N \left| \frac{x_{1i} - x_{2i}}{x_{1i}} \right| \tag{8}$$

MAPE is expressed as

$$MSE = \frac{1}{N} \sum_{i=1}^N (x_{1i} - x_{2i})^2 \tag{9}$$

MAPE and MSE were measured for PSD peak value and PSD FWHM. Meanwhile, the IPAF shifts might give a null result, making the MAPE undefined. Therefore, for IPAF shift results, only the MSE value was calculated.

Results and Discussion

Power Spectral Density (PSD) Peak Value

The results for PSD peak value are shown in Figure 4. C-EEG showed an immense PSD peak value at the frontal lobe in resting eyes closed and opened conditions. Statistical tests showed a significant difference in the PSD peak value between both devices at the frontal and temporal lobe. It was shown in Table 2 that the p-value at the frontal and temporal lobe was always lower than the significance level (0.05).

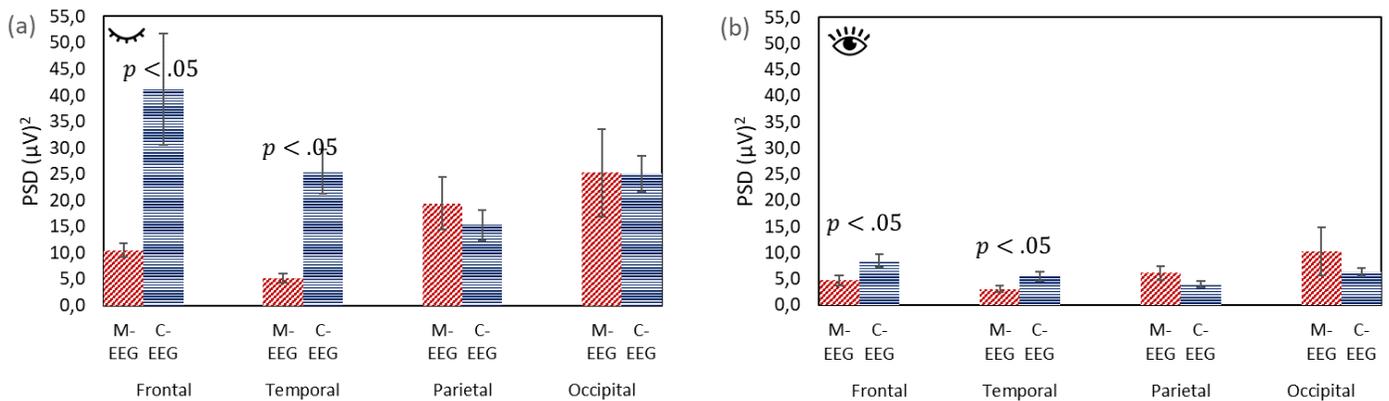


Figure 4. Bar chart for PSD peak value between M-EEG and C-EEG for condition (a) resting eyes closed and (b) resting eyes opened

MAPE and MSE from PSD peak value also appeared to be significant at the frontal and temporal lobes. Although the p-value at the parietal and occipital lobes was larger than the significant level, MAPE and MSE appeared to be large enough. These large MAPE and MSE results indicated a significant difference between both devices per subject expressly.

The significant difference may indicate that C-EEG had a lower signal-to-noise ratio (SNR) than the medical EEG device, as was found by Duvinage in their experiments [6]. The difference in PSD peak value at the frontal and temporal lobe might be caused by external interference that was recorded by the device, specifically electromyography (EMG) signals. Electrodes at the frontal and temporal lobe might result in the recording of signals by the movement of the eyeballs and the eye blinks. This interference was detailed by Goncharova *et al.*, who found EMG signal contaminations at the frontal and temporal area on their EEG data [19]. No significant difference was found in the PSD peak values at the parietal and occipital lobes. However, the PSD peak values in those areas had a large SE. It means that further research using more subjects is needed for better accuracy.

Table 2. The p-value, MAPE, and MSE for PSD peak value between M-EEG and C-EEG

| Parameter | Condition | Brain Lobes | | | |
|-----------|---------------------|-------------|----------|----------|-----------|
| | | Frontal | Temporal | Parietal | Occipital |
| p-value | Resting Eyes Closed | 0.004 | 0.0001 | 0.47 | 0.99 |
| | Resting Eyes Opened | 0.02 | 0.04 | 0.15 | 0.40 |
| MAPE (%) | Resting Eyes Closed | 242.19 | 539.67 | 68.11 | 165.85 |
| | Resting Eyes Opened | 147.44 | 137.36 | 71.99 | 112.90 |
| MSE | Resting Eyes Closed | 1107.79 | 648.86 | 294.35 | 905.08 |
| | Resting Eyes Opened | 30.32 | 17.92 | 19.76 | 330.81 |

Power Spectral Density Full Width at Half Maximum (PSD FWHM)

Figure 5 shows the PSD FWHM for both devices. Table 3 shows the statistical results for p-value, MAPE, and MSE. PSD FWHM from M-EEG measurements tended to be lower than the PSD FWHM from C-EEG measurements, except at the temporal lobe in resting eyes closed condition. The statistical results showed that in the resting eyes closed state, the difference between PSD FWHM from both devices was significant at the frontal and parietal lobes. Meanwhile, the difference was significant at the parietal and occipital lobes in resting eyes opened condition. However, the difference in the eye open state at the frontal lobe became insignificant. The significant difference between both devices showed that C-EEG had a worse frequency resolution than M-EEG.

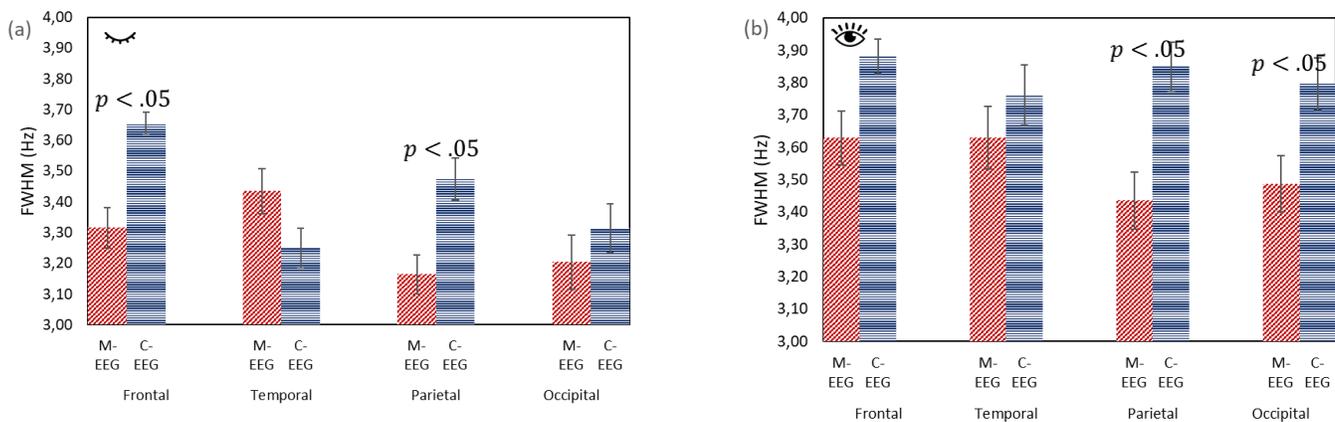


Figure 5. Bar chart for PSD FWHM between M-EEG and C-EEG for condition (a) resting eyes closed and (b) resting eyes opened

The significant differences between PSD FWHM from both devices could be explained using the uncertainty theory in measurement. The theory mentioned that the value of a physical quantity from a measurement result will always have some degree of uncertainty [20]. It means that the value obtained from a measurement will always have an error with a specific value. The larger the error, the more accurate the obtained value. In this case, PSD FWHM became the error from the actual EEG signal frequency. PSD FWHM on C-EEG is bigger than M-EEG. This indicates that the uncertainty in the C-

EEG is greater than that of the M-EEG. This might happen because the sample rate of C-EEG was lower than that of M-EEG. The lower sample rate gave C-EEG fewer data than M-EEG for the same period. It resulted in C-EEG having a worse accuracy than M-EEG.

Table 3. The p-value, MAPE, and MSE for PSD FWHM between M-EEG and C-EEG

| Parameter | Condition | Brain Lobes | | | |
|-----------|---------------------|-------------|----------|----------|-----------|
| | | Frontal | Temporal | Parietal | Occipital |
| p-value | Resting Eyes Closed | 0.01 | 0.07 | 0.002 | 0.37 |
| | Resting Eyes Opened | 0.07 | 0.33 | 0.001 | 0.01 |
| MAPE (%) | Resting Eyes Closed | 7.92 | 8.93 | 10.78 | 9.79 |
| | Resting Eyes Opened | 7.22 | 8.11 | 13.18 | 11.77 |
| MSE | Resting Eyes Closed | 0.08 | 0.15 | 0.17 | 0.19 |
| | Resting Eyes Opened | 0.09 | 0.13 | 0.26 | 0.23 |

Individual Peak Alpha Frequency (IPAF) Shift

As shown by Figure 6, in Q1 and Q3, there were different characteristics in IPAF shifts between C-EEG and M-EEG. Meanwhile, all IPAF shifts were negative in every lobe in Q2 and positive in relaxation. However, the statistical results in Table 4 showed no significant difference between both devices except in relaxation at the frontal.

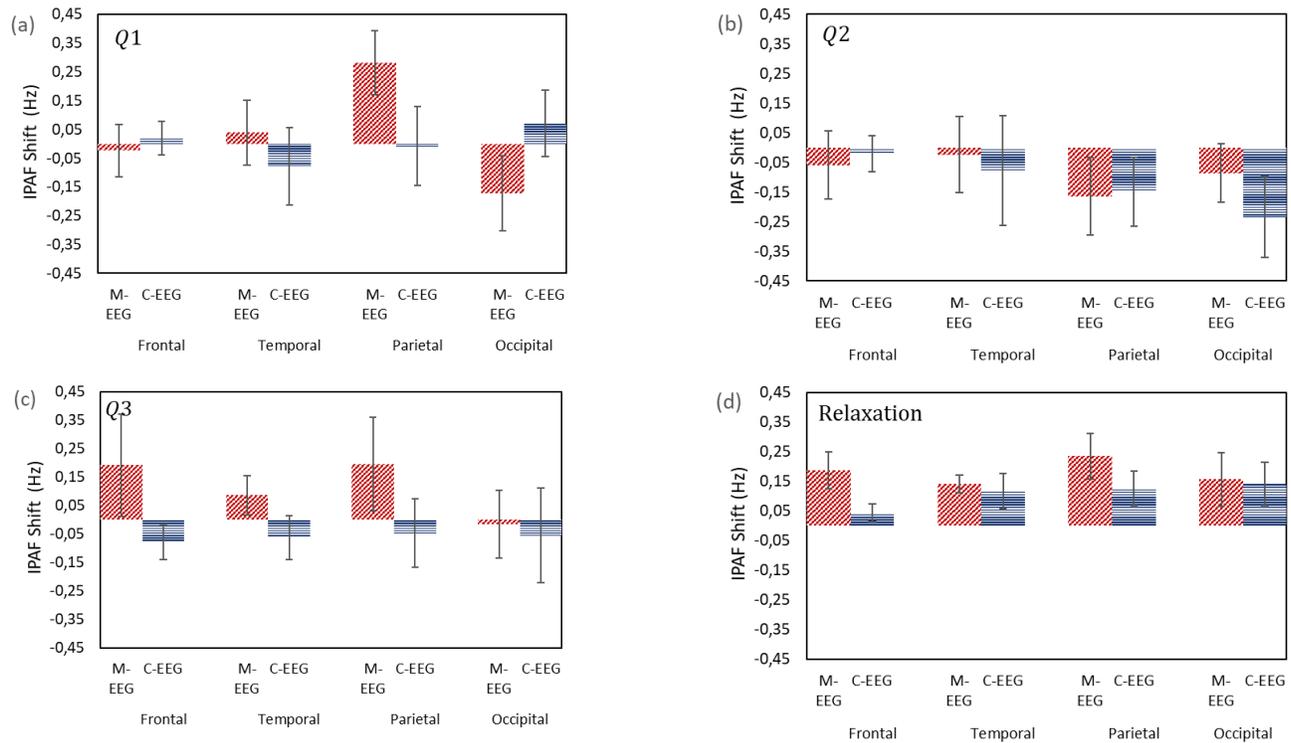


Figure 6. Bar chart for IPAF shift between M-EEG and C-EEG in conditions (a) Q1, (b) Q2, (c) Q3, and (d) Relaxation

The results that showed no significant difference in IPAF shifts indicated that C-EEG could detect the shifts well. This result was consistent with other research findings that C-EEG could record changes in electrical activity regarding memory demands [21,22]. Klimesch *et al.* mentioned that IPAF tends to decrease (negative) or not change when subjects do memory activities, depending on subjects' performance [18]. Subjects with poor performance tend to have their IPAF decrease when doing memory tests, but subjects with good performance tend not to have any IPAF changes. There could be no separation between subjects based on their memory performance in this experiment. Klimesch *et al.* also mentioned that attention demands also contribute to the increase of IPAF. This might explain how some subjects had their IPAF increased. Another factor that might influence the increase in IPAF was the form of the examination that was conducted. During the exam, subjects read the question that was

displayed. Based on the research by Angelakis and Lubar, IPAF tends to increase after subjects are reading [23]. The finding of this experiment showed that it is necessary to do another form of cognitive test, besides memory test, as an assessment for IPAF shifts. Should a memory test still be conducted, it is advised first to assess subjects' performance on the memory test.

Table 4. The *p*-value and MSE for IPAF shift between M-EEG and C-EEG.

| Parameter | Treatment | Brain lobes | | | |
|-----------------|----------------------------------|-------------|----------|----------|-----------|
| | | Frontal | Temporal | Parietal | Occipital |
| <i>p</i> -value | Q1- Resting Eyes Opened | 0.68 | 0.51 | 0.11 | 0.18 |
| | Q2- Resting Eyes Opened | 0.82 | 0.81 | 0.93 | 0.39 |
| | Q3- Resting Eyes Opened | 0.15 | 0.16 | 0.24 | 0.85 |
| | Relaxation - Resting Eyes Opened | 0.09 | 0.73 | 0.26 | 0.89 |
| MSE | Q1- Resting Eyes Opened | 0.27 | 0.23 | 0.48 | 0.49 |
| | Q2- Resting Eyes Opened | 0.15 | 0.66 | 0.31 | 0.56 |
| | Q3- Resting Eyes Opened | 0.57 | 0.18 | 0.76 | 0.68 |
| | Relaxation - Resting Eyes Opened | 0.08 | 0.04 | 0.13 | 0.14 |

The comparison of results described above does not apply generally to all types of EEG, both medical and consumer-grade. The above results only apply to EEG with the specifications given in Table 1. and on measurements for healthy male subjects. Another thing to note is that this study was limited to measurements for healthy male subjects. This study has not discussed comparisons for measurements in cases of disorders or diseases.

Conclusions

A study has been carried out to see whether there is a difference in the results of alpha signal analysis between measurements using consumer and medical grade EEG. This research was done specifically for healthy male subjects. It was found that in resting eyes closed and opened conditions, the differences in PSD peak between both devices were significant at two brain lobes. C-EEG results were 147.44 – 5262.62 % lower than M-EEG results in the frontal area. Also, C-EEG results were 137.36 – 539.67 % lower on the temporal area than M-EEG results. In resting, eyes closed condition, significant differences in PSD FWHM between both devices at frontal (C-EEG had 7.92 – 11.13 % lower results than M-EEG) and parietal (C-EEG had 10.78% lower results than M-EEG) lobes. In resting eyes opened condition, significant differences were found in PSD FWHM between both devices in some areas. At the frontal area, C-EEG had 8.22% lower results than M-EEG. At the parietal area, C-EEG had 13.18% lower results than M-EEG. At the occipital area, C-EEG had 11.77% lower results than M-EEG. Based on the cognitive test results, there was no significant difference in IPAF shifts, except at the frontal lobe (MSE 0.08).

Based on the results of IPAF shifts, it was concluded that C-EEG could read EEG signals against time well, even though this tool is not certified for clinical use. However, PSD FWHM shows that the quality of EEG signal reading from C-EEG is not as good as M-EEG. Based on the PSD peak values and PSD FWHM, it was also concluded that C-EEG could not read EEG signal amplitudes and M-EEG devices (with 24.20 – 50.30% differences). It is advised for further research to acquire data from more subjects and to group cognitive test subjects based on their memory performance.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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