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ORIGINAL PAPER

Effect of proximity to high-voltage fields: results of the neural network model and experimental model with macaques

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Abstract
An important biological hazard that is caused by the placement of power transmission lines in the vicinity of cities and villages is the computation of the magnetic and electric fields around these lines. Therefore, the present research objective was to study the effect of high-voltage fields on the effect of the neural network model on the brain and to compare the results of this model with the results of behavioral and biological analyses of primates. In this research, two adult male macaques were selected for the experiments. Prior to inclusion in the research, the primates were exposed to behavioral tests, hormonal assays (melatonin and cortisol), and MRI-assisted brain anatomy analyses using special kits. The monkey in the experimental group was exposed to a 3 kV/m high-voltage field for 4 h a day for a month, after applying electric field simulations. In addition, the behavioral elements of the primates in the experimental and control groups were analyzed during the treatment. Computation models were used in this research, and the results were compared to experimental data. Behavioral elements manifested in the form of changes such as reduced activity, isolation, reduced appetite, and sleep disorders during applying electric field simulations of the monkey that was exposed to the high-voltage field. Based on the results of the simulation model and the variations of the behavioral, hormonal, and anatomical elements, the decrease in the activity of the brain cortex, sleep disorders, and isolation were indicative of depression in the monkey exposed to the high-voltage field.

Keywords High-voltage field · Depression · Melatonin · MRI · Cortisol · Spiking neural network model · Monkey

Introduction

Depression is a psychological disorder that can minimize the patient's efficiency (Videbech and Ravnkilde 2004; Sapolsky 2001; Goodwin and Jamison 2007). Different factors such as anxiety and sleep disorders are involved in the development of depression (Goodwin and Jamison 2007). Another factor substantially contributing to the development of depression is the environmental factor, which is associated with the role of electric and magnetic fields (Crasson 2003; Nadeem et al. 2003; Cook et al. 2002). The quantity of these electric and magnetic fields has increased in the industrial countries with the advancement of technology, and thus, the risks of these fields increase day by day. The effects of these fields play a major role in psychological disorders such as learning and memory disorders and depression (Crasson 2003; Carpenter 2013). In this research, the neural network modeling was used along with biological, behavioral, and anatomical examinations to study the effects of high-voltage electric fields (400 kV transmission line) on the depression of male rhesus macaques.

It is necessary to calculate the electric and magnetic fields around power transmission lines to prevent the effects of these fields on humans due to the proximity of these lines to the power generation centers, cities, and villages. Many studies have been carried out on the effect of low-frequency electromagnetic rays on the performance of different parts of the nervous system and memory of humans and animals in the past decade (Crasson 2003; Cook et al. 2002; Lai and Singh 1997; Beale et al. 1997).

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In spite of the important research carried out on human samples to study the effects of electromagnetic fields, the research on human models has been more precise and comprehensive. An important animal model used for scientific studies is the rhesus macaque (Lai and Singh 1997; Beale et al. 1997; Stevens et al. 1993). Since 93% of the genes of humans and rhesus macaques are the same, researchers have considerably utilized this animal in their cognitive tests (Orban et al. 2003). In addition, cognitive–behavioral investigations are among the state-of-the-art studies conducted on this animal.

The brains of the vertebrae, humans in specific, are among the most complicated systems in the universe, and many researchers have tried to discover the secret of the complexity of the brain (Markram 2012; Markram et al. 2011). However, in spite of these considerable efforts, many of the dimensions of the human brain and mind are yet to be discovered. In addition, the pace of the research on the brain and neuroscience has increased in the past decades as the humans have been fiercely determined to discover the secrets of this complicated system.

The experimental approach provides valuable information on the brain, but it has serious limitations which call for the development of alternative approaches. In this regard, computation and modeling approaches are of significant importance, because by creating precise computation models, it is possible to easily study the behavior of model elements and parameters. Nevertheless, there might be no possible means of conducting an experimental investigation of these elements and parameters. Due to this characteristic of computation models, this approach has been increasingly used by researchers (Chudler and Bergsman 2016; Mitchell et al. 2008; Bullmore and Sporns 2009).

One of the main characteristics of vertebrae is the neural relationship in which many neurons connect with another neuron via axons and dendrites (Mitchell et al. 2008; Adolphs 2009; Wang and Kriegstein 2008; Loh et al. 2007; Izhikevich 2007). These neurons affect other neurons and are affected through the axons and dendrites. A synapse is where a neuron connects with another neuron. A neuron is normally connected to several thousand neurons via a synaptic connection and receives synapses from those neurons. Synapses are among the most important brain structures for many reasons. From the biological point of view, neurons are highly organized and therefore perform accurately and live long. In engineering terms, it could be stated that neurons are highly stable, and from the computational point of view, it could be stated that neurons play the main role in the transmission and processing of information. In other words, neurons allow the brain to learn, memorize, and adapt. Since synapses are the core of neuronal communications, synaptic disorders are the roots of many brain and psychological disorders (Sala et al. 2015; Lau and Zukin 2007). From the clinical point of view, synapses are also the main target of medical treatment or medical care.

Melatonin, N-acetyl-5-methoxytryptamine, is a hormone secreted by the brain pineal gland and contributes to the adjustment of the sleep and wake cycle of the body. The release of melatonin is stimulated in the dark and is inhibited in the light (Blask 2009). One of the most important consequences of exposure to electromagnetic fields is the impaired secretion of the melatonin natural hormone, and the decrease in the melatonin hormone under the effect of electromagnetic fields results in sleep disorders. The impaired secretion of this hormone also causes various psychological disorders such as depression, immune system deficiency, and sleep patterns in children. The consequences of these conditions are autism, epilepsy, Down syndrome, or cerebral palsy (Sapolsky 2001; Goodwin and Jamison 2007; Reiter 1993; Gruber et al. 2000).

Cortisol is the most important hormone secreted by the adrenal gland in response to stress and emotional stimuli. Impairment of the natural secretion of this hormone leads to neural and cognitive diseases. An excessive decrease in this hormone results in a lack of movement, isolation, and depression, and any factor excessively increasing the concentration of plasma cortisol results in abnormal instability and behavior. Furthermore, an increase in the cortisol level guarantees the impairment of learning and memory. Hence, variations of the plasma cortisol levels influence memory, learning, and psychological disorders. The present research goal was to determine whether the high-voltage electric field affects the results of simulated neural models of the brain. It was also tried to determine whether the effects of high-voltage fields lead to behavioral, hormonal, and anatomical changes in the male rhesus macaques (Dedovic et al. 2009; LaBar and Cabeza 2006).

Depression is a continuous and lasting change in mood that may affect different dimensions of life. Depression is characterized by feelings of worthlessness, guilt, loneliness, frustration, sorrow, and continuous doubt about one's own abilities. Some of the symptoms of depression include excessively long or short sleep, weight gain or loss, and overeating or lack of appetite. Hence, any impairment of the natural secretion of melatonin impairs the natural cycle of life, which is a chief component of depression (Sapolsky 2001; Goodwin and Jamison 2007; Hickie and Rogers 2011).

Materials and methods

The study samples were two adult male rhesus macaques aged between 4 and 5 years with an average weight of 4 kg. The primates entered the research after adapting to the environment (for 12 months). The lighting, temperature, and moisture of the room used to keep the animals met the standards, and the animals were kept 12 h in the dark and 12 h in the light. All of the ethical principles of international rules were abided by as regards the transportation, and the location and method of retention (Baqiyatallah Medical University Medical Ethics Committee number 112–1394).

In protocol one, the monkey was exposed to a simulated 3 kV/m high-voltage electric field for 4 h a day for a month and the other monkey was kept as the control sample in an area without an electric field (Kazemi et al. 2018).

The high-voltage electric field used in this research was an effect of exposure to a 400-kV, 50-Hz transmission line on human that simulated (3 kV/m) in the Amirkabir University of Technology (Tehran Polytechnic), The High-Voltage Laboratory (HVL). To simulate this field, two metal sheets (2*2 m sheets) were placed at the bottom of the cage and on top of the cage by a crane. The distance between the two sheets was 2 m, and a voltage of 6 kV was applied to the sheets to create a uniform 3 kV/m field in the 1*1*1-m Teflon cage.

The behavioral analyses before, after, and during applying electric field simulations of two primates were carried out and recorded by a camera. Moreover, 5 cc of blood samples was obtained from each primate. To measure and compare the variations of the serum concentration of the hormones, some specialized diagnosis kits were used. The cortisol hormone (0.04–200 ng/ml) was obtained from the American MyBiosource Company, and melatonin (15.62–100 pg/ml) was obtained from the same company. The levels of these hormones were measured using the ELISA method, and the variations of the concentrations of the hormones were measured in three stages (before, after, and during applying electric field simulations).

The volume measurements of the hippocampus and amygdala were taken using MRI images of the samples before and after applying electric field simulations in DICOM LiteBox (Tekieh et al. 2017; Van Ooijen 2005). The neural model simulation was also conducted in MATLAB 2016b based on Loh et al. (2007).

Neural network models

Neural networks have different functions such as selecting the input, controlling the gain, reducing turbulence, and selective reinforcement of activities, which is the basis of the simple and complicated models of the primary visual cortex (Tsodyks et al. 2006; Seung 2003; Izhikevich 2003; Maass 1997). Two types of neural networks have attracted more attention among the researchers: the fire rate model and the spiking model. In the fire rate models, elements such as neurons produce the fire rate instead of producing action potentials. On the other hand, in the spiking models time dynamics occur in a fraction of a millisecond to open the channels and describe collective network processing that lasts for several seconds. Therefore, the fire rate models reduce the need for calculation by avoiding the short periods of time during which the action potentials occur. In addition, it is possible to conduct easier mathematical analyses because of the highly simpler formulation of these models. However, there are certain constraints on these models. For instance, these models cannot be used in the fire time and correlation analyses, which are significantly important in understanding the behavior and functions of the nervous system. Moreover, the fire rate models are only useful when the fire times of the neurons in a network are uncorrelated and the concurrency is small. In this case, the results of the fire rate models will be the same as the spiking models. On the other hand, spiking models are capable of modeling and displaying more biological detail because of having more parameters and details. In addition, it is possible to analyze the fire times and their correlations in these models (Tsodyks et al. 2006; Seung 2003; Izhikevich 2003; Maass 1997).

Spiking model

One way of modeling neuron populations is to create these populations using the basic computation neuron models and connect the models using synaptic models. Given the wide range of neural models and different types of synaptic models, it is possible to describe any behavior in any part of the brain with the physiological details such as synaptic currents and their dynamics, neural receptors, and ion channels using computation models (Izhikevich 2003).

Introducing the research spiking model

A spiking model for the network used in this research is introduced in this section. This model was used, analyzed, and discussed in (Tsodyks et al. 2006; Seung 2003; Izhikevich 2003; Maass 1997).

The structure of the neural network is illustrated in Fig. 1. This network is composed of three pyramidal neuron pools and one inhibitory neuron pool. Although the neurons are interconnected, the synaptic strength of the neurons of each

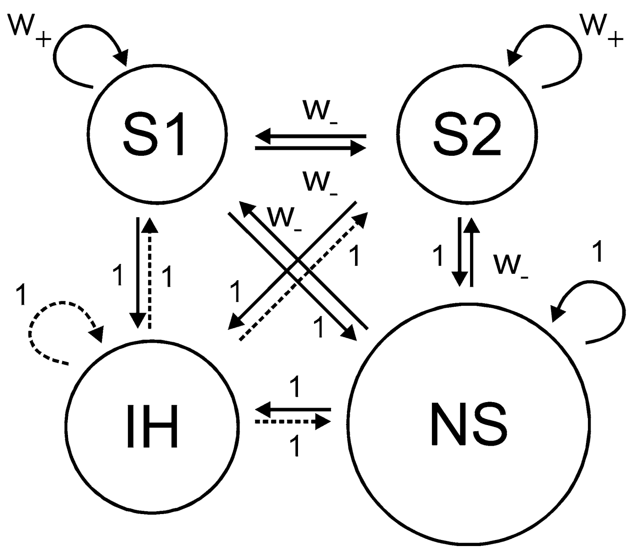

Fig. 1 Structure of the neuron network (Loh et al. 2007)

neuron pool is stronger than its links to other neurons. In this figure, the synaptic strength of the neurons and that of the connections between the pools are depicted. The solid lines represent excitatory connections and the dashed lines show inhibitory connections (Loh et al. 2007).

The S1 and S2 neuron pools are the attractor neurons of this network. The neurons in the NS neuron pool are the group of neurons used to describe the activities of other pyramidal neurons in that part of the cortex, and IH represents inhibitory neurons (Fig. 1).

To describe the dynamics of the neuron membrane voltage, the simple yet effective LIF model was used. The synaptic currents in this model include the AMPA, NMDA, and GABA neural receptors. Each neuron receives the following four types of current: off-network AMPA receptor currents, AMPA receptor currents from intra-network excitatory neurons, NMDA receptor currents from intra-network excitatory neurons, and GABA receptor currents from intra-network

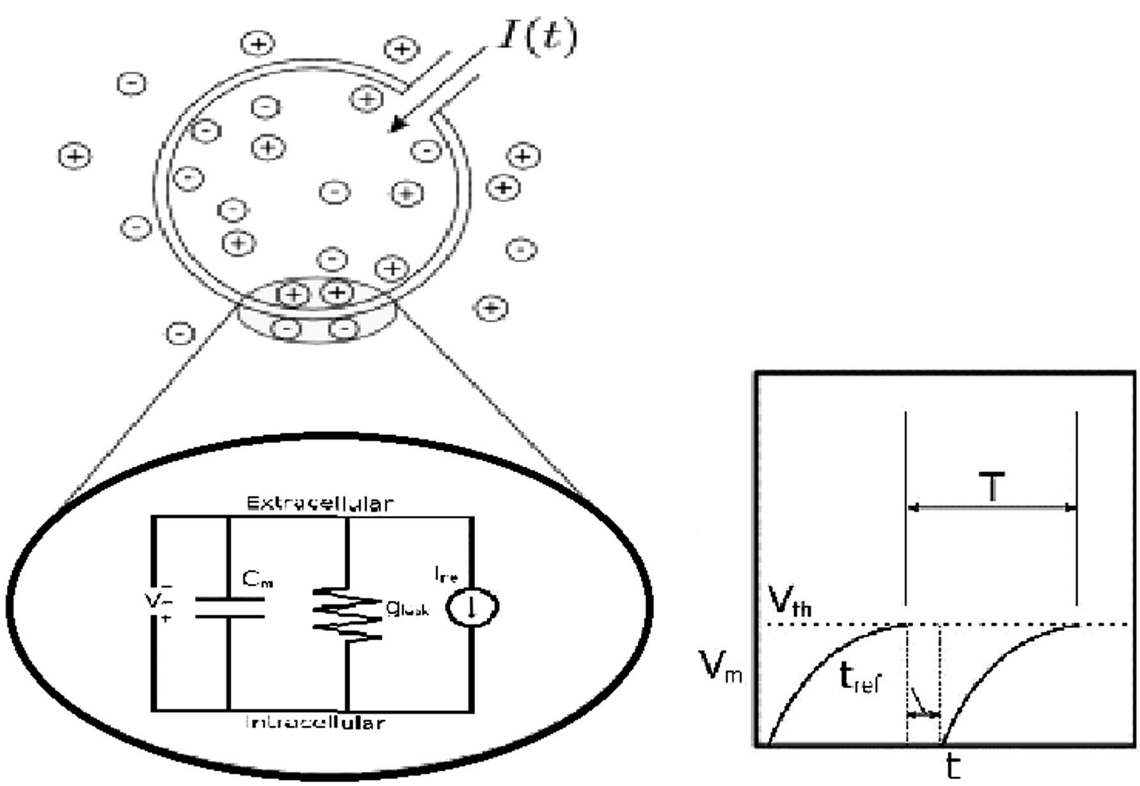

Fig. 2 The neuron cell body, the equivalent electric circuit, and the response (membrane potential difference) to the external or synaptic current, $I(t)$ (Tsodyks et al. 2006)

inhibitory neurons (Wang and Kriegstein 2008; Loh et al. 2007; Lau and Zukin 2007; Salunke et al. 2014; Monyer et al. 1994).

The off-network AMPA receptor currents describe the activity of the neurons in other parts of the cortex that provide inputs to that network. In this model, each neuron receives 800 synapses with off-network AMPA receptors that lead to the background activities of the neurons. In addition, each neuron receives 400 synapses with the AMPA and NMDA receptors from the excitatory neurons and 100 synapses with GABA receptors from the network inhibitory neurons. In the self-stimulatory activity state, the inhibitory current from the inhibitory synapses of the network dominates the excitatory currents produced by the network excitatory synapses. However, this trend is reversed in the stable state. In the following, the LIF equation is used to calculate the membrane voltage (Chudler and Bergsman 2016; Bullmore and Sporns 2009; Loh et al. 2007; Izhikevich 2007; Tsodyks et al. 2006; Izhikevich 2003; Churchland and Sejnowski 2016; Demuth et al. 2014; Burke et al. 2005; Rao et al. 2002).

$$C_{\mathrm{m}}\frac{\mathrm{d}V(t)}{\mathrm{d}t} = -g_{\mathrm{m}}\left(V(t) - V_{\mathrm{L}}\right) - I_{\mathrm{syn}}. \tag{1}$$

If

$$\begin{cases} V(t^{*}) > V_{\mathrm{th}} \\ V(t) = V_{\mathrm{reset}} \\ t^{*} < t < t^{*} + t_{\mathrm{ref}} \end{cases}, \tag{2}$$

where V, VL, V_{reset}, and V_{th} represent the cortex voltage, neuron resting voltage, neuron recovery potential, and neuron fire threshold voltage, respectively. C_{m}, and g_{m} also denote the membrane capacitance and membrane electrical conductivity, respectively (Fig. 2).

The values of these parameters are different for excitatory and inhibitory neurons. Moreover, I_{syn} is the synaptic current received from the neuron, and it can be of four types as mentioned. The varying gate model was also used to describe the different synaptic receptor currents. These currents are described in the following (Videbech and Ravnkilde 2004; Wang and Kriegstein 2008; Izhikevich 2007).

$$\begin{aligned} I_{\mathrm{syn}}(t) = {} & g_{\mathrm{AMPA,ext}}\left(V(t) - V_{\mathrm{E}}\right)\sum_{j=1}^{N_{\mathrm{ext}}} s_j^{\mathrm{AMPA,ext}}(t) \\ & + g_{\mathrm{AMPA}}\left(V(t) - V_{\mathrm{E}}\right)\sum_{j=1}^{N_{\mathrm{E}}} w_{ji}^{\mathrm{AMPA}} s_j^{\mathrm{AMPA}}(t) \\ & + \frac{g_{\mathrm{NMDA}}\left(V(t) - V_{\mathrm{E}}\right)}{1 + \left(\frac{[Mg^{2+}]}{3.57}\right)\exp\left(-0.062V(t)\right)}\sum_{j=1}^{N_{\mathrm{E}}} w_{ji}^{\mathrm{NMDA}} s_j^{\mathrm{NMDA}}(t) \\ & + g_{\mathrm{GABA}}\left(V(t) - V_{\mathrm{I}}\right)\sum_{j=1}^{N_{\mathrm{I}}} w_{ji}^{\mathrm{GABA}} s_j^{\mathrm{GABA}}(t), \end{aligned} \tag{3}$$

where $S^{\mathrm{AMPA,ext}}$, S^{AMPA}, S^{NMDA}, and S^{GABA} are the variables of the synaptic currents gate and correspond to the off-network AMPA receptors, the intra-network AMPA, NMDA and GABA receptors, and the maximum $g^{\mathrm{AMPA,ext}}$, g^{AMPA}, g^{NMDA}, and g^{GABA} of those receptors. Moreover, V_{E} and V_{I} are the resting voltage of the excitatory and inhibitory neuron synapses, respectively. $[Mg^{++}]$ indicates the concentration of intra-neuron magnesium in the NMDA channels, and w_{ji} shows the synaptic weights of the neurons and neuron pools. The equations describing the variables regulating the current passing through the synapses are written as follows:

$$\frac{\mathrm{d}s_j^{\mathrm{AMPA,ext}}(t)}{\mathrm{d}t} = -\frac{s_j^{\mathrm{AMPA,ext}}(t)}{\tau_{\mathrm{AMPA}}} + \sum_k \delta\left(t - t_j^k\right), \tag{4}$$

$$\frac{\mathrm{d}s_j^{\mathrm{AMPA}}(t)}{\mathrm{d}t} = -\frac{s_j^{\mathrm{AMPA}}(t)}{\tau_{\mathrm{AMPA}}} + \sum_k \delta\left(t - t_j^k\right), \tag{5}$$

$$\frac{\mathrm{d}s_j^{\mathrm{NMDA}}(t)}{\mathrm{d}t} = -\frac{s_j^{\mathrm{NMDA}}(t)}{\tau_{\mathrm{NMDA,decay}}} + \alpha x_j(t)\left(1 - s_j^{\mathrm{NMDA}}(t)\right), \tag{6}$$

$$\frac{\mathrm{d}x_j(t)}{\mathrm{d}t} = -\frac{x_j(t)}{\tau_{\mathrm{NMDA,rise}}} + \sum_k \delta\left(t - t_j^k\right), \tag{7}$$

$$\frac{ds_j^{\mathrm{GABA}}(t)}{dt} = -\frac{s_j^{\mathrm{GABA}}(t)}{\tau_{\mathrm{GABA}}} + \sum_k \delta\left(t - t_j^k\right), \tag{8}$$

where τ_{AMPA}, $\tau_{\mathrm{NMDA,decay}}$, and τ_{GABA} are the time constants of the GABA, NMDA, and AMPA receptor genes, respectively. The $\tau_{\mathrm{NMDA,rise}}$ is also the time constant of the rise of the NMDA receptor, and $\delta(t)$ is the Dirac function, which activates all of the fractions of the related receptors following each potential. The S1 and S2 neuron pools in this network are two memories that upon external excitation can switch from the self-stimulatory mode to the stable mode, vice versa.

Results and discussion

The observation of the behavior of the monkey exposed to the simulated 3 kV/m electric field (effects of exposure to a 400-kV, 50-Hz transmission line) (Fig. 3) showed considerable changes as compared to the control sample. The experimental sample was completely solitary, impatient, and motionless and suffered low appetite and weight loss (approximately 1.5 kg).

The concentrations of the blood plasma melatonin and cortisol decreased in the monkey exposed to the 3 kV/m high-voltage electric field (Figs. 4, 5).

Considerable changes were observed in the analysis of the brain anatomy of the monkey exposed to the high-voltage electric field using the MRI hippocampus and amygdala images. In other words, the high-voltage field reduced the size of the amygdala and hippocampus sections by 10.5% (the learning and memory sections) after applying electric field simulations period, but the control sample showed no considerable variation (Fig. 6).

In the monkey exposed to the high-voltage field, the assessment of the levels of melatonin revealed the sleep disorders of the experimental sample. During applying electric field simulations, signs such as solitude, loss of appetite, and weight loss manifested in the experimental group primate. On the other hand, the examinations showed that the aforementioned indicators were the signs of depression and were reflective of a decrease in the natural physical activity, brain

Fig. 3 The cage of the monkey exposed to the simulated field

performance, and performance of the neural network. Now it is time to determine whether the same result is obtained with the neural simulation model.

Exposure of a body to an electric field increases the polarization capacity of that body.

Hence, it is assumed that the membrane capacitance escalates with an increase in the field exposure because the membrane polarity (dielectric) increases under the effect of the field and C also escalates. The effect of the increase in the membrane capacitance on the dynamic behavior of the neuron and neuron population is described in the following.

To analyze the response of this neuron, the external input is first assumed to be zero. If the neuron is released from its initial state, its voltage converges to the inverse voltage of the leakage channels. Therefore, for the stable state we have:

$$\begin{cases} \frac{\mathrm{d}V(t)}{\mathrm{d}t} = 0 \\ -g_{\mathrm{L}}\left(V(t) - V_{\mathrm{L}}\right) + I_{\mathrm{syn}}(t) = 0 \\ I_{\mathrm{syn}}(t) = 0 \end{cases} . \tag{9}$$

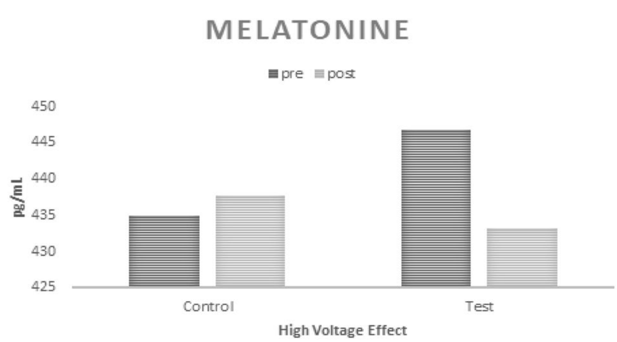

Fig. 4 The reduction in the concentration of the blood plasma melatonin in the experimental sample as compared to the control primate

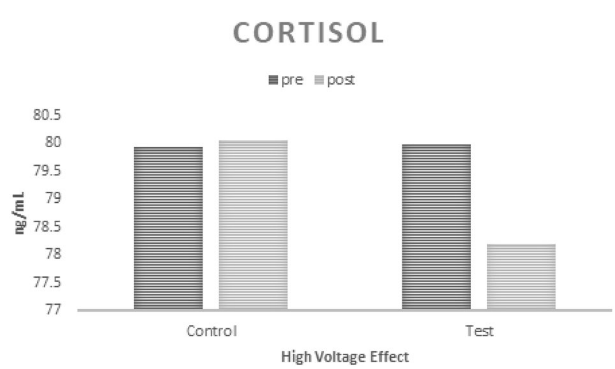

Fig. 5 The decrease in the concentration of the blood plasma cortisol in the experimental group monkey as compared to the control group primate

Therefore:

$$\lim_{t\to\infty} V(t) = V_L. \tag{10}$$

If the excitation is carried out to make the neuron fire only once (e.g., the input is a pulse with the satisfactory range and duration), the neuron behavior will be as shown in Figs. 7a and 8a. For a subthreshold input current, we have:

$$\begin{cases} -g_{\mathrm{L}}\left(V(t) - V_{\mathrm{L}}\right) + I_{\mathrm{syn}}(t) = 0 \\ I_{\mathrm{syn}}(t) = I = \mathrm{cte} \end{cases} . \tag{11}$$

Therefore, the neuron does not fire after the pulse input, but the voltage of its membrane potential increases (Figs. 7b, 8b). If the neuron input current is a suprathreshold current, we have:

$$\lim_{t\to\infty} V(t) = \frac{I}{g_{\mathrm{L}}} + V_{\mathrm{L}} > V_{\mathrm{th}}. \tag{12}$$

Therefore, when the potential difference of the membrane increases after the neuron fires and exceeds the threshold, it fires the neuron and the firing continues (Figs. 7c, 8c).

The objective is to study the effect of the increase in the membrane capacitance at the neuron fire rate, and it is assumed that the average synaptic current flowing into the neuron is invariant, low, and near the threshold. The membrane voltage is obtained by solving the differential equation.

If $t_i = 0$ and $t_f = T$, then

$$V(T)e^{\left(\frac{g_{\mathrm{L}}}{C}T\right)} - V(0) = \frac{I_{\mathrm{mean}}}{g_{\mathrm{L}}}e^{\left(\frac{g_{\mathrm{L}}}{C}T\right)} - \frac{I_{\mathrm{mean}}}{g_{\mathrm{L}}}, \tag{13}$$

$$T = \frac{C}{g_{\mathrm{L}}} \ln\left(\frac{g_L V(0) - I_{\mathrm{mean}}}{g_L V(T) - I_{\mathrm{mean}}}\right). \tag{14}$$

Since $V(T) = V_{\mathrm{th}}$ and $V(0) = V_{\mathrm{reset}}$, therefore

$$T = \frac{C}{g_{\mathrm{L}}} \ln\left(\frac{g_L V_{\mathrm{reset}} - I_{\mathrm{mean}}}{g_L V_{\mathrm{th}} - I_{\mathrm{mean}}}\right). \tag{15}$$

Finally, the neuron fire rate is calculated with the following formula:

$$f = \frac{1}{T + t_{\mathrm{ref}}}. \tag{16}$$

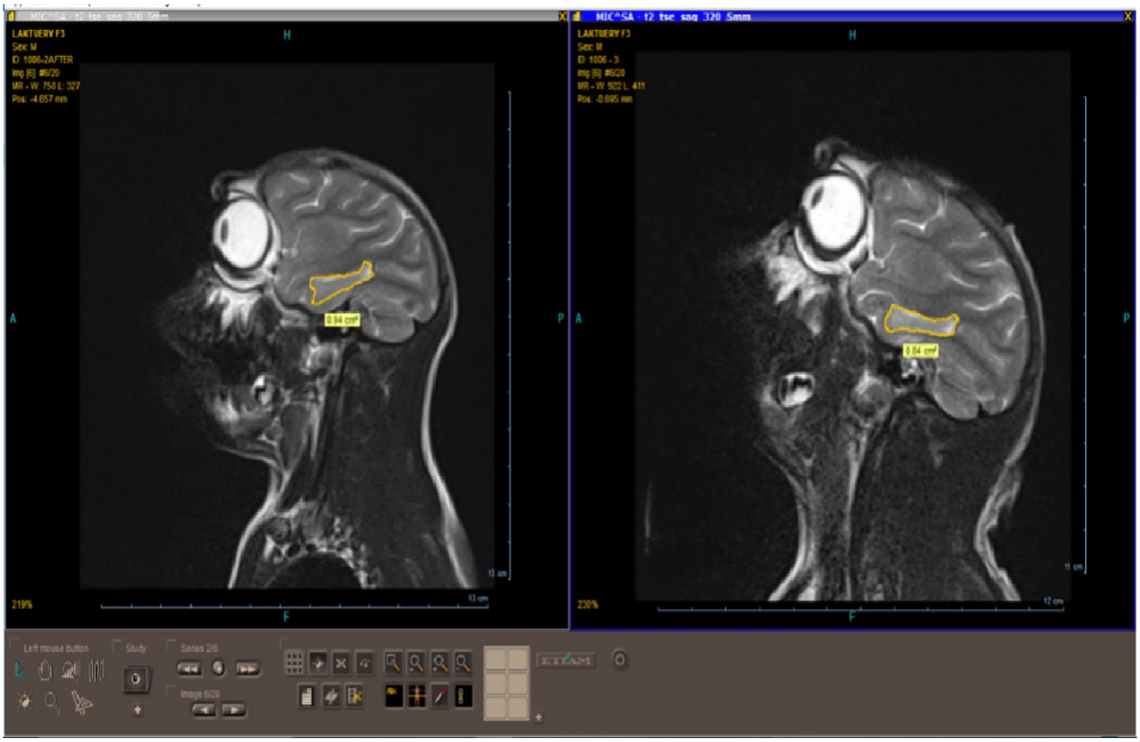

Fig. 6 The changes to the MRI images of the volumes of hippocampus and amygdala in the experimental group monkey before and after applying electric field simulations

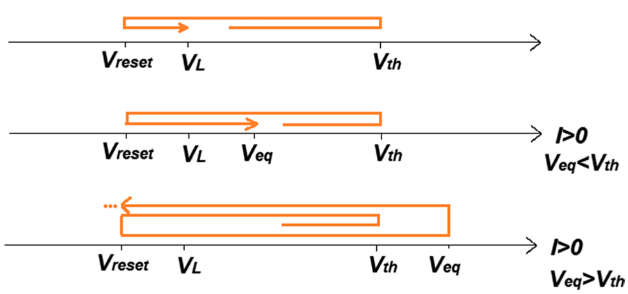

Fig. 7 The neuron behavior with different hypothetical inputs: **a** the input is only a pulse; **b** the input is a pulse and a subthreshold current; **c** the input is a suprathreshold current

As seen in relation formula 15, if C (the membrane capacitance) increases, the neuron fire time escalates and the neuron fire rate decreases (Izhikevich 2007).

Although the behavior of each neuron plays an important role in the cognitive, perceptional, and emotional brain activities, this is the collective behavior of the neurons that accounts for higher brain activities. Hence, a number of LIF neurons were juxtaposed in a network, which consisted of eight pyramidal neurons (excitatory) and two inhibitory neurons (interneurons). The S1 and S2 neurons model the memory in this complex, and a considerable increase in the fire rate of these neurons results in the activation of the memory. The NS neurons are the adjacent neurons, and the interneurons (IN) are the neurons that exist in that part of the brain cortex. All of these neurons are interconnected with similar weights. Each neuron receives excitatory inputs from 800 neurons outside of the region mainly via the AMPA receptors. The excitatory neurons stimulate the pyramidal neurons and interneurons via the glutamate neurotransmitters and the NMDA and AMPA receptors. The interneurons also suppress the pyramidal neurons and other interneurons via the GABA neurotransmitter and its receptors. Figure 9 shows the raster diagram and the fire rate diagram of all of the neurons. As shown in this figure, the activity of the neurons decreased considerably in the cortex after the escalation of the capacitance.

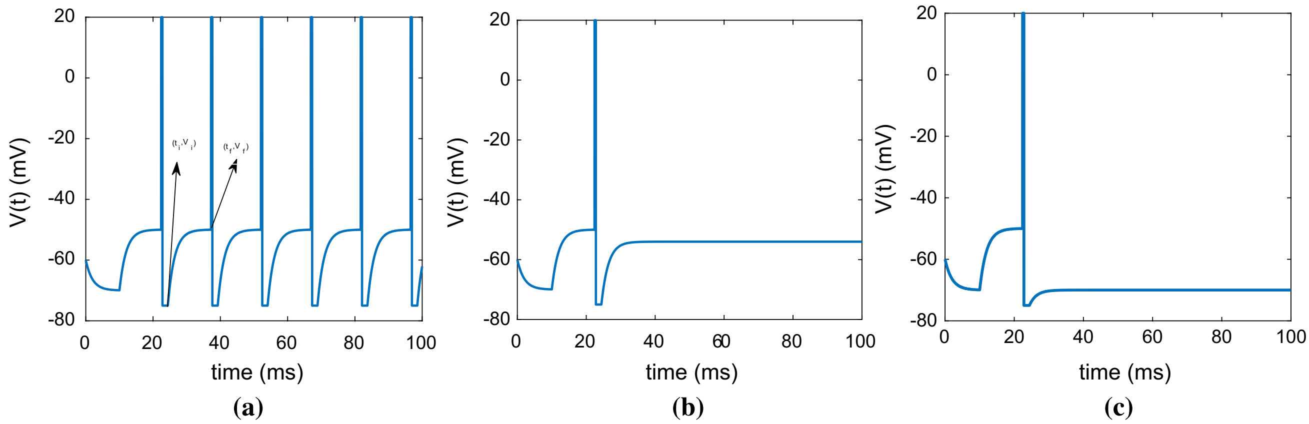

Fig. 8 The neuron response to pulse inputs: **a** pulse + subthreshold, **b** suprathreshold, **c** *ti* is the neuron integration start time and *tf* is the fire time

The raster diagram (Guo et al. 2012) shown in Fig. 9 (the bottom images) depicts the moment S1, S2, NS (six neurons), and IN (two neurons) fire (top to bottom).

In the fire rate diagram shown in Fig. 9 (the top images), the blue, red, green, and black diagrams show the fire rates of neuron S1, neuron S2, NS neurons, and IN neurons, respectively.

A decrease in the cortex activity reflects cognitive, emotional, perceptional, or sensory impairments depending on the region affected. For instance, the fMRI (functional magnetic resonance imaging) examinations showed that a decrease in the activity of DLFPC reduces the memory functionality (Hare et al. 2014; Chen et al. 2004; Liang et al. 2011). The decrease in activity in the DMPFC and amygdala regions is associated with depression and a lack of response to the negative emotional stimuli. Moreover, the simulated model explains the mechanism of the decrease in the memory and emotional reaction and depression (Fig. 9).

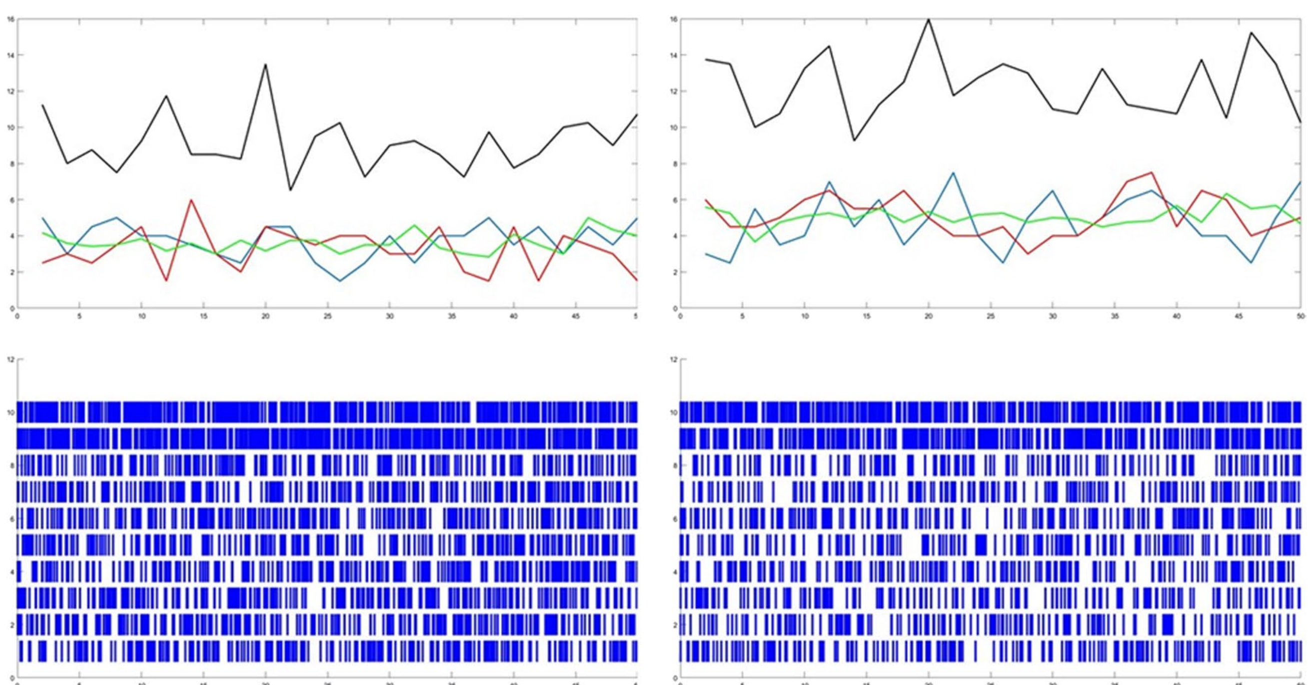

Fig. 9 Top: The fire rate diagrams; bottom: raster diagrams; left: the raster diagram and fire rate diagram of all neurons in the base state without changes and with zero electric field; right: the raster diagram and fire rate diagram of all neurons in the state of exposure to a 3 kV/m electric field that increases capacitance

Discussion

Behavioral elements are among the means of identifying changes in primates following experiments. The experimental monkey was highly aggressive, wicked, active, and conscious before the experiment and showed excelled learning and memorizing abilities. However, considerable changes were observed in the behavioral elements of this primate, which was exposed to a 3 kV/m high-voltage electric field. In other words, from the beginning of applying electric field simulations, the behavioral changes increased over time. The aggressive behavior subsided gradually and the animal's appetite was so low that a weight loss was observed. A decrease in concentration and cooperation was observed, and the monkey demonstrated sleep disorders, lack of motion, and solitude which are some of the signs of depression. However, these changes were not observed in the control primate (Videbech and Ravnkilde 2004; Sapolsky 2001; Loh et al. 2007; Izhikevich 2007; Blask 2009; LaBar and Cabeza 2006; Hickie and Rogers 2011; Tekieh et al. 2017; Burke et al. 2005; Chaddock et al. 2010; Salzman and Fusi 2010; Frodl et al. 2006; Aliyari et al. 2018).

Research results also revealed that the concentration of the blood plasma melatonin hormone decreased in the monkey exposed to high-voltage electric fields. In addition, melatonin significantly contributes to the sleep and wake cycle, and any impairment of the secretion of this hormone results in the sleep disorder, which is another characteristic sign of depression. Investigations also indicated that electromagnetic fields inhibit the secretion of this hormone and a decrease in the release of melatonin leads to the sleep disorder, which subsequently reduces concentration, attention, memory, and learning (Kazemi et al. 2018). The rest of the research findings indicated that the concentration of blood plasma cortisol decreased in the monkey exposed to the high-voltage field. Moreover, cortisol plays a major role in stress and anxiety, which significantly contribute to the development of depression. The excessive decrease in the cortisol level also results in a lack of motion and indifference, which are the signs of depression. In fact, an abnormal increase or decrease in cortisol may be indicative of depression. Furthermore, abnormal changes are substantially involved in cognitive damages such as impairment of learning and memory (LaBar and Cabeza 2006; Brady et al. 2011; Van Petten 2004; Constantinidis and Procyk 2004; Laakso et al. 1995; Soininen et al. 1994; Squire 1992). Finally, the MRI-assisted examinations of the anatomy of the hippocampus and amygdala of this monkey showed a decrease in the volume of these components, which is a sign of cognitive changes such as reduced learning and memory functionality (Videbech and Ravnkilde 2004; Tekieh et al. 2017; Laakso et al. 1995; Soininen et al. 1994).

The neural simulation model was created to study the performance of the human brain cortex, and different results were obtained by changing the certain elements of the model in each state and condition.

After placing a dielectric in an electric field, the dipole direction converges to the field lines, and with an increase in the electric field power, more dipoles form in line with the field. It is also assumed that the neuron membrane polarity increases by placing a neuron in a high-voltage electric field. Therefore, this assumption was used in the neural network simulation model as the membrane capacitance increased and the model performance was recorded. The application of this model led to a result similar to the experimental state result, which involved a decrease in the performance membrane neural network model or in other words led to depression (Videbech and Ravnkilde 2004; Sapolsky 2001; Goodwin and Jamison 2007; Hickie and Rogers 2011; Burke et al. 2005; Frodl et al. 2006; Wilson 1988). Hence, the results of the neural simulation model and the experimental results suggest that proximity to high-voltage fields increases the probability of development of depression. Hence, the results of studying the primates can be generalized to humans. On the other hand, it could be concluded that the resulting model can yield satisfactory results of the effect of high-voltage fields on humans by changing the characteristic indicators.

In general, the results of the neural simulation model, the behavioral and hormonal assays, and the MRI imaging were indicative of the development of depression in the monkey that was exposed to the simulated 3 kV/m high-voltage field (effects of exposure to a 400-kV, 50-Hz transmission line). Hence, proximity to high-voltage masts (because of the place of residence, workplace, etc.) and constant exposure to high-voltage electric fields may lead to psychological disorders such as depression.

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Compliance with ethical standards

Conflict of interest The authors have no potential conflict of interests pertaining to this journal submission.

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