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Spatial Interaction Image of Electroencephalography Signal during Epileptic Seizure on Flat Electroencephalography

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Abstract: Electroencephalogram (EEG) is widely used for recording the brain electrical activity. It plays an important role in the detection and classification of epilepsy seizures. In addition, it is believed to possess the ability to detect the location of epileptic focus to some degree. In this study, an EEG data during seizure obtained is analysed and transformed into an image form, namely Flat EEG (*f*EEG). The *f*EEG is a method for mapping high dimensional signal into a low dimensional space. The *f*EEG of the obtained signal is clustered and the interactions of the cluster centers are studied and presented in this study.

Keyword: EEG, Epileptic, Flat EEG, Spatial Interaction, Gravity Model

Introduction

Epilepsy is a common disorder disease in the nervous system, regardless of geographical location, races or social class. It describes the condition of a patient having recurring "spontaneous" seizures due to the sudden development of synchronous firing in the cerebral cortex caused by lasting cerebral abnormality. Even though surgical treatment is possible for patients, the success of the surgery is highly dependent on the detection of exact localization of epileptic focus.

Fortunately, EEG was invented and widely used for recording the brain's electrical activity. Generally EEG technique can be categorized into two: Intracranial and scalp. Basically intracranial EEG provides several advantages over scalp EEG (Salanova *et al*., 1993), however the disadvantages are accompanied by significant discomfort and risk of a major complication such as haemorrhage infection are not negligible (Fisch, 2010). On the other hand, scalp EEG may be less sensitive, but it provides the best overview for detecting the localization of the epileptogenic zone (Noachtar and Rémi, 2009).

Though scalp EEG is imperfect in terms of sensitivity, it is considered as the best method used in epilepsy analysis which focuses on the detection and classification of epilepsy seizures. Nonetheless, the aid from a highly skilled electroencephalographer or neurophysiologist are still needed to give best visual inspection of EEG signal (Sanei and Chambers, 2007). Due to this restriction, we are driven to study the spatial analysis of EEG signals during seizure.

Related Works

In this section, the works done by previous researchers of our research group are reported, namely flat EEG and Fuzzy Neighbourhood Image. In addition, the prototype model of the Spatial Interaction Image are reviewed as follows.

Flat EEG

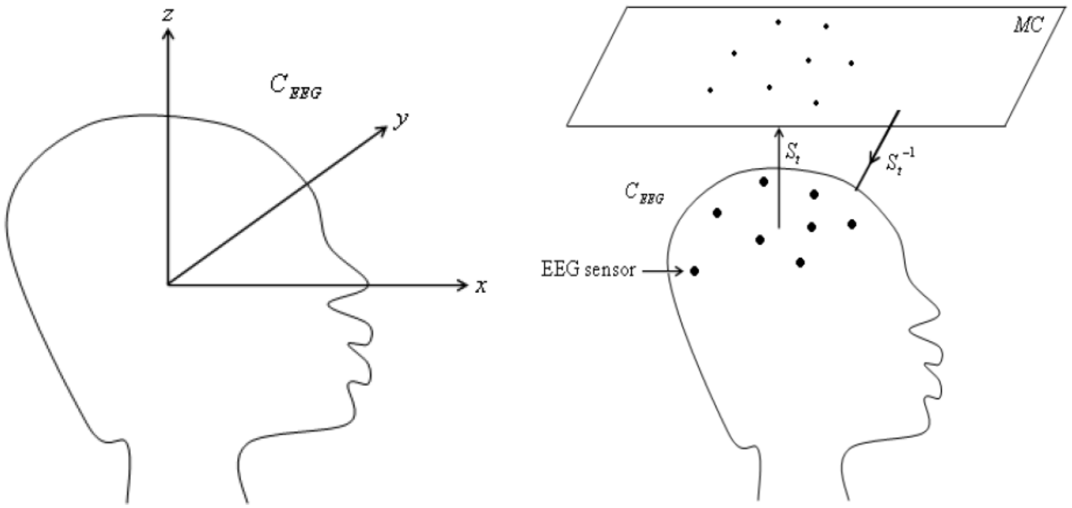
Zakaria (2007) developed a method in mapping high dimension signals, namely EEG signals into low dimensional space (MC). A coordinate system, namely Fauziah's EEG coordinate system (Fig. 1a) was introduced such that:

$$C_{EEG} = \left\{ \left((x, y, z), e_p \right) : x, y, z, e_p \in \mathbb{R} \, and \, x^2 + y^2 + z^2 = r^2 \right\}$$

where, r is the radius of a patient head. Furthermore, the mapping of CEEG to MC is defined as S_t: $C_{EEG} \rightarrow$ MC (Fig. 1b) such that:

$$S_t\left(\left((x, y, yz), e_p \right) \right) = \left(\frac{rx + iry}{r+z}, e_p \right) = \left(\frac{rx}{r+z}, \frac{ry}{r+z} \right)_{e_p,(x,y,z)}$$

where, MC = $\{((x,y)e_p): x,y,\ e_p \in \mathbb{R}\ \}$. Both C_{EEG} and MC were designed and proven as 2-manifolds (Zakaria, 2007).



(a) (b)

Fig. 1. (a) EEG Coordinate System (b) EEG Projection

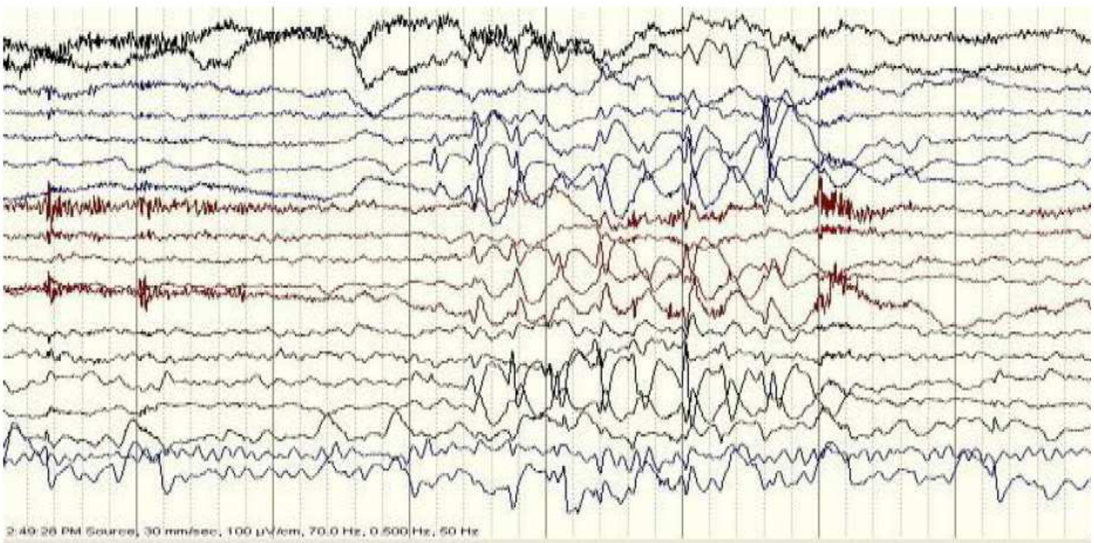
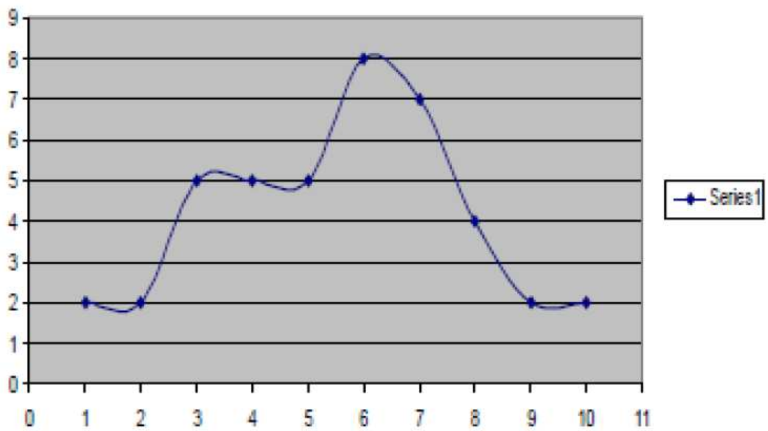
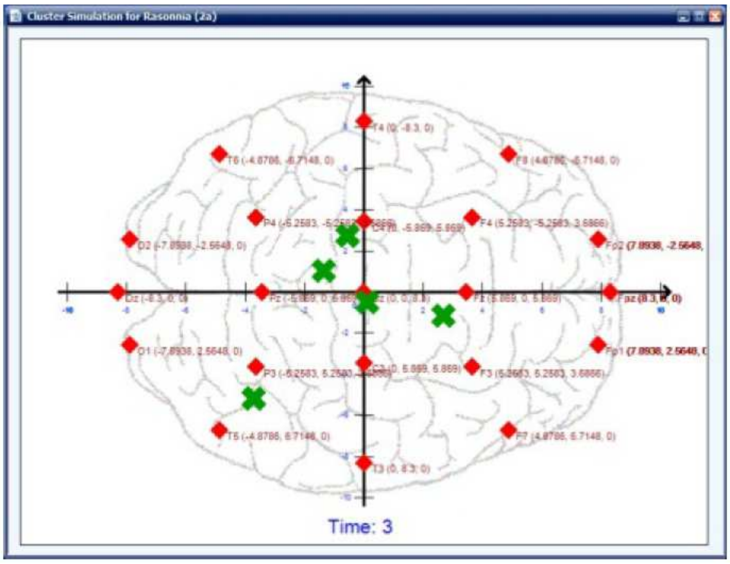


Fig. 2. EEG signal during seizure



(a)



(b)

Fig. 3. Flat EEG

The mapping S_t was designed to be a one to one function as well as being conformal. After the mapping, the data obtained can be clusterised by Fuzzy c-Means (FCM) clustering algorithm, followed by cluster validity test, namely Partition Coefficient (PC) and Compactness Separability (CS), in order to enable EEG signal during seizure as in Fig. 2 to be compressed (Fig. 3a) and analysed second by second (Fig. 3b) (Zakaria, 2007; Ahmad *et al*., 2006).

Fuzzy Neighbourhood Image

As further study on *f*EEG, Ahmad and his co-researchers constructed *f*EEG as a digital space (Fig. 4) (Ahmad *et al*., 2009; Ahmad, 2009). They proved that the digital space of the *f*EEG is an Alexsandr off space and applied relational topology in order to incorporate topological space of real time recorded EEG signal with digital *f*EEG. This construction is a key foundation of *f*EEG which has been linked with the idea of fuzzy information granulation. Furthermore, Abdy and Ahmad (2013) introduced a membership function μ_{c_j} at time t:

$$\mu_{c_j}\left(p_i\right)_t = \frac{\left(v_j\right)_t}{\left(v_j\right)_t + d\left(p_i, c_j\right)t} \tag{1}$$

where $\left(v_j\right)_t$ is the electrical potential c_j at time t; and:

$$d\left(p_i, c_j\right)_t = \sqrt{\left(\left(x_{c_j} - x_i\right)^2 + \left(y_{c_j} - y_i\right)^2\right)}$$

Is the distance between pixel p_i and cluster center c_j at time t for *f*EEG.

Spatial Interaction Model

According to Kingsley and Fotheringham, a spatial interaction is a broad term encompassing any movement over space that results from a human process (Haynes and Fotheringham, 1984). For example, in our work the interaction will be the flow of potential differences between cluster centers. The original concept of spatial interaction comes from the universal law of gravity, namely Isaac Newton's law of gravity. Between interaction models, the gravity model is the most widely used type of interaction model (Haynes and Fotheringham, 1984). It is a mathematical formulation which utilizes the gravitational force concept. The model is widely used to analyse and forecast spatial interaction patterns (Philbrick, 1971). Since first introduced by Carey (1858), types of gravity models keep on increasing along with the development of applications. Example include gravity model to determine the market area boundary, doubly constrained gravity models for commodity flows analysis, gravity models for studying the migration flows and so on.

The basic assumption concerning many spatial interaction models is that flows are a function of the attributes of the locations of origin, the attributes of the locations of destination and the friction of distance between the concerned origins and the destinations. The general formulation of the spatial interaction model is as follows (Haynes and Fotheringham, 1984):

$$T_{ij} = f\left(V_i, W_j, S_{ij}\right)$$

Where:

T_{ij} = Interaction between location i (origin) and location j (destination)
V_i = Attribute of the location of origin i

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W_j = Attribute of the location of destination j
S_{ij} = Attribute of separation between the location of origin i and the location of destination j

Image Form of Spatial Interaction on *f*EEG

Our aim in this section is to view the interaction relationship between cluster centers in the image form at *f*EEG. There are some definitions which need to be reviewed.

Mathematical Background

Definition 1 (Cluster Center) (Abdy and Ahmad, 2013)

Let $\mathbb{C}$ be the set of all cluster centers at time t, i.e.: $\mathbb{C}_t = \{c_1, c_2, c_3, \ldots, c_m\}$, where m = number of cluster centers at time t. Each cluster center carries its position with electrical potential on *f*EEG, i.e.: $(c_j)_t = ((x_j, y_j), v_j)_t$, with v_j = electrical potential of the cluster center jth. Let $\mathbb{P}$ be the set of entire pixels of *f*EEG, thus $\mathbb{C}_t = \{((x,y),v) | x, y \in \mathbb{P}, v \in \mathbb{R}^+\}_t$ where $\mathbb{P} = \{P_1, P_2, P_3, \ldots, P_n\}$ such that $P_k = (x_k, y_k)$, or in short: $\mathbb{C}_t \subset \mathbb{P}$.

Definition 2 (Domain) (Yong et al., 2013)

The set of pair-wise cluster centers interaction on *f*EEG is defined by:

$$\mathbb{C}^2 = \left\{ \begin{matrix} (c_1, c_2), \ldots, (c_1, c_m), (c_2, c_3), (c_2, c_4) \ldots, \\ (c_2, c_m), \ldots, (c_{m-1}, c_m) \end{matrix} \right\} \tag{2}$$

Definition 3 (Interaction model)(Yong et al., 2013)

The interaction model, $T: \mathbb{C} \times \mathbb{C} \to \mathbb{R}$ is defined by:

$$T_{ij_{P_k}} = \frac{v_i^{\lambda} v_j^{\alpha}}{d_{ij}^{\beta}}, \; d_{ij} \neq 0 \tag{3}$$

Where:

$T_{ij_{P_k}}$ = Pair-wise cluster centers interaction between ith and jth cluster centers with respect to P_k
d_{ij} = Euclidean distance between cluster center ith and jth
v_i, v_j = Electrical potential of cluster center ith and jth respectively
λ, α = The fuzzy values (in crisp form) of respective pixel on cluster ith and jth
β = The distance decay parameter

By considering each cluster center c_j at time t forms a fuzzy region of the potential difference on the *f*EEG, each pixel will carry a fuzzy membership value, λ with respect to cluster center ith (or α with respect to cluster center jth) which can be determined from $\mu_{c_j}(P_k)_t$. A fuzzy membership function had been defined by Abdy and Ahmad (2013) (refer Equation 1), however the consideration of vi in the function is not satisfied with respect to the gravity model, where λ, α are other variables beside v_i, v_j. Thus, a new membership function is introduced and given by the following.

Definition 4 (Fuzzy Membership Function)

The fuzzy membership function of P_k with respect to c_j is defined by:

$$\mu_{c_j}(P_k)_t = \left(\frac{d_{\max_t} - d(P_k, c_j)_t}{d_{\max_t} + d(P_k, c_j)_t} \right)^{\frac{1}{2}} \tag{4}$$

Where:

$d_{\max_t}$ = The maximum distance between all the entire pixels on *f*EEG at time t
$d(P_k, c_j)_t$ = The distance between pixel Pk and cluster center cj at time t

It has been shown that Equation 4 satisfies some properties as follows.

Theorem 1

Suppose that $\mu_{c_j}(P_k)_t$ is a fuzzy membership function of c_j on P_k, then:

$$\lim_{d(P_k, c_j)_t \to \infty} \mu_{c_j}(P_k)_t = 0$$

Proof:

$$\lim_{d(P_k, c_j)_t \to \infty} \mu_{c_j}(P_k)_t = \lim_{d(P_k, c_j)_t \to \infty} \left(\frac{d_{\max_t} - d(P_k, c_j)_t}{d_{\max_t} + d(P_k, c_j)_t} \right)^{\frac{1}{2}}$$

$$= \left(\lim_{d(P_k, c_j)_t \to \infty} \frac{d_{\max_t} - d(P_k, c_j)_t}{d_{\max_t} + d(P_k, c_j)_t} \right)^{\frac{1}{2}}$$

$$= \left(\frac{\lim_{d(P_k, c_j)_t \to \infty} d_{\max_t} - \lim_{d(P_k, c_j)_t \to \infty} d(P_k, c_j)_t}{\lim_{d(P_k, c_j)_t \to \infty} d_{\max_t} + \lim_{d(P_k, c_j)_t \to \infty} d(P_k, c_j)_t} \right)^{\frac{1}{2}}$$

$$= \left(\frac{d_{\max_t} - d_{\max_t}}{d_{\max_t} + d_{\max_t}} \right)^{\frac{1}{2}}$$

$$= \left(\frac{0}{2d_{\max_t}} \right)^{\frac{1}{2}}$$

$$= 0$$

$$\therefore \lim_{d(P_k, c_j)_t \to \infty} \mu_{c_j}(P_k)_t = 0$$

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Theorem 1 shows that if a pixel is very far from a cluster center, the fuzzy membership of the pixel with respect to the cluster center will go to 0.

Theorem 2

Suppose that $\mu_{c_j}\left(P_k\right)_t$ is fuzzy membership function of c_j on P_k, then:

$$\lim_{d\left(P_k,c_j\right)_t\to\infty}\mu_{c_j}\left(P_k\right)_t=1$$

Proof:

$$\lim_{d\left(P_k,c_j\right)_t\to 0}\mu_{c_j}\left(P_k\right)_t=\lim_{d\left(P_k,c_j\right)_t\to 0}\left(\frac{d_{\max_t}-d\left(P_k,c_j\right)_t}{d_{\max_t}+d\left(P_k,c_j\right)_t}\right)^{\frac{1}{2}}$$
$$=\left(\lim_{d\left(P_k,c_j\right)_t\to 0}\frac{d_{\max_t}-d\left(P_k,c_j\right)_t}{d_{\max_t}+d\left(P_k,c_j\right)_t}\right)^{\frac{1}{2}}$$
$$=\left(\frac{\lim\limits_{d\left(P_k,c_j\right)_t\to 0}d_{\max_t}-\lim\limits_{d\left(P_k,c_j\right)_t\to 0}d\left(P_k,c_j\right)_t}{\lim\limits_{d\left(P_k,c_j\right)_t\to 0}d_{\max_t}+\lim\limits_{d\left(P_k,c_j\right)_t\to 0}d\left(P_k,c_j\right)_t}\right)^{\frac{1}{2}}$$
$$=\left(\frac{d_{\max_t}-0}{d_{\max_t}+0}\right)^{\frac{1}{2}}$$
$$=\left(\frac{d_{\max_t}}{d_{\max_t}}\right)^{\frac{1}{2}}$$
$$=1$$
$$\therefore\lim_{d\left(P_k,c_j\right)_t\to 0}\mu_{c_j}\left(P_k\right)_t=1$$

Theorem 2 indicates that when a pixel is near to the location of a cluster center, the fuzzy membership of the pixel with respect to the cluster center will move to 1.

Theorem 3

Let $c\in\mathbb{C}_t$ and P_i, $P_k\in\mathbb{P}$. If $d(P_i, c)\geq d(P_k, c)$, then $\mu_c(P_i)_t\leq\mu_c(P_k)_t$.

Proof

Let $d(P_i,c)\geq d(p_k, c)$ and $\mu_c(P_j)_t=\left(\frac{d_{\max_t}-d\left(P_i,c\right)_t}{d_{\max_t}+d\left(P_i,c\right)_t}\right)^{\frac{1}{2}}$, $\mu_c(P_k)_t=\left(\frac{d_{\max_t}-d\left(P_k,c\right)_t}{d_{\max_t}+d\left(P_k,c\right)_t}\right)^{\frac{1}{2}}$. Let $s_1=d_{\max_t}-d\left(P_i,c\right)_t$, $s_2=d_{\max_t}-d\left(P_k,c\right)_t$, $f_1=d_{\max_t}+d\left(P_i,c\right)_t$ and $f_2=d_{\max_t}+d\left(P_k,c\right)_t$.

Since $d_{\max_t}\geq 0$, $d(P_i, c)_t\geq 0$ and $d(P_k, c)_t\geq 0$, we have $s_2\leq, f_1\geq f_2$, thus:

$$\frac{s_1}{f_1}\leq\frac{s_2}{f_2}$$
$$\sqrt{\frac{s_1}{f_1}}\leq\sqrt{\frac{s_2}{f_2}}$$
$$\sqrt{\left(\frac{d_{\max_t}-d\left(P_i,c\right)_t}{d_{\max_t}+d\left(P_i,c\right)_t}\right)}\leq\sqrt{\left(\frac{d_{\max_t}-d\left(P_k,c\right)_t}{d_{\max_t}+d\left(P_k,c\right)_t}\right)}$$
$$\mu_c\left(P_i\right)_t\leq\mu_c\left(P_k\right)_t$$

Theorem 3 shows that the membership value of a pixel which is closer to cluster center will always be greater than the other.

Since each pixel carries different fuzzy membership values which correspond to every single cluster center respectively, the interaction relationship is the total of the pair-wise cluster centers interaction index, which is defined as follows.

Definition 5 (Yong et al., 2013)

Total interaction of all cluster centers on a pixel, P_i is given as:

$$T_{total_{P_i}}=k\frac{v_{c_1}^{\lambda}v_{c_3}^{\alpha}}{d_{c_1c_2}^{\beta}}+k\frac{v_{c_1}^{\lambda}v_{c_3}^{\alpha}}{d_{c_1c_3}^{\beta}}+\cdots+k\frac{v_{c_{m-1}}^{\lambda}v_{c_m}^{\alpha}}{d_{c_{m-1}c_m}^{\beta}}\tag{5}$$

Furthermore, the transformation of total interaction index of each pixel $T_{total_{P_i}}$ into an image index is given by the following definition.

Definition 6 (Image Index)

The image index, I_{P_i} is given as:

$$I_{P_i}=\frac{T_{total_{P_i}}}{\max\left[T_{total_{\mathbb{P}}}\right]_t}\tag{6}$$

However, the level of grey-scale is given as:

$$I_{P_i}'=1-I_{P_i}\tag{7}$$

Spatial Interaction Image Model

Based on the definitions in Section 3.1, the spatial interaction image model can be explained by the following algorithm:

Step 1: Choose the values for constant, k and distance decay parameter, β in Equation 3.

Step 2: Calculate the μ_{c_j} for all $P_i \in \mathbb{P}$ corresponding to all $c_j \in \mathbb{C}_t$ by Equation 4.
Step 3: Determine all sets of cluster centers which interact with each other by Equation 2.
Step 4: Compute the pair-wise cluster centers interaction index, $T_{c_j,c_{k_{P_i}}}$ for all c_j, $c_k \in \mathbb{C}^2_t$ and $P_i \in \mathbb{P}$ by Equation 3.
Step 5: Obtain the total interaction index, $T_{total_{P_i}}$ for all $P_i \in \mathbb{P}$ by Equation 5.
Step 6: Transform the total interaction index, $T_{total_{P_i}}$ into image index, I_{P_i} by Equation 6.
Step 7: Refine the image index, I_{P_i} to image data, I_{P_i}' by Equation 7.
Step 8: Plot the image by using Matlab.

In order to implement the spatial interaction image algorithm as described above, an example (3×3 pixels) is given in Table 1.

Given $\mathbb{C} = \{c_1, c_2, c_3\}$, $\mathbb{P} = \{P_1, P_2, P_3,\ldots,P_n\}$(Table 2). First, the assumption for constant k is 1 and β is 2. By applying Equation 4, the fuzzy membership values for all $P_i \in \mathbb{P}$ corresponding to all $c_j \in \mathbb{C}_t$ were obtained as shown in Table 2.

From Equation 2, the $\mathbb{C}_2$ was determined with $\mathbb{C}_2 = \{(c_1, c_2), (c_1, c_3), (c_2, c_3)\}$. Next, the $T_{c_j,c_{k_{P_i}}}$ were computed by Equation 3. After that $T_{total_{P_i}}$ were calculated by Equation 5. $T_{total_{P_i}}$ were then transformed into I_{P_i} by Equation 6 and refined to I_{P_i}' by Equation 7. The obtained results are all shown in Table 3. Finally the I_{P_i}' was used to plot the image by Matlab (Fig. 5).

Table 1. Example of three cluster centers

$\mathbb{C}$	Position x	Position y	Electrical Potential (μV)
c_1	-1	0	554
c_2	1	0	398
c_3	1	-1	53

Table 2. Position of $\mathbb{P}$ and $\mu_{c_j}(P_i)$

$\mathbb{P}$	Position x	Position y	$\mu_{c_j}(P_i)$ c_1	c_2	c_3
P1	-1	1	0.6911	0.3420	0.0000
P2	0	1	0.5774	0.5774	0.3420
P3	1	1	0.3420	0.6911	0.3420
P4	-1	0	1.0000	0.4142	0.3420
P5	0	0	0.6911	0.6911	0.5774
P6	1	0	0.4142	1.0000	0.6911
P7	-1	-1	0.6911	0.4142	0.3420
P8	0	-1	0.5774	0.5774	0.3420
P9	1	-1	0.6911	0.3420	0.0000

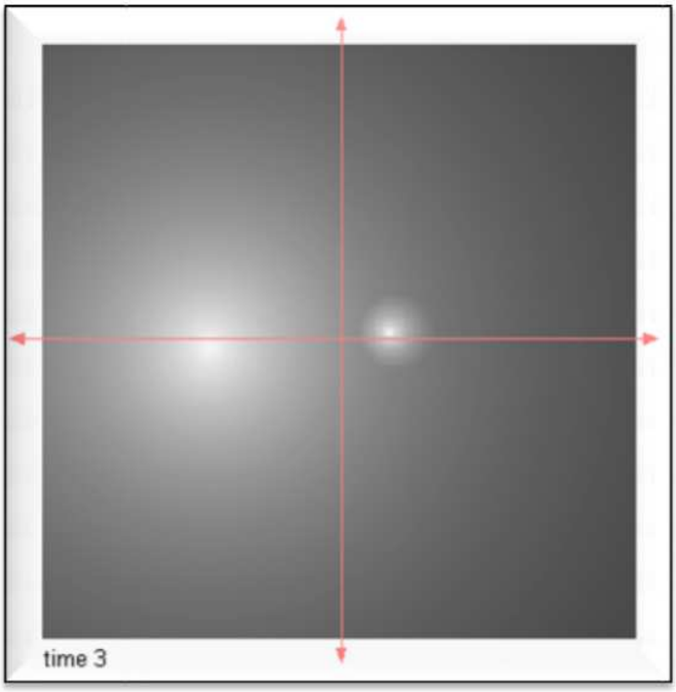


Fig. 4. Image of Cluster Center on *f*EEG at Time = 3s

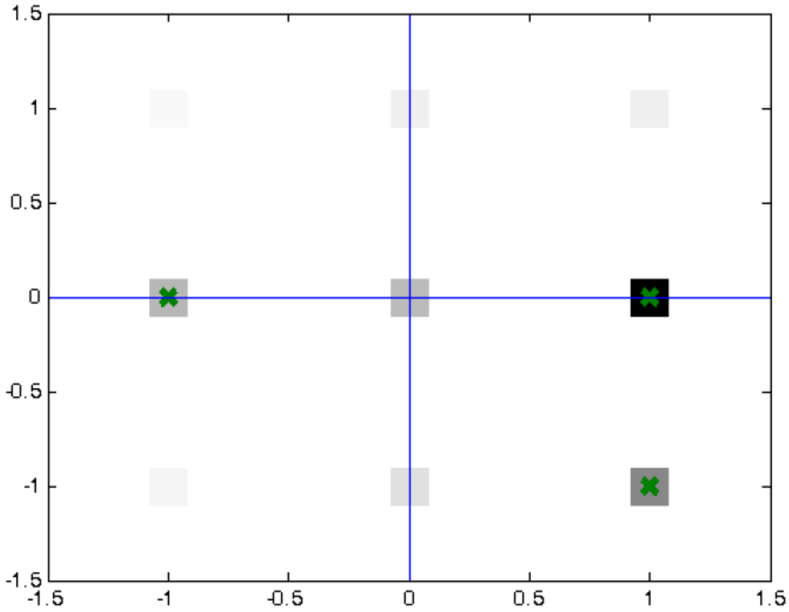
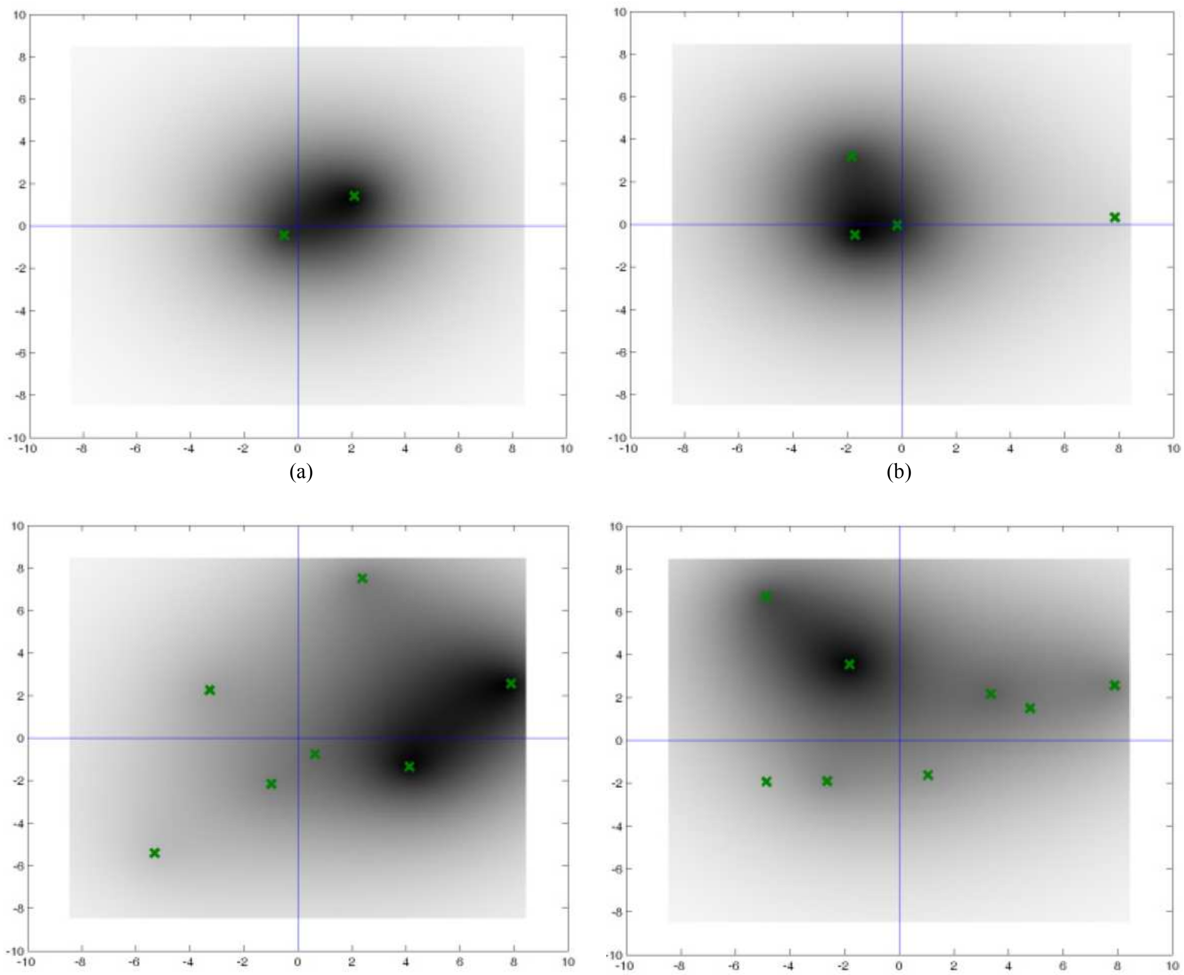


Fig. 5. Example of spatial interaction image



(a) (b)

(c) (d)

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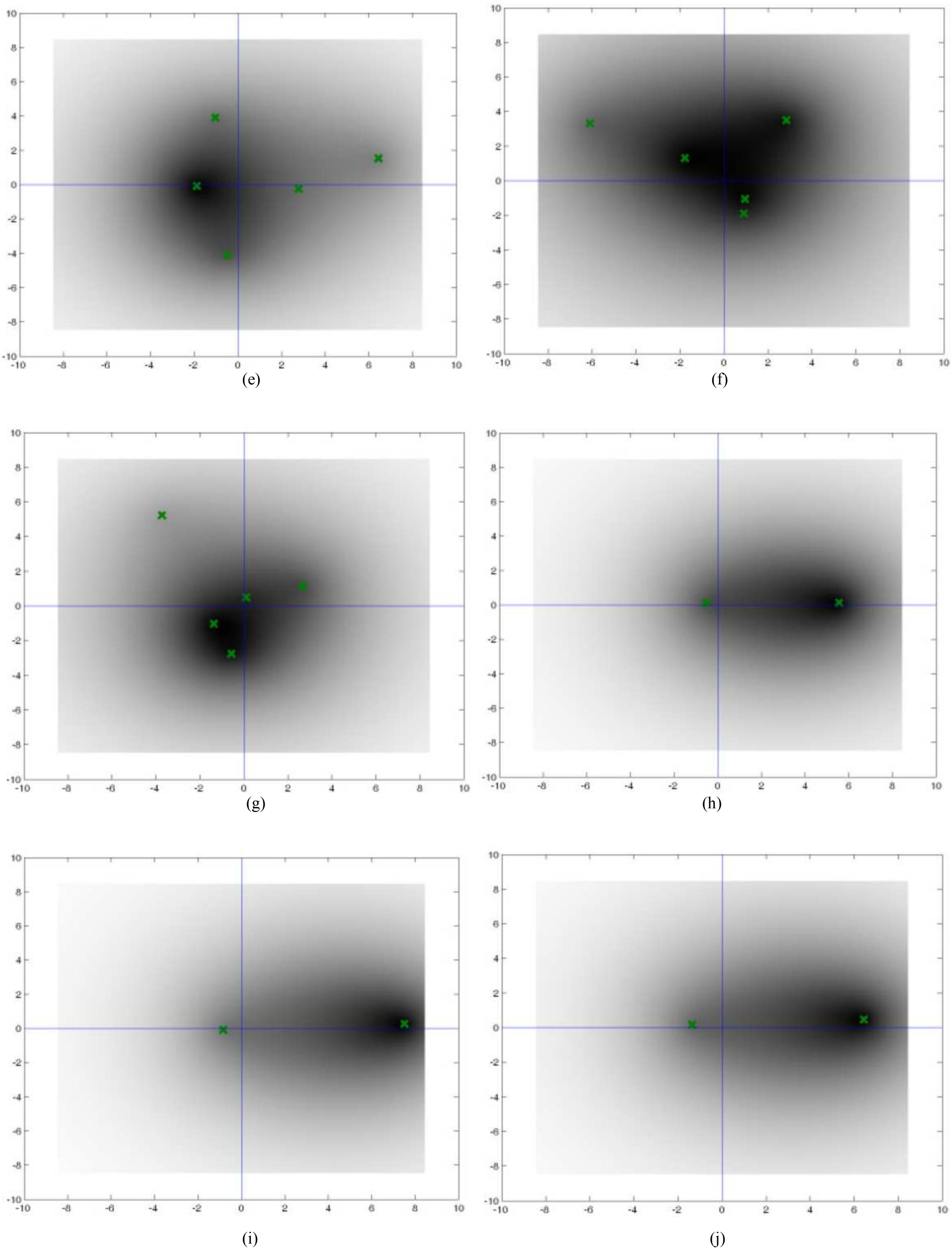

Fig. 6. Image of Interaction Relationship between Cluster Centers (a) Time = 1s (b) Time = 2s (c) Time = 3s (d) Time = 4s (e) Time = 5s (f) Time = 6s (g) Time = 7s (h) Time = 8s (i) Time = 9s (j) Time = 10s

Table 3. Numerical results

$\mathbb{P}$	$T_{c_j,c_k}{}_{P_i}$ (c_1, c_2)	(c_1, c_3)	(c_2, c_3)	$T_{total_{P_i}}$	I_{P_i}	I_{P_i}'
P1	152.4343	15.7404	7.7474	175.9221	0.0232	0.9768
P2	304.0530	29.8330	123.2376	457.1236	0.0602	0.9398
P3	135.8142	8.9851	324.3000	469.0993	0.0618	0.9382
P4	1653.3000	430.8000	46.4000	2130.5000	0.2806	0.7194
P5	1232.1000	155.8000	619.8000	2007.7000	0.2645	0.7355
P6	1362.1000	42.6000	6187.2000	7591.9000	1.0000	0.0000
P7	152.4343	81.5144	40.1213	274.0700	0.0361	0.9639
P8	304.0530	119.2915	492.7820	916.1265	0.1207	0.8793
P9	135.8000	92.0000	3319.0000	3546.8000	0.4672	0.5328

Table 4. 10 sec *f*EEG data of patient A

Time (second)	Position x	y	Electrical Potential (μV)
1st	-0.830829369808531	-0.097886412453860	54.607727312372300
	7.513143840311760	0.258717379025883	398.385082506005000
2nd	-0.525440200836241	0.111494396484144	49.121395288542000
	5.562991421062720	0.120422144740516	236.957551680730000
3rd	-0.561430542370783	-2.772021839269580	78.765430493753400
	0.108866517096809	0.485035890160876	13.912687782826100
	2.687453987153940	1.140889456900350	137.649392091951000
	-1.360756149745810	-1.033142061517170	45.952993867359200
	-3.721333994912600	5.224967128680400	211.908881087833000
4th	-6.094550833456410	3.311550711979810	100.549264099605000
	0.959277364019865	-1.057174163832390	22.439302814243300
	0.910277528000531	-1.902251905528300	5.352827916037340
	-1.771468590734630	1.294124061821980	41.559915845896600
	2.845765607990540	3.498241176339050	149.503625094120000
5th	-1.030750506024720	3.886212966752390	47.401107254677600
	2.794450973426950	-0.250119654481096	4.934408253672210
	-0.483207453070293	-4.128101802488630	87.329038079578500
	6.448369916607520	1.517967513861310	230.553660978112000
	-1.878778392703790	-0.093627718158547	129.238901820005000
6th	-2.634853996682950	-1.906328450017170	119.682576221727000
	-4.874648497855550	6.710952490119380	275.319383851183000
	-1.812217620779190	3.534370356618210	232.467884359512000
	7.893706657032150	2.564606605052210	406.709682092910000
	3.358352065330840	2.163639367496200	71.297852329706900
	1.060566798879670	-1.629505154656370	37.936212312383000
	-4.856345992214460	-1.933095775271050	3.243774958952160
	4.805670604542740	1.498161206196070	2.521467144658670
7th	-3.248830604503820	2.249194730296410	115.706221085479000
	4.139075025375120	-1.338742799939880	263.584445405930000
	-5.290928836093680	-5.405461845156080	227.539193559067000
	0.642807454002276	-0.756176713075783	10.490064597203700
	7.893209382724820	2.564834807722990	467.827296510668000
	2.393484736383740	7.515150056703200	323.469473387105000
	-0.978028187934057	-2.153809837180280	56.915666253504900
8th	-1.836112097866970	3.184005359351830	263.769212546249000
	-1.712545370187930	-0.484550431700511	139.663152283565000
	-0.160570354667316	-0.042732860487975	39.077882860818100
	7.857925010867870	0.334337297187175	383.221124399369000
9th	2.116241204897850	1.411109284300680	269.540284883266000
	-0.500600970885729	-0.438351416782988	66.554043536745900
10th	-1.346488722494170	0.160786955843757	50.647039507685000
	6.451085149645110	0.466535539597915	289.550089392793000

Implementation

In order to implement the spatial interaction image model, a set of 10s fEEG data which contains the information of location of cluster centers and respective potential difference for every second is obtained from Zakaria (2007) as displayed in Table 4. The value for β is assumed to be 2 (Haynes and Fotheringham, 1984) and the constant k is assumed to be 1. The images of interaction relationship are obtained for each second as shown in Fig. 6, with brightness level of pixel representing the levels of interaction force. The computing time of this work is 45.6559 sec by using Matlab version R2010b, with a 32-bit-Win7 OS based computer.

The result shows that the region with darker colour (greater interaction) is slowly expanding from time = 1 s to 6 s. After that, it narrows down from time = 6 s to 9 s and retains a similar size at time = 10 s. However, the size of region colour that is closer to black (the strongest interaction force) is large whenever the cluster centers that carry greater electrical potential (refer to Table 4) are close to each other.

Conclusion

In this study, the modelling of spatial interaction model, namely gravity model is performed on the platform of fEEG for 10 sec' data. The results were shown in grey-scale image form where the levels of interaction force were represented by brightness level of pixel. From there, it can be concluded that the interaction forces are mostly greater when the cluster center are close to each other, even though it may not happen to the "isolated" cluster center. In other words, the region of great interaction forces is highly reliant on the closeness of cluster centers.

In reality, the bio-signals in the brain is generated by positive charge ions (+ K and + Na), which are supposed to repel each other. In this implementation, the interaction forces between cluster centers in fEEG represent the repellent forces between the ions. The greater the repellent forces happening in the brain, the more disturbance is occurring in the functioning of the patient's brain, which lead to epileptic seizure. The identification of these regions of great interaction may be one of the keys for the detection of exact localization of epileptic focus.

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Author's Contributions

Tahir Ahmad: Designed the research plan. Contributed in giving ideas and reviewing the manuscript critically.

Goh Chien Yong: Designed the research plan and organized the study. Coordinated the overall framework and contributed to the writing of the manuscript.

Normah Maan: Participated in giving ideas, reviewing and proofreading the manuscript

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the authors have read and approved the manuscript and no ethical issues involved.

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