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EEG ELECTRODE LOCALIZATION FOR READING-WRITING NEUROPATHWAY: SPECTRAL ANALYSIS APPROACH

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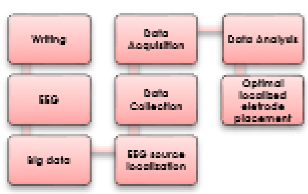
Graphical abstract



Abstract

Writing is a survival skill in schools and many children are reported to have suffered from writing disorder. Emerging technology enables this disorder detectable through monitoring of EEG signals. However, in working with EEG, the lack of methodological approach would lead to gargantuan of data and thus wastage in resources and time. Furthermore, placing of a large number of electrodes on the recording cap will cause discomfort to the subject, with data being more liable to false readings and artifacts. Recognizing the number of electrodes through proper localization plays a fundamental role in improving the overall performance of an EEG acquisition system, thus the objective of this research. This study involves the following phases: Data Collection, Data Acquisition and Data Analysis. Target population are normal and healthy subjects of age between 18 and 25. The EEG signals are recorded with electrodes at activation areas along the documented signal pathway of the brain (C3, C4, P3, P4, O1, O2, T7, FC5) during reading and writing. Fast Fourier Transform (FFT) is applied to transform the EEG in time domain into frequency domain so that signature features in frequency content during relaxation and sentence writing can be extracted. Results showed that relaxation drew on one dominant peak and the frequency content resides in the alpha sub-band while writing activity drew on two dominant peaks, one in alpha and the other in beta sub-band. The frequency range of EEG recorded during relaxation is 8-13 Hz while that during writing is 13-29 Hz, well within the alpha and beta sub-band for the different neuro-activity accordingly. Hence, it can be concluded from experimental results and findings from previous works that electrodes C3/C4, P3/P4, O1/O2, T7 and FC5 are suitable as optimal localized EEG electrode placement for neuro-pathway for reading-writing.

Keywords: Electroencephalogram (EEG), writing, spectral analysis

1.0 INTRODUCTION

Acquiring knowledge through reading is crucial in the development of a child, along with writing; it makes up the essential skills required for a child to progress through their schooling years. There is a neurological disorder that can affect children to properly read, write and spell [1]. Defined as a specific learning disorder by the U.S National Institute of Health, ignorance of it often leads to people believing that these children are slow learner or mentally retarded, an allegation that is popular but totally misleading. A pilot study conducted (year 2000) in a representative primary school of 2,000 pupils near Kuala Lumpur indicated that 7% of pupils at Standard 2 had marked phonological reading difficulties that are related with writing deficit [2]. In 2012, statistical studied from Ministry of Education, Malaysia, revealed 5% or 265,210 of total population 5,304,201 Malaysian students are diagnosed to have writing disorder [3], [4].

It is therefore important to detect writing disorder at an early stage, for an effective therapy. Currently, the gold standard for assessing writing related disorder is based on psychometric method, i.e. subjective observation through questionnaires [4], [5]. The outcomes are heavily reliant on the subjective talent or intuition of the skilled therapist.

Understanding the physiology of how a brain works during writing would provide researchers and practitioners with a better prognosis on the issue of writing disorder. This information is made available through monitoring of electroencephalography (EEG) signals and imaging of the brain through Positron Emission Topography (PET) and Magnetic Resonance Imaging (MRI). Of these methods, EEG is extensively used and better grounded in recording electrical activity produced by the neuronal activity from the scalp surface. Findings from it have substantially contributed to the understanding of brain processes and its function in cognitive tasks [6]–[11], therapeutic effect [12], diagnosis [13] and rehabilitation [14]. It is a non-invasive brain wave acquisition method, cost-effective, portable and can produce high temporal resolution in comparing to other neuro-imaging tools [15]. PET relies on blood flow with exposure to radioactive injection, while accuracy of fMRI is impacted by head motion which severely degrades the measured signal. As such, these two methods are not suitable for children [16]. In addition, the cost of PET and fMRI are expensive and being supine, is not practical for writing task, monitoring and neurofeedback.

EEG has been used to capture signals from the brain to investigate its functional behavior since 19th century. Previous workers reporting on the use of EEG in reading and writing deficit used a large number of electrodes [17]–[20] and bipolar connection[21]–[24]. The same goes to other brain disorders such as autism [25], epilepsy [26] and ADHD [27], [28]. To our knowledge, no report on localization of EEG electrode placement during reading and writing is yet found.

In working with EEG, the pool of data is gargantuan if optimal localization is not identified. Reading through a full set of EEG data from 74 or 128 channels is time consuming and takes up a lot of computing resources. It will also create discomfort to the subjects, especially children of 6 to 12 years old, and hence bring in artifacts that corrupt the EEG signal.

Our study here intends to acquire the frequency content based EEG activities of normal subjects to make recommendation on a reduced set of EEG electrode for reading-writing. Based on previous studies, signatures in frequency content of the EEG signals will be examined. The approach will constitute an objective method to determine an optimal set of EEG electrode placement along the neuro-pathway for reading-writing. First, theories to transform EEG signals from time domain at recording to frequency domain are elaborated. Then, the demographic information on subject population, experimental setup, data acquisition, pre-processing and feature extraction are presented in the Methodology Section. Finally, features processed and extracted by Fast Fourier Transform (FFT) during relaxation and sentence writing are discussed.

2.0 THEORY

2.1 Neuro-pathway Representation of Reading and Writing

With reference to Figure 1, three stages are involved in the process of reading-writing. First is the pictorial stage, a momentary period where learner "photograph" a few words. The pictorial stage activates visual cortex region in the Occipital lobe where human perceives 80 percent information by eye from the external and acts as a visual processing. Second is the phonological stage, where they learn to decode graphemes into phonemes. The Angular gyrus area located at Parietal lobe is stimulated to initiate early stage of word interpretation that converts visual stimulus into its linguistic meaning.

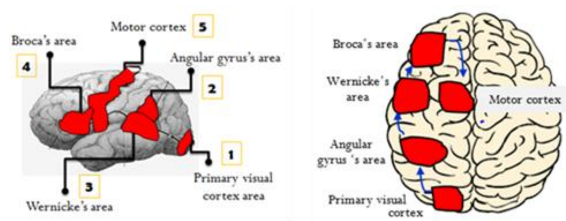


Figure 1 Neuro-pathway for reading-writing for a normal learner, in lateral view (left), and top view (right)

Third is the orthographic stage, where word recognition becomes fast, automatic and well-arranged, by activating the Wernicke's area, which involves language comprehension and sited at the Temporal lobe. The hippocampus located in the same lobe is heavily associated with the formation of memories. This stage also encompasses Broca's area in the Frontal lobes which organized the motor behaviour crucial for smooth writing [17], [29], [30].

At the writing stage, the motor sensory region is involved. Seitz *et al.* [16] deliberates that motor and premotor cortical areas of sensory processing, including the superior parietal cortex, were activated, in relation to the left inferior frontal gyrus and left inferior parietal cortex. Notably, for normal learner, all the information transferred mainly involved in left hemisphere of the brain.

2.2 EEG Source Localization

Localization of active sources of brain is named as EEG source localization. The EEG source localization provides information for the study on physiological, mental and functional abnormalities of brain. The localization in selective electrode placement can improve the overall performance of an EEG acquisition system.

Recent task-based EEG studies, using actual or imaginary wrist movement through joystick, provide promising evidence of classifying real movements associated to the analysis of EEG recorded from only electrode C3 [31], [32]. Another EEG study investigates the involvement of electrode C3/C4 (left/Right sensorimotor cortex) and P3/P4 (left/Right parietal of angular gyrus area), during actual and imagining writing on normal healthy control [33]. In detecting attentive reading, data from eight pair of electrodes includes: Fp1, F3, C3, P3, T5, O1, Fp2, F4, C4, P4, F7, T7, F8, T4, T6 and O2 were acquired and classified using KNN classifier [16]. Another pilot study approached attentiveness during reading using 15 channels (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4) and revealed significant features with band power algorithm [34]. Walker *et al.* [4] reviewed previous studies involving T7 for neurofeedback training based on cortical stimulation in normal reading comprehension. Stimulation of reading speed and comprehension is developed by increasing Beta activity of 16-18 Hz at left mid-temporal area (T7). Other studies found a linear increase in Beta activity at T7 in reading difficulty, showed that this area is highly associated with reading comprehension [35]. Recent study on event related potential (ERPs) on engagement of frontal lobe (F3, Fz, and F4) in reading in English found that semantic judgment was strongly concentrated at the frontal cortex [36]. The use of FC5 and FC6 are reported in [37] in recognizing reading pattern of different document analysis. Klimesch *et al.* [38] made use of electrodes P3, CP5, FC5 and O1 in investigating attentional area during words and pseudo words reading in healthy control and dyslexic subjects approaching EEG methods. Results shown that children with dyslexia corresponds to lower alpha on right hemispheric sites while strong Beta produced at FC5 (articulation, organization); CP5 and P3 (understanding semantic) in controls.

2.3 Fast Fourier Transform (FFT)

Joseph Fourier discovered frequency analysis of Fourier transform in his work *On the Propagation of Heat in Solid Bodies* in early 1807 [39], [40]. He introduced a Fourier transform (FT), a combination of sine and cosine waves into superposition, in his effort to solve the heat equation. Outcome from these two waves produce a time domain signal. A time domain signal can be transformed into its frequencies through a Fourier transform and vice versa, with equation (1.0) and (1.1).

$$F(w) = \int_{-\infty}^{\infty} f(t) e^{-jwt} dt \tag{1.0}$$

$$f(t) = \int_{-\infty}^{\infty} F(w) e^{jwt} dw \tag{1.1}$$

Later, in 1965, Cooley-Tukey presented a new algorithm named Fast Fourier Transform or FFT [41], [42]. FFT is devised from a revolutionary technique for computation of the Fourier transform, known as a Discrete Fourier Transform (DFT). General equation of DFT is given by (1.2):

$$F(n) = \sum_{k=0}^{N-1} x(k).e^{\frac{-j2\pi kn}{N}} \tag{1.2}$$

where, *F(n)* is the amplitude at frequency; *n* and *N* represents the number of discrete samples taken, *x(k)* is the time wave that is converted into a frequency spectrum by the DFT and the exponential term is known as the ‘twiddle factor’.

Benefit of FFT algorithm includes speeding up calculation of DFT, which is used to transform a continuous time signal into frequency domain and required $N \log_2 N$ operations. $N \log_2 N$ is when N is a power of 2. Hence, a FFT of length $N=2^m$ can be reduced to mN=2 FFTs of length 2.

Five steps are required to compute the FFT, starting with the DFT (1.2). By substituting the exponential term (1.3) into (1.2), the DFT equation is now become (1.4):

$$W_N^{kn} = e^{\frac{-j2\pi kn}{N}} \tag{1.3}$$

$$F(n) = \sum_{k=0}^{N-1} x(k).W_N^{kn} \tag{1.4}$$

The second step is to apply Danielson-Lanczos Lemma theory, which split the idea of Cooley-Tukey FFT into even and odd terms. The equation now becomes:

$$F(n) = \sum_{k=0}^{N-1} x(k).W_N^{kn} = E + O \tag{1.5}$$

However, the expansion of Danielson-Lanczcos Lemma can be improved with Euler’s formula (1.6), which makes the calculation easier.

$$W_N^{kn} = \cos\left(\frac{-j2\pi kn}{N}\right) + j\sin\left(\frac{-j2\pi kn}{N}\right) \tag{1.6}$$

where $k*n$ = 0 to N-1, for N=2, $k*n$ = 0 to 1. Alternatively, the expansion of Danielson-Lanczcos Lemma can be proven by using the exponential term of Twiddle factor. This factor describes a rotating vector, which rotates in increments according to the number of samples, N. The Twiddle Factor is then combined with the Danielson-Lanczcos Lemma to produce the Butterfly Diagram. The symmetrical summation and differentiation of DFT calculation involving exponential is then determined for every two points and two frequencies as follows,

$$F(0) = x(0) + W_2^0 .\ x(1) \quad (1.7)$$

$$F(1) = x(0) - W_2^0 .\ x(1) \quad (1.8)$$

3.0 METHODOLOGY

3.1 Data Acquisition Instrumentation

EEG data acquisition instrumentation was setup by connecting the highly flexible supernarrow seams cap, g.GAMMAcap to the Ag/AgCl of g.GAMMAsys active electrode system. The highly conductive and viscous g.GAMMAgel was applied to electrodes attached on 12-mm openings of the g.GAMMAcap. This step is essential to ensure low electrode skin impedance. A driver box named g.GAMMAbox was connected to the g.MOBIlab+ and acquired EEG signal wirelessly via Bluetooth 2.0 to a personal computer. g.MOBIlab+ integrated the EEG signal into real-time system via SIMULINK named g.HIsys.

3.2 Subject Population and Experimental Setup

EEG signals of 49 healthy volunteers (21 males and 28 females), aged between 22 and 25 years, were recorded. All the subjects are right-handed. Exclusion criteria include any neurological disability, brain injury, psychiatric symptoms, family history of genetic disorder and the use of psychoactive medications at the time of EEG recordings. Approval from local institutional ethics and written informed consent signed by participant have been obtained.

For acquisition of EEG signals, eight electrodes were used (see Figure 2) according to the extended International 10-20 system [43]. Fpz and right mastoid were selected as ground and reference respectively. The signals were sampled at 256 Hz by means of a single portable biosignal amplifier.

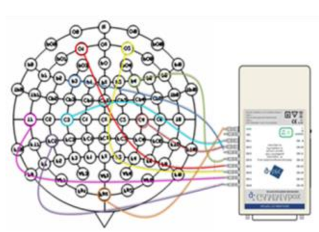


Figure 2 Locations of the electrode on the 74 channels of g.GAMMAcap2 with eight monopolar channels connected to g.GAMMAbox

3.3 Design of Task

In this study, six experimental tasks were designed. This paper presents only findings from Task 1 and Task 2.

For Task 1, subjects were seated on a chair comfortably and reminded to avoid any head movement during recording. Then, instrumental music was played throughout a recording session of 120s with eyes closed.

Task 2 dictates the subjects to read and write sentences prepared in three foreign languages; Spanish, German and French. All the words were displayed in sentence case on a computer screen. Then, the subjects were asked to copy those sentences onto a sheet of paper. The recording period is 120s per passage, with 20 seconds of relaxation in between tasks, in order to prevent fatigue. Video recording was made to aid in determining the exact start and stop time of task.

3.4 Data Analysis

EEG data acquired from C3, C4, P3, P4, O1, O2, T7 and F5 were pre-processed in order to reduce muscular and ocular artifacts. Initially, raw EEG data were visually inspected for artifacts from electro-myogram (EMG) having frequency between 50-3000Hz and electro-oculogram (EOG) having frequency between 0.1-10Hz [44]. The artifacts were first filtered and excluded using a bandpass FIR filter with frequency of interest between 8 to 30Hz. Subsequently, EEG data were analyzed using the frequency domain FFT as described in Section 2.3. Both analysis programs were implemented in MATLAB.

4.0 RESULTS AND DISCUSSIONS

This section discusses the results from EEG recording during relaxation state with eyes closed and writing state.

4.1 EEG Signals during Relaxation

Figure 3a and 3b show the raw EEG signal during relaxation and its filtered version respectively, while Figure 4 shows the frequency spectrum of the filtered signals, at C3 electrode only. Due to constraint of space, results from all other electrodes are summarized in Table 1.

It is observed that the amplitude scales the highest at lower alpha activity of frequency spectrum, signifying prevailing frequency component of neuro-activity during relaxation. This fact evidences that alpha rhythm is more ample and the subject is at rest and the underlying cortex is found to be sedentary[15], [45], [46].

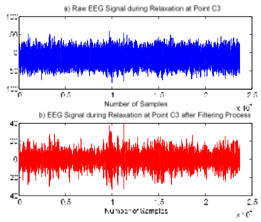


Figure 3 (a) EEG at relaxation stage (b) EEG at relaxation stage after band-pass filtering

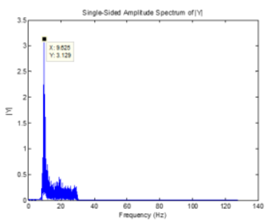


Figure 4 Filtered EEG spectrum during relaxation at point C

With reference to Table 1, it can be observed that the frequency of peaks falls within the range of 8-13Hz, the alpha sub-band for relaxation [15], [21].

In comparing paired electrodes; C3 with C4, P3 with P4, and O1 with O2, it is found that electrodes associated with the left hemisphere of the brain (C3, P3 and O1) generates EEG spectrum of higher amplitude than those on the right (C4, P4 and O2). This implies the brain of normal subjects engaged more on the left hemisphere compared to the right hemisphere during relaxation. This is found in agreement with findings from Sklar *et al.* [21], where prominent logarithmic plot of spectral is found with the P3-O1 normalized spectrum at 9-14 Hz band. Another work also displays significant activity at P3 when independent component analysis (ICA) is applied to resting-state fMRI data in 10 subjects [47]. Beckmann *et al.* [48] found similar results using the probabilistic independent component analysis (PICA) approach, showing parietal areas lead to severe deficits in spatial attention; electrodes T7 and FC5 equally show similar frequency range of activation on the left hemisphere as electrodes C3, P3, and O1. From a pilot study with 14 normal healthy subjects, Schurz *et al.* [49] found stronger connectivity between left middle temporal gyrus and left inferior frontal gyrus during resting-state fMRI, though with eyes open.

Table 1 Frequency of EEG Signals in Alpha Subband during Relaxation

Electrodes	Male (Hz)	Female (Hz)	Frequency Range (Hz)
C3 (L)	8.73 – 11.25	8.59 – 12.47	8.59-12.47
C4	8.75 – 10.98	8.59 – 12.42	8.59-12.42
P3 (L)	8.75 – 12.72	8.63 – 12.60	8.63-12.72
P4	8.66 – 11.23	8.59 – 12.42	8.59-12.42
O1 (L)	8.75 – 11.93	8.63 – 11.94	8.63-11.93
O2	8.75 – 11.92	8.63 – 11.56	8.63-11.56
T7 (L)	8.61 – 11.25	8.84 – 12.23	8.61-12.23
FC5 (L)	8.73 – 12.05	8.96 – 12.20	8.73-12.20

4.2 EEG Signals during Sentence Writing

Figure 5a and b show the raw EEG signals and the filtered signals during sentence writing at C3, while Figure 6 its frequency spectrum during sentence writing.

The EEG spectrum during writing is found to draw on two dominant peaks, one in the alpha and the other in beta sub-band. The peak in the alpha sub-band is attributed to moments at which the subjects pause during writing while beta sub-band is ascribed to higher neuro-activity during writing. Notably, the EEG spectrum produced during writing adopts a 'crown' shape.

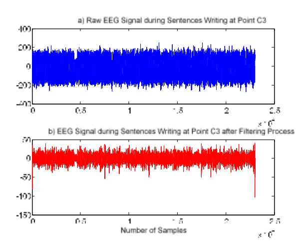


Figure 5 (a) EEG signal during sentence writing (b) EEG signal during sentence writing after band pass filtering

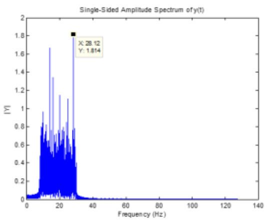


Figure 6 Frequency spectrum of EEG signals during sentences writing at point C3

From Table 2, it can be observed that the frequency range for both male and female normal subjects lie between 13.16 – 28.30 Hz and 13.34 - 29.31 Hz during writing correspondingly. This is coherent with previous studies on frequency of grasping a pen between 9 to 24 Hz [50], writing in the range of 13 to 29 Hz [50] and slow finger movement in ranges of 16 to 21 Hz as recorded by [51].

Electrodes C3, P3 and O1 are found to generate higher EEG frequency in comparison to electrodes C4, P4 and O2. This result is in agreement with the theory that normal subjects are left-lateralized [52]–[54]. The result from C3/C4 electrode for imagined right hand movement showed that the righting motor of 7 out of 12 subjects was higher at C3 than C4 [55]. This is supported by findings from Ismail *et al*. [33] that the frequency range generated from imagined writing has the same frequency range as that generated from the actual writing using spectral analysis. These results clearly indicate that writing is primarily organized in the language-dominant hemisphere, which is also in consistent with fMRI findings [18].

Further analysis revealed that the frequency range produced from T7 and FC5 equals to that from C3, P3 and O1, which indicates high neuro-activity during writing. From the functional neuro-anatomy of writing, the area in the middle frontal gyrus superior to Broca's area is said to organize the motor behaviour necessary for fluent writing [30]. It is also found to be active in good writers during pseudo-letters writing, while poor writers exhibit activation in temporal area, which is related to memory, showing their struggle in memorizing before expressing in the form of words or text[56].

5.0 CONCLUSIONS

Our work here intends to investigate effects on electrode locations O1/O2, P3/P4, C3/C4 and T7 and FC5 during reading-writing, to make them a reduced set of electrodes to study the reading-writing neuro-pathway. It is found that the EEG spectrum of these electrode display differently during relaxation and writing. Relaxation drew on one dominant peak with frequency content in the alpha sub-band, while writing activity drew on two dominant peaks, one in alpha and the other in beta sub-band. The frequency range of EEG recorded from these electrode during relaxation is 8-13 Hz, while that during writing is 13-29 Hz, within the sub-bands known for the different neural activities accordingly. It can be concluded that the reduced set of electrodes are suitable for studying neuro-activity along the neuro-pathway for reading-writing, based on spectra based activities recorded during relaxation and reading-writing and also support from previous findings.

Table 2 Frequency of EEG Signals in Beta- Subband during Sentence Writing

E	**Male (Hz)**			**Female(Hz)**			**Frequency Range (Hz)**
	Passage 1	**Passage 2**	**Passage 3**	**Passage 1**	**Passage 2**	**Passage 3**	**Passage**
C3 (L)	**13.68 – 28.13**	**13.56 – 28.09**	**13.35 – 28.09**	**13.49 – 26.18**	**13.38 – 19.63**	**13.48 – 21.16**	**13.35 – 28.09**
C4 (R)	13.16 – 28.12	13.46 – 28.09	13.57 – 28.09	13.56 – 19.21	13.38 – 17.00	13.42 – 18.16	13.16 – 27.38
P3 (L)	**13.41 – 28.13**	**13.84 – 27.97**	**13.42 – 28.09**	**13.66 – 27.36**	**13.38 – 20.48**	**13.68 – 19.12**	**13.75 – 28.13**
P4 (R)	13.21 – 28.55	13.20 – 27.97	13.67 – 28.09	13.59 – 17.56	13.38 – 16.96	13.61 – 17.27	13.20 – 27.98
O1 (L)	**13.42 – 28.13**	**13.83 – 27.97**	**13.42 – 28.09**	**13.34 – 25.87**	**13.47 – 28.03**	**13.61 – 26.33**	**13.34 – 27.38**
O2 (R)	13.48 – 28.12	13.55 – 27.97	13.24 – 28.09	13.56 – 23.01	13.76 – 21.97	13.59 – 21.41	13.24 – 26.98
T7 (L)	13.34 – 28.27	13.25 – 28.30	13.83 – 28.09	13.47 – 29.05	13.48 – 27.21	13.48 – 26.91	13.25 – 29.05
FC5 (L)	13.45 – 28.13	13.51 – 28.00	13.63 – 28.09	13.66 – 27.38	13.52 – 29.31	13.56 – 26.02	13.45 – 29.31

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