氏　名　(本籍)	おおもり　としあき 大　森　敏　明　　　(岩手県)
学 位 の 種 類	博　士（情報科学)
学 位 記 番 号	情　博　第 278　号
学位授与年月日	平成１６年３月２５日
学位授与の要件	学位規則第４条第１項該当
研究科、専攻	東北大学大学院情報科学研究科（博士課程）情報基礎科学専攻
学位論文題目	Dynamical Neural Network Models for Memory Function and for Oscillatory Phenomena in Brain (脳における記憶機能および振動現象に関する動的ニューラルネットワークモデル)
論文審査委員	（主　査） 東北大学教授　堀口　剛　　東北大学教授　中尾　光之 東北大学教授　矢野　雅文（工学研究科）　東北大学助教授　田中　和之

論 文 内 容 要 旨

Chapter 1　*Introduction*

The brain of animals of higher order is a remarkable organ which exhibits brain functions such as memory, cognition, attention, consciousness and so on. Clarification of brain functions is one of important subjects for scientific research in the 21st century. Investigation of the brain functions of animals of higher orders including the human by using neural networks is considered to be very important in order to understand the brain itself; physical models of the brain functions by means of neural network models are useful in order to clarify properties of a part of the brain by numerical simulations or analytical methods. By using biologically plausible neural network models, it may be possible to understand results obtained by physiological and behavioral studies. Then we may give some suggestions to experimental studies from those theoretical approaches.

The memory is one of basic functions in the brain since the memory function is deeply associated with other brain functions such as cognition, attention, consciousness and so on. Hence modeling of the memory function and its investigation are important in order to understand the brain functions. In the present thesis, we construct neural network models for the memory function in the hippocampus and that for working memory.

Brain waves are considered to be deeply associated with the brain functions by experimental studies using electroencephalography or other methods. In order to understand the brain functions, it would be essential to clarify the mechanism of the emergence of the brain waves. In the present thesis, we construct neural network models for oscillatory phenomena in the hippocampus, which are associated with the memory function, and also those for oscillatory phenomena in thalamus, which are concerned with control of information transmission in the brain.

Since the information processing in the brain is performed dynamically in order to deal with the external inputs from the changing environment, it is important to investigate dynamical aspects of the information processing in the brain. Therefore, we construct dynamical neural network models for the brain functions and also those for the oscillatory phenomena in the brain.

Thus, in the present thesis, we propose dynamical neural network models for memory function and those for oscillatory phenomena and investigate dynamical properties of the models and emergence of the brain waves.

The present thesis consists of six chapters. In Chapter 2, we propose and investigate neural network models for memory functions in the hippocampus. In Chapter 3, we propose and investigate neural network models for oscillatory phenomena in the hippocampal CA region. In Chapter 4, we construct a minimal model for working memory by using one-compartmental Hodgkin-Huxley neurons. In Chapter 5, we propose and investigate neural network models for oscillatory phenomena in the thalamic system. We give conclusion of the thesis in Chapter 6.

Chapter 2 Neural Network Models for Memory Function in Hippocampus

2. 1 Noise Effect on Memory Recall in Neural Network Model of Hippocampus

We proposed a three-layered neural network model for memory function in the hippocampus with deterministic noise and that with stochastic noise. We investigated noise effect on the memory recall and dependence of the memory recall on the strength of external input by numerical simulations. We showed degree of recall as a function of the inverse of noise level, β, for the hippocampal model with deterministic noise in Fig. 1. We found that reasonable values of noise improve the memory recall in the both models. Thus it turned out that the noise effect is important for the memory function in the hippocampus. We also found that the strength of external input is an important factor for the memory recall.

2. 2 Neural Network Model with Excitatory Neurons and Inhibitory Neurons

We proposed a three-layered neural network model of the hippocampus with excitatory neurons and inhibitory neurons. We allocated an inhibitory neuron in each layer and assumed that each excitatory neuron and the inhibitory neuron have mutual connections within a layer. By numerical simulations, we investigated a role of the inhibitory neurons on the memory recall. We showed dependence of degree of memory recall on thresholds in the model without inhibitory neurons in Fig. 2 (a) and that with inhibitory neurons in Fig. 2 (b). Degrees of recall are shown by gray levels and the case of bursting is indicated by meshed area. Brighter area indicates the case of better memory recall. From these figures, we found that stability of memory recall is enhanced by the introduction of inhibitory neurons. Thus, it turned out that the inhibitory neurons are important for the memory function in the hippocampus.

Chapter 3 Neural Network Models for Oscillatory Phenomena in Hippocampal CA Region

3. 1 Neural Network Model for Oscillatory Phenomena in Hippocampal CA3 Region

We proposed a neural network model for oscillatory phenomena in hippocampal CA3 region with excitatory neurons and inhibitory neurons. We assumed that each neuron obeys a Hodgkin-Huxley equation and the model consists of a layer of the excitatory neurons and that of the inhibitory neurons. We investigated properties of oscillatory phenomena and dependence of oscillatory phenomena on synaptic strength by numerical simulations. The obtained results show that the theta oscillation and the gamma oscillation emerge in both layer. We showed dependence of dominant frequency of spike correlation in the layer of excitatory neurons on the synaptic strength between excitatory neurons in Fig. 3. From this result, we found that excitatory neurons are important for emergence of oscillatory phenomena in the hippocampal CA3 region. We also found that inhibitory neurons are important for oscillatory phenomena in the hippocampal CA3 region. From these results, it turned out that both excitatory neurons and inhibitory neurons are important for oscillatory phenomena in the hippocampal CA3 region.

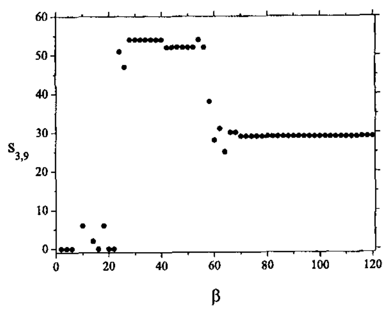

Fig. 1

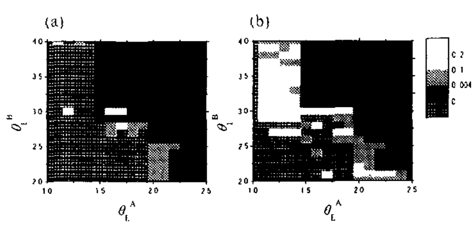

Fig. 2

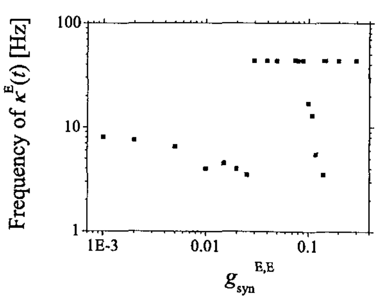

Fig. 3

3. 2 Neural Network Model for Oscillatory Phenomena in Hippocampal CA1-CA3 Region

We proposed a three-layered neural network model for oscillatory phenomena in hippocampal CA1-CA3 region consisting of a layer of CA1 pyramidal cells, that of CA3 pyramidal cells and that of interneurons. Each neuron is assumed to obey a Hodgkin-Huxley equation. By numerical simulations, we showed that the delta and the theta oscillation emerge under the given gamma oscillation in the proposed model. Furthermore, we found that the delta, the theta and the gamma oscillation emerge in the whole neural network as shown in Fig. 4. From the dependence of the oscillatory phenomena on the synaptic strength, we found that the delta and the theta oscillation emerge on the layer of the CA1 pyramidal cells for small values of synaptic strength, which is from the layer of the CA3 pyramidal cells to that of the CA1 pyramidal cells, whereas only the gamma oscillation exists on the layer of the CA1 pyramidal cells for large values of the synaptic strength, which is from the layer of the CA3 pyramidal cells to that of the CA1 pyramidal cells. On the other hand, we found that the delta and the theta oscillation emerge on the layer of the CA1 pyramidal cells for large values of synaptic strength, which is from the layer of the CA1 pyramidal cells to that of the interneurons. These results suggest that the effect of neuromodulation is important for the emergence of oscillatory phenomena in the hippocampal CA region.

Chapter 4 Neural Network Model for Working Memory with Hodgkin-Huxley Neurons

We proposed a minimal model for working memory by using one-compartmental Hodgkin-Huxley neurons. We assumed that there exist excitatory neurons and inhibitory neurons. The excitatory neurons are distinguished as several groups of selective neurons and one group of non-selective neurons. The selective neurons are assumed to form subpopulations in which each selective neuron belongs to only one of subpopulations. The non-selective neurons are assumed not to form any subpopulation. Synaptic strengths between neurons within a subpopulation are assumed to be potentiated. By numerical simulations, we found that persistent firing of the selective neurons, which corresponds to the retention of memory as the function of the working memory, occurs in the proposed model as shown in Fig. 5. We found a kind of phase transition for the degree of retention of firing of the selective neurons as a function of the degree of potentiation of synapses between selective neurons as shown in Fig. 6. Furthermore, we found that the strength of external input and the strength of NMDA synapse are important factors for dynamical behaviors of the network; for example, if we enhance the strength of the external input to a subpopulation while the persistent firing is occurring in other subpopulation, the persistent firing occurs in the subpopulation or is sustained against the external input. These results reveal that the neural network as for the function of the working memory is controlled by the neuromodulation and the external stimuli within the proposed model.

Chapter 5 Neural Network Models for Oscillatory Phenomena in Thalamic System

5. 1 Oscillatory Phenomena in Neural Network Model with Thalamic Reticular Neurons and Cholinergic Neurons

We proposed a two-layered neural network model for oscillatory phenomena in thalamic system consisting of a layer of thalamic reticular neurons and that of cholinergic neurons. The thalamic reticular neurons are assumed to be described as Hodgkin-Huxley neurons with calcium current. We introduced a dynamics of concentration of acetylcholine, which depends on state of the cholinergic neurons and assumed that conductance of the thalamic

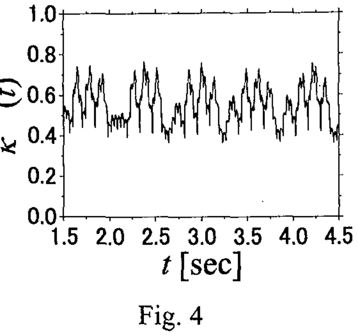

Fig. 4

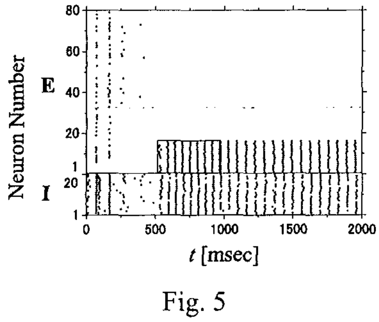

Fig. 5

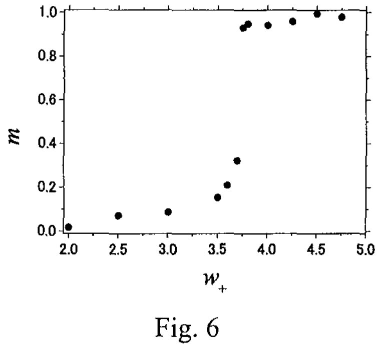

Fig. 6

reticular neurons is dynamically regulated by neuromodulation due to the acetylcholine. We investigated an effect of neuromodulation due to the acetylcholine on the oscillatory phenomena in the layer of the thalamic reticular neurons. We showed states of neurons and time evolution of the concentration of the acetylcholine in Figs. 7 and 8, respectively. In Figs. 7 and 8, we found that a dynamical transition between a bursting state and a resting state occurs in the layer of the thalamic reticular neurons by the effect of the acetylcholine. From these results, it turned out that the effect of the neuromodulation due to the acetylcholine is important for the oscillatory phenomena in the thalamic system.

5. 2 Oscillatory Phenomena in Neural Network Model with Thalamocortical Neurons, Thalamic Reticular Neurons and Cholinergic Neurons

We proposed a three-layered neural network model for oscillatory phenomena in the thalamic system consisting of a layer of thalamocortical neurons, that of thalamic reticular neurons and that of cholinergic neurons. We assumed that the thalamocortical neurons and the thalamic reticular neurons are described as Hodgkin-Huxley neurons with calcium current and cation current and those with calcium current, respectively. We introduced a dynamics of concentration of the acetylcholine, which depends on the state of the cholinergic neurons and assumed that conductance of the thalamocortical neurons and the thalamic reticular neurons are dynamically regulated according to the concentration of the acetylcholine. By numerical simulations, we investigated an effect of neuromodulation on the oscillatory phenomena in the layer of the thalamocortical neurons and that of the thalamic reticular neurons. We showed a state of neurons in Fig. 9. We found that a dynamical transition between a bursting or spiking state with subthreshold oscillation (Fig. 10) and a resting state occurs in the layer of the thalamocortical neurons. We also found that a dynamical transition between a bursting state (Fig. 11) and a resting state occurs. From these results, it turned out that the neuromodulation is important for the dynamical transition in the oscillatory phenomena in the thalamic system.

Chapter 6 Conclusion

We proposed dynamical neural network models for memory function in the brain and those for oscillatory phenomena in the brain. By numerical simulations we found that the memory recall is improved by the effect of noise and inhibitory neurons. Furthermore, it turned out that both excitatory neurons and inhibitory neurons are important for the memory function and oscillatory phenomena. We also found that an effect of neuromodulation is important for emergence of oscillatory phenomena in the brain.

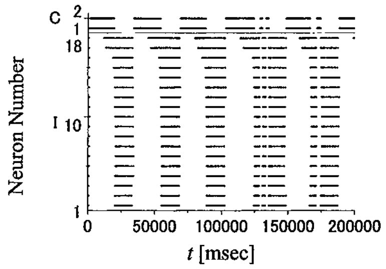

Fig. 7

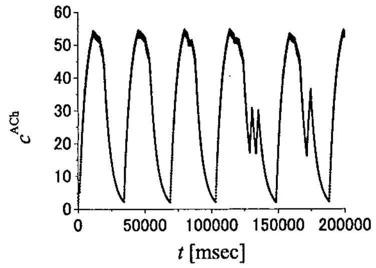

Fig. 8

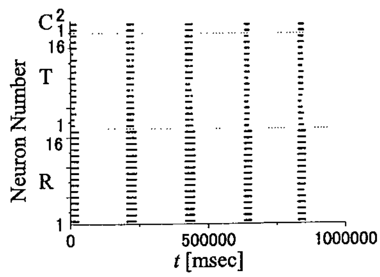

Fig. 9

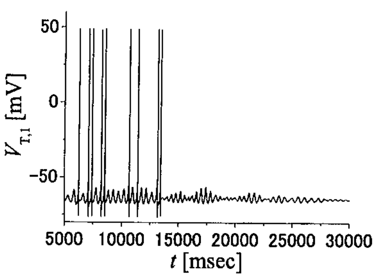

Fig. 10

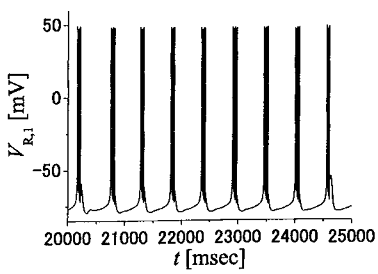

Fig. 11

論 文 審 査 の 結 果 の 要 旨

脳の記憶機能や脳波の発現機構を解明することは，認識，注意，意識など脳の高次機能の研究に関連した重要な課題である。本論文は海馬における動的記憶についてのノイズや抑制性ニューロンの役割，ワーキングメモリに関するミニマムモデルの構築，また海馬系や視床系における脳波の発現について，生理学的知見に基づいた動的ニューラルネットワークモデルを提案して数値実験を行い，得られた研究成果をまとめたもので全文６章よりなる。

第１章は序論である。

第２章では，海馬系の記憶機能について，ノイズの効果を取り入れたニューラルネットワークモデルを提案して数値実験を行い，適当なノイズの下では記憶の想起がノイズのない場合に比べて２倍程度向上する結果を得た。さらに，抑制性ニューロンの働きにより，記憶想起が安定することを示した。これらは重要な知見である。

第３章では，海馬ＣＡ領域における振動現象を研究している。Hodgkin-Huxley ニューロンを用いて，ＣＡ１錐体ニューロン層，ＣＡ３錐体ニューロン層，介在ニューロン層の３層ニューラルネットワークモデルを提案し，抑制性ニューロンと興奮性ニューロンの協調により，ガンマ振動とシータ振動に加えて，デルタ振動が発現することを示した。

第４章では，行動や意志決定に関与していると考えられるワーキングメモリの研究を行っている。ニューロン集団の持続的な発火を得るためには，従来のマルチコンパートメントモデルは必要なく，シングルコンパートメントモデルで十分であることを示した。またニューロン集団内のＡＭＰＡとＮＭＤＡの興奮性シナプスの強さの関数として，発火持続時間が相転移的な振る舞いをすることを見出した。これは注目に値する結果である。

第５章では，視床系の振動現象を研究するために２層および３層ニューラルネットワークモデルを提案して数値実験を行っている。３層モデルにおいて，視床系ニューロンのコンダクタンスを調節するアセチルコリンの効果により，振動現象の動的な遷移が発現することを示した。これは視床系における情報伝搬の制御を解明する上で重要な知見である。

第６章は結論である。

以上要するに本論文は，動的ニューラルネットワークモデルを構築して，脳の記憶機能と脳波の発現機構を研究したものであり，情報基礎科学，情報統計物理学ならびに神経回路学の発展に寄与するところが少なくない。

よって，本論文は博士（情報科学）の学位論文として合格と認める。