FUNCTIONAL RELEVANCE OF ‘EXCITATORY’
GABA ACTIONS IN CORTICAL INTERNEURONS:
A DYNAMICAL SYSTEMS APPROACH

HIROSHI FUJI*, KAZUYUKI AIHARA†, and ICHIRO TSUDA‡

*Department of Information and Communication Sciences, Kyoto Sangyo University
Kyoto 603-8555, Japan
fujii@bacco.kyoto-su.ac.jp

†Institute of Industrial Science, the University of Tokyo, and
ERATO Aihara Complexity Modeling Project, JST
Tokyo 153-8505, Japan
aiham@sat.t.u-tokyo.ac.jp

‡Department of Mathematics, Hokkaido University
Sapporo 060-0810, Japan
tsuda@math.sci.hokudai.ac.jp

Received 17 April 2004
Accepted 5 May 2004

The non-classical, but frequently reported behavior of GABA_A receptor-mediated excitation in mature CNS has long been regarded as a puzzle. We theorize that the function of cortical GABAergic interneurons, which might constitute a subsystem of brain’s GABA interneurons, is their ability of switching from inhibitory action to excitatory action depending on the level of spatio-temporal activity in progress. From the perspective of a dynamical systems approach, such “excitatory” GABAergic responses may serve to temporarily invoke attractor-like memories when extensively activated by, for example, top-down signals as category information or attention, while an ongoing background state of GABA changes its action to inhibition, returning the dynamical nature of the memory structure back to attractor ruins.

Keywords: Attractor ruin; chaotic itinerancy; Milnor attractor; GABAergic interneuron; activity-dependent excitatory GABA action;

1. Introduction

GABA is known as the principal mediator of inhibition, but there exist numerous reports that GABA may play an excitatory role under some conditions.

First, it is known that GABA_A acts as an excitatory transmitter during developmental stage, and it is after some maturation period that GABA transforms its functional action into inhibitory. The excitatory nature of GABA_A in neonatal period may be due to the change of Cl⁻ homeostasis causing the upward shift of the
reversal potential $E_{GABA}$. What is the functional role of such GABA-mediated "excitatory" actions? Although there are controversies, it is argued that this may be due to the necessity of sculpting network circuits in developing period [9, 10, 11, 25]. After the maturation period, "GABA needs to become inhibitory in a hurry to stabilize the new neural nets" [66].

The puzzle surrounding the GABA action begins at this point. There are a number of findings indicating that GABA$_A$-receptors mediate a depolarizing action in mature CNS neurons [4, 8, 32, 48, 49, 57, 64, 84]. (See, also [27, 67].) It is reported that when intensively activated, dendritic GABA$_A$ receptors excite rather than inhibit post-synaptic neurons, which are normally hyperpolarized by brief GABA$_A$ receptor activation. For example, Staley et al. [64] showed that while a single distal orthodromic stimuli induces hyperpolarizing GABA$_A$ receptor mediated PSP$_S$ (post-synaptic potentials), a train of 40 stimuli at 200 Hz yielded additional late depolarizing potential, and this depolarization is strong enough to modulate the voltage-dependent $Mg^{2+}$ block of synaptic NMDA receptor activations. Staley et al. called this synapse-specific phenomenon as "activity-dependent GABA$_A$ receptor-mediated depolarization", and emphasized that this should be distinguished with the rapid activity-independent GABA$_A$ depolarizing responses during developmental period. We may abbreviate such activity-dependent excitatory GABA actions as "eGABA".

What is the functional consequence of this eGABA action? There could be several scenarios, but it appears that very few attempts have been made to systematically study the functional consequences of the phenomenon.

The purpose of this paper is, partly, to give a short review of the apparently strange GABA action, and then give possible theoretical implications on its functional consequences. A key might exist in its role of consolidating memory structure dynamics, and our hypothetical standpoint might present a key to solve the puzzle of eGABA action. We shall propose that the puzzle could be solved if viewed from a dynamical systems standpoint, and which could open a new prospect in memory dynamics. At the same time, we would like to address both experimental and theoretical significance of eGABA action in the organization of cognitive functions.

In the next section, we first introduce the concept of attractor ruins, and then in Section 3 we review the experimental data about eGABA actions. In Section 4 we turn to our main subject - functional consequences of eGABA actions, and propose a new scenario on the role of eGABA actions in mature CNSs.
2. Dynamical Systems View to Cortical Dynamics and Cognitive Functions

2.1. Itinerant dynamics in brain activity

Transitory chaotic phenomena have been observed in experimental brain studies, accompanied with behavioral and perceptual stages of the animal. In olfactory systems, Freeman and colleagues report the appearance of chaotic transitions between quasi-attractors with related to perceptive stages of odors [18, 19, 20, 63]. Transitory appearance of synchronized states among desynchronized states in local field potentials (LFP) of cat visual cortex is reported by Gray [26], where a synchronized state is postulated to be related to binding process of fragmentary visual information. Kay observed the propagation of wave packets of γ- and δ- range activity [37, 38] in different stages of olfaction perception, and the irregular appearance of synchronization of large phase difference [21]. A common feature of these phenomena is chaotic and itinerant transitions between behavioral states.

How should we interpret and describe transitory dynamics in the brain?

2.2. Chaotic itinerancy among attractor ruins

Brain activity, and memory dynamics in particular, have often been considered in terms of “attractors”. Classical attractors, i.e., attractors in the geometric sense are primarily concepts in low-dimensional dynamical systems, and do not provide an appropriate language for the interpretation of those transitory dynamics observed in the brain. To describe such dynamics typically appears in high-dimensional dynamical systems, a non-classical concept of dynamical states which include both stability and instability is necessary.

The concept of chaotic itinerancy, proposed firstly by Ikeda [30], Kaneko [33] and Tsuda [72] describes the recurrent process of the genesis of ordered states and their collapses, where the notion of “attractor ruin” play the key role in the description of itinerancy dynamics. Roughly, an attractor ruin is a “ruin” in that there are orbits approaching and stay there for a while, but may simultaneously possess repelling orbits from itself. Intuitively, an itinerant dynamics may appear as a composition of ruins of fixed points, limit cycles, tori and/or chaos, together with orbits that connect those “attractor ruins”. In fact, those ruins are not attractors in the classical sense, and we shall redefine them later. Chaotic itinerancy may be characterized as a state of dynamics that transiently itinerates among attractor ruins. A chaotic itinerancy has particular characteristics in its structure and dynamics. For such materials, please refer to the papers [36], or [35].

Suppose that a dynamical system has multiple stable states. It means that the system has multiple-stable geometric attractors. The phase space is divided by basins of attraction, and the dynamics of the system is such that it asymptotically approaches one of the attractors in the phase space, which is determined by the initial
state. What would happen if such a system is destabilized so that all the attractors lose stability? In other words, what would be the dynamics in a phase space where no stable attractors exist but ruins? If the level of destabilization is strong enough, it would lead to a turbulent state. However, for some destabilization level, one would expect an intermediate state something between turbulent and ordered states, and which would transit among attractor ruins intermittently. It is now known that such itinerant dynamics appear in high-dimensional dynamical systems in a variety of areas, e.g., optical systems, electro-chemical systems, ecosystems, protein dynamics, acto-miosin systems, rat limbic system, and human EEG (see, Kaneko and Tsuda (eds.), Focus Issue: Chaotic Itinerancy [34]), and recognized that it is universally observed phenomena.

What characterizes “attractor ruins” in mathematical sense? At the present moment, it is not fully understood. However, attractor ruins must have unstable manifolds to some directions in its neighborhood. The Milnor attractor and its perturbed structures are eligible to be an attractor ruin. By definition, a Milnor attractor possesses a positive measure of attracted orbits, but simultaneously may possess repelling orbits from the attractor. A Milnor attractor may thus provide a mechanism of allowing both transition and rejections to and from a state. For the detailed definition of the Milnor attractor, see e.g., [52].

It is noted that the concept of attractor ruins may include a wider class of nonclassical attractors than the Milnor attractor, but the details of attractor ruins are not yet formalized. By this reason, we may use the term “attractor ruins” in this article to include possible but unknown classes of ruins.

An explicit example of a dynamical system was given by Tsuda and Umemura [76] where no stable geometric attractors exist. Their locally coupled circle maps each of which possesses an identical Milnor attractor transformed firstly to tori as the coupling strength is increased, and then there appear an itinerant chaotic dynamics connecting those tori.

Another example of a complete dynamical system in which a beautiful but complicated Milnor attractor inhabits is reported in Tsuda, Fujii and their colleagues ([77], this issue). The model is a system of class $I^*$ neurons locally coupled by gap junctions, which exhibits chaotic alterations between synchronous and desynchronized states.

The significance of the concept of “attractor ruins” is in its potential ability of overcoming the conceptual difficulty of the attractor view to the memory, as how to cope with binding for novel stimuli, temporal or sequential aspects as episodic memory, etc., and also difficulty in interpreting those transitory dynamics in the brain. We claim that “memories” in the brain inhabit in the form of attractor ruins rather than conventional geometric attractors, which provides a contemporary framework on memory dynamics in the brain. An attractor ruin could be regarded as a shot of “memory trace”, and an itinerant dynamics among a sequence of ruins as an episodic memory. One of the authors argued how an “episodic memory” is
organized in the hippocampal system, as well as the role of Cantor coding in category formation in the cortex [74, 75], while Aihara et al. [1, 3] studied possible role of itinerant dynamics in memory searching within chaotic network systems. For further discussions on cognitive roles of itinerant dynamics, refer to [74, 75].

2.3. Principles of genesis of attractor ruins

How is the itinerant dynamics organized in the brain? We are far from understanding the physiological and mathematical mechanism of memory formation, nor its form of existence in in situ brain. It is pointed out, however, that (at least) three principles may take part in the genesis of ruins.

(1) Delayed feedback: Delay-differential equations can, in principle, exhibit chaotic itinerancy as well as fully developed chaos [30]. This suggests that a delayed feedback loop in the cortical networks may produce chaotic itinerancy if the feedback yields a certain degrees of instability: strong enough for destabilizing attractors, but weak enough to suppress chaotic motion. Actually, Freeman [17] observed chaotic behaviors in the olfactory bulb, which possesses feedback connections with the olfactory cortices such as the prepyriform cortex and the anterior olfactory nucleus. Freeman found that the delayed feedback would be a necessary condition for the existence of chaos, investigating the system without feedback from the cortex by cutting off the lateral olfactory, where chaos disappeared and the system exhibited damped oscillations. Because this is not a sufficient condition for the existence of chaos, the term of delayed feedback does not necessarily guarantee the presence of chaos. However, chaos can appear under some restriction on parameters such as the strength of the feedback and the delay time. Furthermore, for the presence of chaotic itinerancy, some delicate conditions appear to be necessary. Actually, Freeman found a similar transitory phenomenon to chaotic itinerancy under a certain parameter condition, and also obtained essentially the same phenomenon in computer simulations of his model KIII on olfactory systems.

(2) Gap junction-coupled interneuron systems: Gap junction-coupled neuronal systems can, in principle, exhibit emergent spatio-temporal chaotic dynamics if neurons possess a certain condition on its ionic channel properties. In fact, gap junction-coupled class I* [23, 77] neurons show a transitory dynamics of synchronized and desynchronized states even under a spatially and temporally constant injected background currents. The authors showed that this transitory dynamics could be regarded as being itinerant around a Milnor attractor possessing a beautiful internal structure ([77], this issue). The transient synchrony of local field potential observed by Gray [26] might be interpreted as a consequence of interplay of this interneuron dynamics and the pyramidal cell systems in the cortex.
(3) **Inhibition of attractors**: Inhibitory actions can turn an “attractor” into “attractor ruins”, and which could be a dynamic trigger of switching between an “attractor” dynamics and itinerant dynamics among ruins. This is an expression of the general principle that inhibitory neurons may make the memory structure dynamical. (See, Section 4.) Prototypical examples have been described by Tsuda [71, 73, 74] in the study of dynamic associative memory and episodic memory formation. In conventional neural network model of associative memory, an attractor embedded in recurrent connections of excitatory neurons is a representation of memory of an event or a pattern. Attractor networks may be regarded as an expression of the retrieval process of memory, in which its activity eventually reaches a stationary state represented by each attractor. An addition of local or global negative feedbacks via inhibitory neurons can in principle destabilize such attractors. In the balance between stability and instability, the attractors can become neutrally stable, which gives rise to the genesis of Milnor attractors, leading to emergence of itinerant dynamics.

Chaotic itinerancy among Milnor attractors can also be born in a system of coupled chaotic neurons [1, 2, 3]. This shows also switching of memory dynamics between attractor and itinerant motion. Mechanism of the chaotic itinerancy in globally coupled map is explained by the presence of crisis-induced intermittency and change of stability along the direction of the orthocomplement on invariant subspaces [41]. Hierarchical structure among invariant subspaces in chaotic networks with associative dynamics is also clarified [40].

The view that “inhibition could turn an attractor into an attractor ruin under a certain condition” is a hypothetical statement derived from dynamical systems considerations, which might provide us a “theoretical link” between the concept of “itinerant dynamics” and “inhibition” in the brain. With this in mind, one may wonder what kind of physiological processes could “link” the two theoretical concepts of “itinerant dynamics” and “inhibition”, and on which question this paper will focus.

3. **Excitatory Actions of GABA$_A$ - Experimental Evidence**

Two distinct processes of excitatory GABA actions have been reported, which occur under different conditions and on different time scales. One is the rapid activity-independent GABA$_A$ depolarizing responses during developmental period [14, 24, 25, 56, 62]. The other is activity-dependent GABA$_A$ receptor-mediated depolarization in adult [4, 8, 32, 48, 49, 57, 64, 84]. (See, also [27, 67].) The two phenomena are different in their ionic processes and time scales.
3.1. Developmental stage

The homeostasis of ionic concentrations between intra- and extra-cellular neurons, in particular for the $Cl^-$, is more dynamic than had been assumed. In fact, it is known that GABA is excitatory in the immature brain. Also, GABA-releasing synapses are formed first, and glutamatergic contacts appear later in the developing stage. In the neonatal period, the $Cl^-$ importer NKCC1 expression, which transport $Cl^-$ ions from the outside to the inside of the cell predominates as compared with the KCC2, the $Cl^-$ exporter expression which transports $Cl^-$ ions in the opposite direction. Thus because of the predominance of NKCC1, intracellular concentration of $Cl^-$ is relatively high during the developmental stage, leading to depolarizing GABA reversal potential $E_{GABA}$. Activation of GABA$_A$ receptors generates efflux of chloride ions and an excitation. As GABAergic synapses are gradually formed with maturation, KCC2 increases, while NKCC1 decreases, resulting in net decrease of $[Cl^-]_i$ , which turns the nature of GABAergic action into “inhibitory” [11].

Why such a complicated process is required?

It appears that there are general agreements among physiologists in that this subtle series of processes may be due to the necessity of sculpting network circuits in the developing period. Ben-Ari [11] hypothesized that this is a solution to the difficulty of how to excite developing neurons to promote growth and synapse formation while avoiding the potentially toxic effects of a mismatch between GABA-mediated inhibition and glutamatergic excitation.

Fukuda [24, 25, 62] pointed out that constructing GABAergic circuits firstly as excitatory networks may be more advantageous for Ca$^{2+}$ production which is necessary for LTP processes. In fact, the depolarization produced by GABA is strong enough to remove the voltage-dependent Mg$^{2+}$ block from NMDA channels and inducing an increase in $[Ca^{2+}]_i$. Also the strategy to “transform” of GABA actions later to an inhibitory one does not necessitate to have a mechanism of synapse formation specially designed for inhibitory synapses. The critical role of GABA in the developmental stage of primary visual cortex has also been reported [16, 29].

Then why GABA$_A$ should be transformed to act as an inhibitory transmitter?

This appears to be a trivial question since GABA has been regarded as the principal mediator of inhibition. In fact, agents that block GABA synapses generate seizures. Hence, it is a natural assumption that “GABA need to become inhibitory in a hurry to stabilize the new neural nets” (Staley and Smith, 2001 [66].)

3.2. Activity-dependent excitatory GABA$_A$ actions in mature CNS

However, the story may not be so simple. There are numerous reports that GABA$_A$ receptors have a depolarizing action even in mature CNS neurons. It is reported that
when intensively activated, dendritic GABA_A receptors excite rather than inhibit neurons. Initially hyperpolarizing postsynaptic GABA_A responses shift to depolarizing during prolonged GABA release.

Staley et al. [64] showed that while a single distal orthodromic stimuli produced hyperpolarizing GABA_A receptor-mediated PSPs in a CA1 pyramidal cell, a train of 40 stimuli at 200Hz produced an additional late depolarizing potential. Moreover, GABA-mediated depolarization was sufficient to modulate the voltage-dependent $Mg^{2+}$ block of synaptic NMDA receptor activation, and high-frequency stimuli evoked robust spiking.

The experiments reported by Kaila et al. [32] using both sharp microelectrodes and whole-cell-pipettes in the presence of ionotropic glutamate antagonists provided some measure about the time course of eGABA actions. A train of 40 pulses at 100Hz applied to the stratum radiatum in CA1 close to the intracellular recording site evoked a fused sequence of initially hyperpolarizing fast IPSPs. The hyperpolarizing phase of the fused response reached its peak amplitude of approximately -10 mV usually within 20-50 ms, and then turned promptly (within 200-300 ms) into a prolonged depolarization that often had an amplitude sufficient to trigger a burst of action potentials.

3.2.1. Anionic gradient shift model

The GABA_A ionosphere is selectively permeable to anions of chloride Cl$^-$ and bicarbonate $HCO_3^-$, and the mechanism of depolarization should involve the flux of these anions. Kaila and Voipio [31] showed in direct measurements of [Cl$^-$] and [$HCO_3^-$] in crayfish muscle fibers that prolonged activation of GABA_A receptors can lead to accumulation of intracellular [Cl$^-$] and [$HCO_3^-$]-dependent depolarization. Based on this work, Staley et al. [64] have proposed the anionic gradient shift model, which claims that the eGABA action is the result of an asymmetric, activity-dependent collapse of the opposing electrochemical gradients of Cl$^-$ and bicarbonate. They [64, 65] proposed that the mechanism of the eGABA is an activity-dependent shift of the GABA reversal potential $E_{GABA}$ toward $E_{HCO_3^-}$.

The resting $E_{GABA}$ is primarily determined by $E_{Cl^-}$ because the permeability of Cl$^-$ is five times that of $HCO_3^-$. However, by intense GABA activations, the Cl$^-$ gradient decreases. Although the shift in the Cl$^-$ gradient is eventually corrected, $HCO_3^-$ gradient is more rapidly compensated by the regeneration due to carbonate anhydrase $H_2CO_3$ catalysis. Thus, the electrochemical gradient for Cl$^-$ collapses more significantly than does the $HCO_3^-$ gradient. As a result of these processes, $E_{GABA}$ shifts toward $E_{HCO_3^-}$ (-12 mV at physiological internal pH (7.0-7.2), which is more positive than resting membrane potential [32]).

Kaila et al. [32] argued that the postsynaptic [$HCO_3^-]$ alone cannot explain the activity-dependent positive shift of $E_{GABA}$ in pyramidal cells. They stressed that eGABA actions are due to depolarizing effects of increased $K^{+}_{o}$ generated by a local network of GABAergic interneurons, although Staley and Proctor [65] argues...
that \([K^+]_o\) effects are not necessary for eGABA actions.

The experimental data introduced above suggested that the activity-dependent
eGABA actions are synapse-specific, and the depolarization is *dendritic*. (See, however,
Gulledge and Stuart [27].) The scenario of Staley *et al.* [64] explains why the
shift of \(E_{GABA}\) toward \(E_{HCl}\) is a slow process. The experimental data by e.g.,
Kaila *et al.* [32] shows that it may take a few hundred ms until eGABA actions due
to high frequency stimulations trigger spike firings under the presence of glutamate
agonists. This time course could be shorter when excitatory AMPA spikes might
work in concert with eGABAs as may be the case in *in situ* brains. This is almost
equivalent to the time scale of “psychological time” for perception, and of synaptic
NMDA receptor activations via removal of voltage-dependent \(Mg^{2+}\) blocks.

Staley *et al.* [64] emphasized that one of the functions of eGABA is to provide
activity-dependent modulation of the \(Mg^{2+}\) block of the NMDA receptor, and to reg-
ulating NMDA depolarization mechanism of synaptic plasticity. Szalismy and Erdi
[70] pointed out that the depolarizing/hyperpolarizing effects of GABA \(A\) synapse
have a beneficial role in synaptic weight resetting in the hippocampus.

3.3. Brain phenomena proposed to be related to “eGABA” actions

Let us review the possible “role” or experimentally observed brain phenomena, which
have been claimed to be related to eGABA actions.

Epileptogenesis has always been postulated to be a possible consequence of
eGABA under a certain condition.

3.3.1. Epileptogenesis

Cohen *et al.* 2002 [15] showed that under a pathological condition depolarizing
GABA actions may induce interictal epileptic activity in human temporal lobe.

Epileptogenesis appears not to be the unique function of eGABA actions, and
there is evidence that they might work in higher cognitive functions in a non-
pathological condition. There exist several arguments related to eGABA actions
that may deserve special attention.

3.3.2. Relation to up-down two state transitions

The phenomenon of *up and down* two-state transition in *subthreshold* membrane
potentials has long been observed both in neostriatum [39, 58, 59, 60, 68, 69, 82, 83]
and neocortex [7, 45]. Anderson *et al.*, 2000 [7] wrote about how this phenomenon
looked like experimentally as “when monitoring the membrane potential on in-
dividual trials, we were struck by the presence of large, low frequency, bistable
fluctuations”. The large, two-state fluctuations occur in neurons both in awake
and anesthetized animals, which are not time locked to stimulus, and nearly syn-
chronously in nearby neurons. Also, up-down timing was reported to be hardly reg-
ular [68]. Neuronal mechanisms, as well as functional meanings of these fluctuations
are not known. In neseciumatum, GABA_A actions from FS (fast spiking) cells onto MS (medium spiny) principal cells may play a role with an interplay with AMPA and NMDA activation in the transition to up state from down state [60, 67]. Also, GABA input to proximal apical dendrite during when an MS cell is in up state could promote action potential firing in response to both sub-, suprathreshold excitation of basal dendrites if \( V_{\text{rest}} \) (the resting potential) < \( E_{\text{GABA}} \) [27]. Enhance of NMDA receptor activation in more distal dendritic compartments, in turn, influence synaptic plasticity and may enhance dendritic spike initiation.

What could be the functional significance of the two state transition? In view of the fact that spikes are generated only when the pyramidal cell is in up state, and that nearby cells are in up state almost synchronously [7], the group of pyramidal cells in up state might be regarded as a cell assembly related to some behavioral state of the animal.

3.3.3. Collective, synchronized activity of interneurons due to eGABA

Based on the experiments of Michelson and Wong [49, 50] on interactions among interneurons during strong population bursts in the hippocampus, Lämsä [46] proposed that eGABA actions primarily promotes firing in GABAergic interneurons rather than in glutamatergic principal cells in gyrus dentatus. Lämsä claimed that GABA_A excitation provides, together with the gap junction couplings, a mechanism for self-sustained synchronous oscillations (e.g., at gamma frequency).

Lämsä concluded that eGABA actions may strengthen the net inhibition by interneurons to pyramidal cells. However, it remains the possibility as well that the resulting collective, synchronized activity of interneurons would induce excitatory GABA_A actions in the pyramidal cells. Further experimental studies are needed to clarify the role of eGABA and gap junctions in hippocampal/cortical synchrony generations.

3.3.4. Connectionist standpoint - an associative memory model based on disinhibition

Vogel [78, 79] appears to be the only researcher who studied a potential functional meaning of the eGABA action from the standpoint of associative memory. He considered an abstract memory model with a conceptual change to the conventional recurrent network model. The model depends on disinhibition of inhibitory links rather than long-term potentiation of excitatory projections. He investigated the problem of memory capacity of his own model. In his model, couplings between pyramidal cells are only via “interneurons” with eGABA actions, and no direct communications among pyramidal cells are assumed to exist. Interneurons play the role of switching on and off of the pyramidal cell connections through the functioning of eGABA - switching of “excitatory” and “inhibitory” actions. If an interneuron is extensively excited, it will “open” the communication channel between pyramidal
cells via disinhibition. Vogel constructed a large scale network based on his own disinhibition idea, and showed the basic possibility of performing a functional role of a certain level [80].

The study of Vogel is pioneering in the sense that he considered a functional consequence of eGABA from a system-level consideration. However, like other connectionist network models of memory there is little consideration on dynamical aspects of memory in the brain.

We shall discuss in the next section the functional significance of dynamic excitatory and inhibitory actions from dynamical systems standpoints, and propose a hypothetical role of the GABA behavior in the memory structure in the brain.

4. Role of Excitatory Actions of GABA A - A Dynamical Systems View

In order to understand the functional significance of “excitatory” actions that a subsystem of GABAergic interneurons is presumed to possess, one must first reconsider the functional meaning of inhibitory actions. In contrary to an intuitive image, it should be emphasized that GABAergic inhibitory systems may, under a certain condition, bring internal instability in the system. More precisely, inhibitions may destabilize attractors (as components of the memory structure in the brain). Here by the term “destabilization” we mean the “ruinization” of the memory structure under consideration. Attention should be made to the fact that the word “instability” appears in this paper with double meanings. The first one is due to Staley and Smith, 2001 [66], who claimed in Section 1 that “GABA need to become inhibitory in a hurry to stabilize the new neural nets”, where “instability” means epileptic oscillations of the whole system. The second one, proposed by Nicolis and Prigogine [55], which is related to the present context of “ruinization”, claims that instability is necessary to create a new structure and function in dissipative systems.

Although mathematical mechanisms of this destabilization are not fully understood yet, there are several examples that may suggest the existence of such destabilizing phenomena. This section is devoted to discussions of such examples, and the functional relevance of the eGABA action in the brain.

4.1. GABA as dynamic regulator of memory structure

Excitatory actions of GABAergic synapses during developmental period have been discussed in Section 3.1, where it was argued that the eGABA actions may be advantageous in sculpting basic network circuitry. Such a process should probably be taking place, and it seems consistent with the fact that in low level animals such as sea slugs - Hermisenda Classicornis [5] GABA may function as both inhibitory and excitatory transmitters.

Then, we need to ask again the reason why GABAergic neurons - fired from the job as sculptor or just its assistant - must find the new job as an inhibitor when the
brain system is matured.

Cohen et al. 2002 [15] showed that, during pathological conditions, the interictal activity in human temporal lobe epilepsy can be attributed to the eGABA actions. Hence, it is natural to assign the role of inhibiting such epileptic activity to GABA transmitters.

The puzzle lies in the fact that GABA, after the nervous system has matured, functions again as an excitatory transmitter. At least under certain conditions, activity-dependent excitatory GABA may be invited to play a role in sculpting a new memory structure in the interplay with AMPA and NMDA synapses. It is presumed that the strengthening of synaptic efficacy would happen at nearby AMPA synapses, although details are largely unknown. (Note also that GABAergic transmission efficacy itself would have LTP and LTD [43, 47, 61].) In summary, the eGABA activity may perform a significant or at least a supplementary role in constructing and re-organizing memory structures in a certain situation.

A series of questions may arise here. Is the supplementary role of organizing memory attractors the only function carried by the excitatory GABA action? As soon as a new memory structure is successfully built-in in the network as a new attractor, then GABA quickly changes its role to an “auditor” in order to check the enterprise not to go out of control. Why should only GABAs be both excitatory and inhibitory within a timescale of a few hundred ms? Why are AMPA and NMDA synapses not enough for inducing LTP? Why do not other GABAergic or non-GABAergic interneuron systems work as an auditor?

In fact there is a huge diversity among interneurons in the hippocampus and the neocortex. Anatomy, ionic channel characteristics, pharmacological responses, spiking properties as fast or regular spiking, with/without adaptation and bursting etc, are well known factors of the diversity. Even there exist a number of interneurons with GABAergic synapses, with different projection sites as perisomatic, dendritic and so on. (See, e.g., [12].)

The secret may lie not in its excitatory nor in inhibitory aspect, but in its switching of excitatory and inhibitory actions - a function that only GABA could carry. Viewed from this standpoint, a few scenarios unveil in which GABA might act. GABA could be a dynamic regulator of the memory structure.

In the following we may pose a minimum scenario, as well as a maximum scenario in which the eGABA action may play a role in cognitive functions.

The minimum scenario assigns to GABA, firstly at the opening stage, the role of formation of new attractors in the network, in collaboration with AMPA and NMDA channels. Then, GABA changes at consecutive stages its role to an inhibitor. This switching transforms the newly organized “attractor” into an “attractor ruin”. It seems significant that GABA plays an excitatory role jointly with AMPA and NMDA synapses. GABA, which is one of the concerned components that brought the membrane potential to fire, changes its activity from excitatory to inhibitory. This fact may constitute the critical factor in this ruin genesis.
This is a hypothetical scenario, and mathematical justification should be a subject of future study. However, the arguments of Tsuda [74] and of Nara et al. [54] may provide evidence.

Tsuda and his coworkers [42, 71] gave a model-theoretic argument that inhibitory neurons could play a significant role in making the memory structure dynamical. In a neocortical model with pyramidal and stellate neurons, together with Martinotti interneurons, they showed that the network exhibits itinerant behavior, repelling dynamically from one “attractor” and approaching another “attractor”. The specific negative feedback supported by the Martinotti cells may have resulted in the change of the nature of attractors. Although there are several possibilities for the function of the specific inhibitory neurons [74], the role of the inhibitory neuron is in all the cases to temporarily hide the information contained in the states of pyramidal cells during when the pyramidal cell system is in a steady state.

A similar effect can be obtained by the addition of only a local negative feedback to each pyramidal cell via an inhibitory neuron in the recurrent network of pyramidal cells. In this case, the masking effect is only due to continual inhibitions [42]. Similarly, a chaotic neuron model comprising the chaotic neural network has self-recurrent inhibition, that is one of the essential factors to generate chaotic dynamics at the level of the single neuron [2, 3].

Tsuda [74, 75] proposed the possibility that a similar principle may work in hippocampal CA1/CA3 systems. There are two inhibitory inputs - GABAergic and cholinergic to CA3 and also to CA1 from the septum [13]. The septum sends inhibitory projections to CA1/CA3 via another GABAergic inhibitory cells located in CA1/CA3, which in turn inhibit pyramidal cells therein. Hence, the effect on CA3 of efferent spikes from the septum is disinhibition, which makes the memory structure “attractor-like”. On the other hand, when the septum is in an idling state, CA3 exhibits an itinerant state due to inhibition. In this way, inhibition may play the role in switching between attractor and itinerant states.

In a series of papers Nara et al. [44, 51, 53, 54] constructed a recurrent network model of binary “neurons” with the synchronous updating rule, in which they built in several periodic (limit cycle) attractors. The network function as a conventional associative memory with multi-stable attractors. Then, they reduced the number of existing synaptic connectivity r, i.e., the fan-in number to each neuron. What they found was that as r tends smaller, each basin volume decreases. As r reaches a critical value r_c, the basins vanish and the attractors become unstable. The network dynamics appears to be itinerant among all the attractor “ruins”, but stay in each attractor “basin” for considerably longer time steps. Such a dynamics may depend on the r-value and configuration of connectivity, and sometimes the network shows highly developed chaotic dynamics.

However, even in such cases, a one step application of a fragment (40 bits among 400 bits pattern) of an imbedded memory pattern could push the dynamics to make a quick transition to a very near state containing the target memory. Nara
et al. claim that dynamic correlation transiently appears in the chaotic memory dynamics, which may be the basic mechanism of rapid access to limit cycle attractors without searching among a memory store. As Nara refers, this may be in harmony with the Skarda and Freeman’s statement [63] that “chaotic activities allows rapid and unbiased access to every limit cycle attractor on every inhalation, so that the entire repertoire of learned discriminanda is available to the animal at all times for instantaneous access.” A similar quick response to memory fragment input is also observed in memory dynamics of the chaotic neural network [44].

4.2. Perceptual role of inhibitory actions of GABA$_A$

The second scenario for the eGABA action is highly hypothetical, and remains naïve and conceptual.

The report of Kaila et al. on the time course of eGABA activity [32], (see, the argument in Section 3.2) may, however, suggest that it might carry some cognitive role even at the stage of perception. Top down signals as “attention”, “categorical information” etc. may have the possibility to extensively excite a certain subsystem of GABAergic systems. In fact, in order that a new attractor be “registered” in the memory structure, the spatio-temporal activity pattern should at the same time be emerged to be perceived as a unity, whether consciously or not. This suggests that the eGABA might participate in the perceptual stage within the psychological time of a few hundreds ms at a certain situation.

To proceed further, we are obliged to use the two complementary concepts at the same time: “cell assembly” and “dynamical systems”. A cell assembly is defined as a functionally-organized group of cells to perform a particular task [22, 28, 81], and has a close relation with the attractor view of the memory. This is a concept in the physical space, and cannot describe dynamical systems concepts such as “transitions of states”, or the metamorphosis of memory structure due to dynamical (activity-dependent) change of GABA behavior, while the dynamical systems language as “the phase space” does not have means to describe internal interactive processes and the process of learning.

How the perceptual process could be described within the framework of dynamical systems language? A default (or, background) state with low activity may correspond to a point in the phase space far from any “attractor ruins”. The role of input stimuli is to trigger a dynamic transition of “states” to some other state depending on the nature of stimuli. In particular, when a stimulus is a familiar one, it might bring the state immediately near the center of a “ruin”, which is a memory structure organized throughout the sensory, temporal and/or frontal cortices. This might be considered as Freeman’s miracle, which S. Amari has aptly called. This kind of automatic memory recalls might take place in the real brain.

However, the GABA’s turn does not come at this stage. The potential role of eGABA is *not* to trigger the transition of orbits. It is postulated that the eGABA action changes the landscape of the memory structure. In other words, it temporarily
(re-)organizes potentially existing attractors.

Suppose that the brain encounters an externally driven stimulus, but since they are novel or unfamiliar, some kind of attention or reference to categorical information might be required to perceive it as a unity. In such an occasion, eGABA actions might play a role in internal dynamical processes as interactions with those top down signals. We postulate that such a state may correspond to a case where “local” fragmental cell assemblies (fCAs) are triggered by the external stimulus to excite, but are not bound to have a perceptual unity. In dynamical systems language, this may be a state where several “local orbits” are co-running with only weak interactions.\(^a\) We may assume that this ‘NO PERCEPT’ state is due to the lack of coherent activation (e.g., synchrony) among activated fCAs, which a “global” attractor ruin should be expected to possess.

We hypothesize that the eGABA action temporarily “links” those locally activating fCAs by helping strengthen weak interactions between pyramidal cells. This may be done through interaction with top down signals as categorical information or attention, etc. (Even the possibility of feedback excitation of eGABA system from fCAs themselves might also be considered.) An interesting possibility may be that synchrony among gap junction-coupled GABAergic interneuron systems \([23, 77]\) may help create correlated firings among fCAs. (See, also discussions in Section 3.4 \([46]\).)

Thus, activation of excitatory GABA actions temporarily changes the attractor landscape of the memory system by temporal organization of “attractors”. When GABA turns its activity back to inhibitory, the structure which formed a “temporal attractor” breaks down to fragmental cell assemblies, each of which may exhibit a low activity chaotic state. However, as such temporarily linked fCAs cause correlated (or, synchronous) firings for some time, NMDA channels eventually open causing consolidation of a new memory structure. This newly-born structure turns to an attractor ruin in a background state.

It might be possible to view the pool of fragmentally cell assemblies as a brain function prepared for flexible, dynamical organization of memory structure. FCAs that behave as “local” attractor ruins, are building blocks for potentially existing attractors. The role of excitatory GABA, as the dynamic regulator of memory structure, might be to broaden the diversity of representation to cope with higher brain functions, as Fukuda suggested.\(^b\)

\(^a\)The “global” phase space is now supposed to be consisted of several local but dynamically organized spaces with smaller degree of freedom, which may have weak interactions.

\(^b\)Personal communication.
Fig. 1. Schematic Picture of Dynamics in the Phase Space.
When the brain system is in a background state (top-left picture), the three fragmentary cell assemblies (fCAs) exhibit low activities in “local” phase spaces; this is a state far from any attractor ruins. When a stimulus, which is composed of two local “features”, corresponding to, say fCA1 and fCA2, comes in, the two fCAs are triggered to fire. If the stimulus is novel or unfamiliar (top—right), the two activated states are not perceived as a unity due to the lack of coherent (or, synchronous) activity between the two “local” states. The eGABA action may, boosted up by, e.g., attention or top down categorical information, temporarily “link” the fCAs, to unveil or create temporarily a global attractor ruin, which possesses coherent activity (bottom). Note the possibility that fCAs may have further nest structures. Here, the three axes symbolically represent the “directions” of fCAs, and represents “local” phase spaces.

5. Concluding Remarks
The aim of this paper was to study the functional significance of the excitatory GABA (eGABA) action, the presence of which in matured CNS has frequently been reported. The functional role of this phenomenon has been argued by a number of researchers, but still it is regarded largely as a puzzle. It has also been known that there exists a “similar” - but distinct in their ionic processes and time scales, phenomenon of excitatory GABA action in neonatal period. The scope of this paper is to prepare a theoretical, but conceptual, perspective for investigating possible “role” of this eGABA action, rather than to write a flawless “answer paper” to solve the puzzling behavior. Along this line of presentation, we gave hypothetical scenarios which the eGABA action could play in the cognitive function. For this, we firstly
gave a short review about the known experimental data on the phenomenon, and also
our theoretical framework on the memory dynamics, which is based on the concept
of “attractor ruins” and “chaotic itinerancy”. These contemporary concepts on the
memory structure may, in principle, have the basic ability to overcome limitations
of the classical attractor view.

Our basic standpoint is, although most of experimental data about eGABA are
from hippocampal CA1 area and neostriatum, to investigate possible functional
consequences of the phenomenon, assuming the universal presence, under some con-
ditions, of the eGABA action in the hippocampus and the neocortex in view of the
generality of the assumed ionic mechanisms (see, e.g., Staley et al. [64].)

The puzzle surrounding the action of eGABAs may be summarized as “why does
GABA change its action so dynamically?” However, if we change our point of view
and ask “what is the function that only “e-GABAergic” neurons could carry?” the
answer would immediately be disclosed. That is, a possible role of eGABA may not
be “inhibition” nor “excitation”, but “switching” between the two functions. Such a
viewpoint might be in harmony with the opinions such as: GABA cannot simply be
classified as “inhibitory” or “excitatory” [27, 67] and the concept of “discriminative
inhibition” described in CA1 pyramidal neurons by Andersen et al., 1980 [6].

Functional consequences of such “switching” on the cognitive function are, as
described in the previous sections, to make the memory structure dynamic, organi-
zating attractor ruins. Thus, the role of GABA is a dynamic regulator of the memory
structure. This eGABA function may serve to broaden the diversity of information
representation underlying higher brain function.

In both the processes of learning and perception, there may be at least two phases
of dynamics. One is a stable phase and the other is an unstable phase. In early
stage of the processes, stable dynamics should be dominant, because restrictions
are necessary for the formation of memories and sensory information processing.
It is reasonable to think that unstable dynamics before the formation of the seeds
of organization cannot yield diversity of memory systems and sensations. On the
other hand, after the formation of such seeds, instability of the dynamics rather
than the stability plays a role in ensuring diversity. The system will loose flexibility,
if stable dynamics could be dominant at this late stage. The all of recent findings
on activity of GABAergic interneurons are consistent with this two-fold of the roles
of dynamics, and rather some findings suggest its plausibility.

Our hypothetical view on the role of “e-GABAergic” neurons, however, may
be challenged by a number of questions. In view of the diversity of GABAergic
interneurons in e.g., the neocortex, which systems may play the role we have as-
sumed? Who may drive such GABAergic interneuron systems? Such experimental
details are largely unknown at this moment. It is reported also that the activity-
dependent eGABA actions are synapse-specific, and the depolarization is dendritic.
Thus, the eGABA action depends on its spatio-temporal relationship to other de-
polarizing inputs. Both experimental and model-theoretic studies are indispensable.
At the same time, there exists a study [27], which suggests that GABA action is more dynamic than previously reported. They showed that GABA is always excitatory when it acts on dendrites. When injected to soma, the effective GABA action depends on the timing relative to AMPA excitatory input. If the GABA and (super-threshold) depolarizing AMPA input come together, then because of shunting mechanism, GABA acts as inhibitor, but if GABA arrives 2 ms before the (even sub-threshold) AMPA input, the two stimuli together can make the cell to fire. The relation of this study to the activity-dependent excitatory GABA action appears to be not clear, the ionic mechanism of the latter has been reported, e.g., by Staley et al. [64]. Thus, further experimental and theoretical studies would be needed in this regard.

Although our hypothetical argument on the role of eGABA action and possible consequences to memory dynamics remain conceptual, we hope that it may motivate further studies on the phenomenon from both experimental and theoretical standpoints.

Acknowledgments

The authors express their thanks to the other members of the Dynamical Brain Group ("Gang of Five"), Prof. M. Tsukada (Tamagawa University), and Prof. S. Nara (Okayama University). Special thanks are due Prof. A. Fukuda (Hamamatsu University School of Medicine), for discussions and valuable suggestions. The first and the second authors (H.F. and K.A.) were supported by the Advanced and Innovative Research Program in Life Sciences, while the third author (I.T.) was partially supported by Grant-in-Aid no. 12210001 on priority areas (C), Advanced Brain Science Project, Advanced Brain Science Project, Grant-in-Aid no.15650033 for Creative Scientific Research and also supported by Grant-in-Aid for formation of COE, both from Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government.

References


[46] Länsä K., GABA$_A$ Receptor-Mediated Excitation in the Hippocampus of Adult and Newborn Rats (Dissertation, Faculty of Science, University of Helsinki, 2000).


[77] Tsuda I., Fujii H., Tadokoro S., Yasuoka T., and Yamaguti Y., Chaotic itinerancy as a mechanism of irregular changes between synchronization and desynchronization in a neural network (this issue).


