Characterization of Individual Alpha Frequency of EEG Signals as an Indicator of Cognitive Fatigue

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Abstract. Cognitive fatigue is a condition caused by monotonous work which involves cognitive function in a long period that influences performance impairment. One of the methods to detect cognitive fatigue is using Individual Alpha Frequency (IAF) of brain waves which was obtained from an electroencephalography (EEG) measurement. This study aimed to calculate IAF values using power spectral density (PSD) as an indicator of cognitive fatigue in the frontal, parietal, and occipital lobes which used a cognitive task as the stimulus. The EEG was measured by using Cadwell Easy\textsuperscript{R} III with a sampling frequency of 250 Hz and the electrode impedance maintained below 20 kΩ. Electrodes on F3, F4, F7, F8, Fz, P3, P4, O1, and O2 were investigated in this study. The data acquisition was conducted in 46 minutes: 3 minutes before, 40 minutes during, and 3 minutes after carrying out the arithmetic test as a cognitive task. The arithmetic test was displayed through the visual display terminal (VDT). In the next stage, the pre-processing was conducted to remove noise and artifacts, followed by PSD calculation using the Welch periodogram. Finally, the values of IAF were calculated by using the Center of Gravity (CoG). The results showed that PSD in all session sorted by the largest values are delta, theta, and alpha wave. As for the IAF pre-task values shifted towards larger alpha frequency in the post-task in frontal and parietal region, showed in vigilance with increasing time spent on task, and shifted towards smaller values in occipital region which fatigue begins to occur in this region and has not occurred in other region.

1. Introduction

Fatigue is a condition of reduced ability and effectiveness of someone in carrying out an activity [1]. Mental fatigue, also known as cognitive fatigue, must be a serious concern because it can cause errors, decrease performance in carrying out daily tasks, lose efficiency and the desire to do something, and cause accidents [1,2]. One way that can be used to bring about fatigue is to use a stimulus in the form of cognitive tasks. In this study participants will be given a cognitive task as a stimulus in the form of a simple arithmetic mental test that is displayed on the visual display terminal (VDT). EEG measurements are carried out at the time before, when, and after doing arithmetic tests in the condition of the eyes open.

Fatigue and cognitive conditions can be measured using psychometric measurement methods consisting of qualitative and quantitative methods. One way is to use quantitative methods, namely by quantifying the effects of fatigue and cognitive performance after being given a stimulus in the form of simple arithmetic problems by measuring the electrical activity of the brain using electroencephalography (EEG). EEG is a tool used to measure the electrical activity...
of the brain, where the measured signal is expressed in terms of the amount of potential difference over time. This signal can be transformed into the frequency domain using power spectral density (PSD) estimation to review its spectral information, especially in research related to cognitive function and fatigue. Another amount that can be sought from PSD is Individual Alpha Frequency (IAF). IAF is a spectral component of alpha frequency (range 7.5 - 12.5 Hz) which is associated as a marker of arousal, attention, and cognitive performance [3,7]. IAF can be used as a stable neurophysiological marker and to detect physical fatigue [5,6]. Increased alpha rhythm is associated with a decrease in the level of alertness and attention as an early indicator of fatigue. IAF value decreased in respondents who experienced physical fatigue [6]. In addition, IAF values shift fluctuatively when a person engages in activities that involve cognitive function [4]. This research aims to calculate the PSD and IAF from EEG signals with a stimulus in the form of simple arithmetic mental problems.

2. Methods

2.1. Data Acquisition

EEG data were recorded from 9 men (19-23 years) who were university students for 46 minutes: 3 minutes before, 40 minutes during, and 3 minutes after performing cognitive tasks. The EEG instrument used was Cadwell Easy III 19 channel placed on the scalp using an international EEG placement principle 10-20 scheme with a montage of ipsilateral ear references. The electrode investigated in this study was in frontal (F3, F4, F7, F8, Fz), parietal (P3 and P4), and occipital lobes (O1 and O2). The sampling frequency and the maximum electrode impedance were 250 Hz and 20 kΩ, respectively.

The cognitive task used as a stimulus was simple mental arithmetic as much of 2000 questions. Subjects were conditioned to sit comfortably and answer the questions correctly as much as possible within 40 minutes. The questions are displayed in the visual display terminal or VDT using the random number function in a spreadsheet. The questions that appear next will adjust the last digit inputted by the subject in the answer column. True or false indicators and timekeeping will be included so that the subject would answer the questions correctly, and the working time can be synchronized with the EEG recording time.

![Figure 1: Figure 3: (A) Position of electrodes using the principle 10-20, and (B) Scheme of subject position during working on cognitive tasks](image)

2.2. Signal Pre-Processing Stage

Signals acquired from EEG measurements then enter the pre-processing stage to remove them from noise and artifacts. Noise is removed using a bandpass filter. This technique will only pass
the signals at certain frequencies, where in this study the expected frequencies are in the range of 0.5 - 35 Hz (delta to gamma). The tool used in this process is to use the function filter on the EEGLAB toolbox. The artifacts were removed using independent component analysis or ICA. This technique will separate brain signals from other signals, using the help of an automatic algorithm, *Automatic EEG artifact Detector based on the Joint Use of Spatial and Temporal features* or ADJUST [9]. The working principle of ADJUST is to eliminate other signals based on statistical parameters for four types of artifacts, which are eye blink, vertical eye movement, horizontal eye movement, and generic discontinuity.

![Figure 2](image1.png)

**Figure 2:** Figure 3: Example of the results of pre-processing stage. (A) Raw signals contains noise and artefacts, (B) Bandpass filter applied on signals, (C) ICA applied on filtered signals

### 2.3. Signal Processing Stage

At this stage, the signal that has entered the pre-processing stage would be calculated its PSD and IAF value.

PSD is a quantity that states the distribution of power contained in a signal to its frequency. Assume we have a finite discrete signal \( x[n] \) with \( n = 1, 2, ..., N \), in the interval \( \delta t \). The equation for transforming the signal in the time domain into the frequency domain uses the DFT equation:

\[
X[k] = \sum_{n=0}^{N-1} x[n]w[m]e^{-2j\pi kn/N} \tag{1}
\]

where:

- \( X[k] \) = discrete signals (µV) in frequency domain (Hz)
- \( x[n] \) = discrete signals (µV) in time domain (s)
- \( N \) = amount of data
- \( k \) = discrete constants 0, 1, ..., \( N - 1 \)
- \( w[m] \) = Hann window function, \( w[m] = 0.5[1 - \cos(\frac{2\pi m}{N})] \)

PSD estimates can be found by directly squaring the DFT value. This method still has disadvantages, particularly related to a large amount of data so that will produce a biased value. Therefore we used a method called Periodogram Welch. The principles were divided data
into segments, applied overlapped segments, and averaged it afterward. The Welch Periodogram was:

\[
S_{xx} = \frac{1}{K} \sum_{k=1}^{K} P_k
\]  

where:

- \(S_{xx}\) = Welch Periodogram (\(\mu V^2\))
- \(K\) = number of overlapped segments
- \(P_k\) = Periodogram, \(P_k = \frac{1}{W} |X_k|^2\)

Individual Alpha Frequency (IAF) is the maximum alpha power value in EEG waves that are in the range of 7.5 - 12.5 Hz [3], and is often used as a marker of a person’s neurophysiological traits and cognitive capacity. One IAF calculation method uses the CoG method which is also called the frequency average method:

\[
IAF = \frac{\sum (a_f \times f)}{\sum a_f}
\]

where:

- \(a_f\) = amplitude of frequency \(f\) (\(\mu V^2\))
- \(f\) = Frequency between 7.5 and 12.5 (Hz)

IAF values obtained from several previous studies in the range of 9.5-11.5 Hz in healthy young adults related to memory performance [7].

![Figure 3](image-url)

**Figure 3**: Illustration of processing stage. (A) Example of EEG signals on P3 electrode that has been pre-processed, (B) Welch periodogram with Hann window, and (C) Alpha wave to calculate its IAF value using CoG method

### 3. Results and Discussion

#### 3.1. Pre and Post Tasks

IAF results for most electrodes show a shift towards a greater frequency, except for the O1 and O2 electrodes whose values shift to smaller values. In the frontal section, IAF values tend to have uniform values. IAF values that increase in postconditions indicate the existence of activities
that involve cognitive processes, according to the findings of Angelakis, et al., [1]. The level of vigilance of a person continues to increase along with the increase in cognitive tasks carried out. The biggest IAF value shift occurred at the Fz electrode which is 0.279 Hz.

3.2. During Cognitive Tasks
In Figure 5, IAF were analyzed for electrode of F3, P3, and O1. The data for 40 minutes is sliced every 4 minutes into 10 parts. This sliced stage is intended to review changes in PSD and IAF values in a short period of time.

At the F3 electrode (Figure 5(a)), the IAF value continued to decrease until it touched the lowest number in the 16th minute, with an IAF value of $8.70 \pm 2.92$ Hz and PSD $1.90 \pm 0.76 \, (\mu V)^2$. After that, the IAF value continues to shift toward large values over time. The biggest IAF value in the 36th minute is $10.14 \pm 0.62$ Hz with a PSD value of $1.93 \pm 0.82 \, (\mu V)^2$.

As for the P3 electrodes (Figure 5 (b)), the IAF value decreased until the 12th minute, then shifted towards a large value up to the 36th minute, and experienced a sharp decrease in the 40th minute, which was $8.63 \pm 2.87$ Hz with PSD of $2.53 \pm 0.88 \, (mV)^2$. The biggest IAF value in the 4th minute was $9.84 \pm 0.56$ Hz with a PSD value of $2.07 \pm 0.92 \, (\mu V)^2$.

In addition, on the O1 electrode (Figure 5 (c)), the IAF value continues to shift towards a large value with increasing time. The largest IAF value in the 32nd minute was $9.90 \pm 0.63$ Hz with a PSD value of $3.38 \pm 0.85 \, (\mu V)^2$.

All charts show a similar pattern, where the IAF shifts to a greater frequency value with an increased PSD than Pre and Post conditions. When working on cognitive tasks, IAF shift towards the largest frequency values in the 20-32 minute time range, then it shift towards a smaller frequency afterwards for most electrodes.

4. Conclusion
IAF can be used as an indicator of cognitive activity. In this study, it ranged from 9-11 Hz, and its shifts towards a large frequency range, along with the enlarged PSD value. It also shows that the subject is in a high cognitive activity condition but has not reached fatigued.
Figure 5: (A) Position of electrodes using the principle 10-20, (B) Scheme of subject position during working on cognitive tasks, and (C) Example of the results of pre-processing stage

Acknowledgments
This study fully supported by P3MI KK NukBio ITB 1000H/i1.C01/PL/2019 and PTUPT 2/E1/KP.PTNBH/2019

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