A MATHEMATICAL MODEL OF BIOFEEDBACK AND ITS RELATION TO NEURAL ACTIVITY

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Abstract: Biofeedback is an acquisition technique of self-regulation ability of a biological function, of which we are normally unaware, through a series of training aided by an additional outer feedback pathway. We proposed a mathematical model of biofeedback in which a learning system on the conscious level learns characteristics of a subconscious regulation system corresponding to the biological function. When the learning converges, the learning system itself becomes an inverse system of the regulation system. Then, if a regulation command is put to the learning system on the conscious level, it drives the regulation system strictly following the command without the outer feedback pathway, which enables voluntary control of the biological function. Based on the model, we measured neural activities relating to a phenomenon of state alteration of consciousness in the course of training in search for an appropriate connection between the learning system and the target regulation system. The situation was modelled as an interpretational change in depth of an ambiguous stereogram. Functional MRI measurement revealed neural activities in bilateral prefrontal area. The results show an important role of neural activities in the prefrontal area in connecting the learning system with the appropriate subconscious regulation system.

Introduction

Biofeedback is an acquisition technique of self-regulation ability of a biological function, of which we are normally unaware. It is characterized by (1) addition of an outer informational pathway to feedback inner physiological condition to a sense such as vision and audition, (2) mental training on the level of consciousness referring the information from the sense, and (3) eventual acquisition of ability to voluntarily control the inner condition without the aid of the outer pathway.

Although biofeedback has been widely applied to treatment of psychosomatic disorder and proved to be effective, its neural basis is still unclear. In order to understand the underlying mechanism of biofeedback, mathematical modelling would be useful. In the present paper the authors proposed a revised version of our mathematical model of biofeedback [1].

In the course of training, if it is in order, trainees sometimes experience an altered state of consciousness in which cognitive framework has changed [2]. In order to explain it based on the model and to seek neurophysiological evidence on it, we conducted an fMRI measurement and showed brain areas relating to the phenomenon.

Modelling

The mathematical model is shown in Figures 1 and 2. The inner condition chosen as the target of biofeedback is controlled in a module consisting of a feedback controller (FC), the corresponding biological function (BFN), and an internal feedback pathway (IFB). The feedback loop leads the inner condition to a desired level guided by an internal control signal (ICS) on the subconscious level.

Here, we hypothesize the existence of a learning system (LS) on the conscious level (Figure 1). Its input is information on the output of the biological function supplied through an additional outer feedback pathway (OFB), and its output is added to the output of the FC. LS learns referring the output signal of FC so that the signal diminishes. The process is referred to as "learning mode".

When the learning proceeds and converges, LS runs into another mode, "voluntary control mode", where OFB is removed and the input of LS is connected to a voluntary control signal (VCS) on the conscious level (figure 2). In this mode LS no longer refers the output of FC, but simply sends its output signal to BFN.

The behavior of LS in both modes will be discussed in detail in the discussion.

Experimental method

Subjects: Six healthy adults (five males and one female) were recruited. Mean age was 32.7 years old, ranging 22-55 years. They were all right-handed.

Apparatus: Functional imaging was conducted on STRATIS *II* MRI system (1.5T, Hitachi Medical Corporation, Japan).

ISSN: 1727-1983

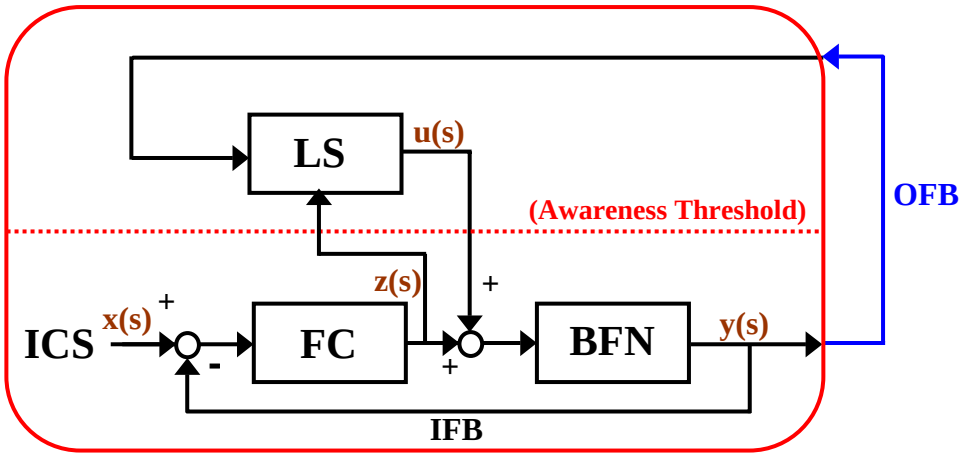


Figure 1: BlockDiagram of Biofeedback in Learning Mode
LS: Learning System, **FC**: Feedback Controller, **BFN**: Biological Function
IFB: Inner Feedback Pathway, **ICS**: Internal Control Signal, **OFB**: Outer Feedback Pathway
x(s), y(s), z(s), and **u(s)**: Laplace tranform of each signal

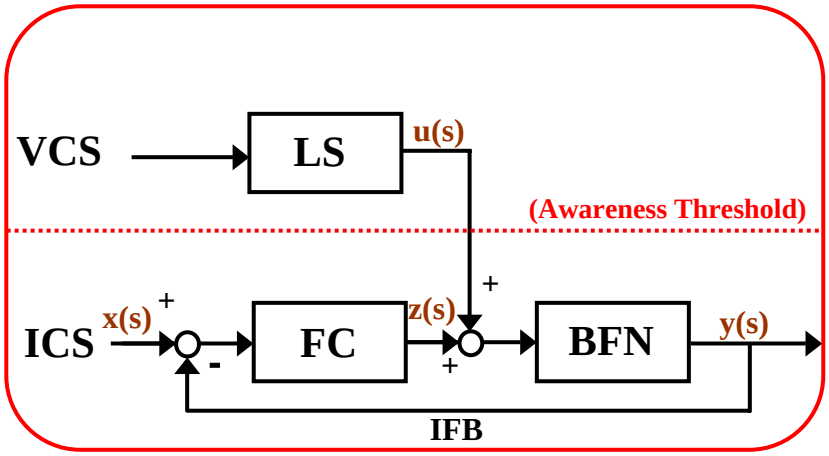


Figure 2: BlockDiagram of Biofeedback in Voluntary Control Mode
LS: Learning System, **FC**: Feedback Controller, **BFN**: Biological Function
IFB: Inner Feedback Pathway, **ICS**: Internal Control Signal, **VCS**: Vokuntary Control Signal
x(s), y(s), z(s), and **u(s)**: Laplace tranform of each signal

Table 1: Notations of Laplace Transform

Category	Item	Laplace Transform
Transfer Function	Learning System (LS)	**L(s)**
	Feedback Controller (FC)	**C(s)**
	Biological Function (BFN)	**K(s)**
Signal	Internal Control Signal (ICS)	**x(s)**
	Output of BFN	**y(s)**
	Output of FC	**z(s)**
	Output of LS	**u(s)**

ISSN: 1727-1983

Visual stimulus was generated on a Windows computer as a stereoscopic image depicted in green and red colors (Figures 3 and 4) and projected onto a screen beside the MRI apparatus. The image was viewed by subjects using a binocular-glasses with a red filter on the right glass and a green filter on the left. First, anatomical images were acquired using a T_1 weighted sequence. Functional images were then acquired using an echo-planar sequence.

Visual images: Two types of random dot stereoscopic images were used as the visual stimulus: ambiguous stereoscopic image and not ambiguous one. The ambiguous stereoscopic image (Figure 3) provided more than two possibilities in depth resolution because of its hirizontally periodic dot pattern. However, in depth sensation, only one depth was perceived at a time with other possibilities suppressed. Before the experiment, each subject was trained to shift from one depth to the other at will in watching the ambiguous image. On the other hand, the nonambiguous stereoscopic image (Figure 4) provided strictly one possibility in depth resolution. Dot dnsity in both images was adjusted to coincide.

Data processing: Image preprocessing was performed using SPM99 software (the Wellcome Department of Cognitive Neurology, Institute of Neurology, UK). The statistical modelling was performed using general linear model implemented on SPM99.

For each subject, images were realigned to the original volume and resampled into a standardized atlas space defined by Talairach and Tournoux [3] using 2mm isotropic voxels. They were then smoothed with a 14mm full width at half of maximum (FWHM) Gaussiam spatial filter.

Statistical analysis: All acquired data were averaged across subjects. State dependent differences in global flow were detected using the analysis of covariance (ANCOVA). Main effects and interactions were assessed by the *t* statistics, subsequently transformed into the z statistics. Localization of maxima was reported within the standard space and their locations were superimposed on the group mean MRI image spatially normalized into the same anatomical space.

Experimental procedure: We conducted a block-designed fMRI measurement of brain activity relating to depth resolution. In a task condition, subjects were instructed to intentionally change their depth interpretation of the ambiguous stereoscopic image projected on the screen. In a control condition, the nonambiguous stereoscopic image was shown on the screen and subjects were asked to watch it.

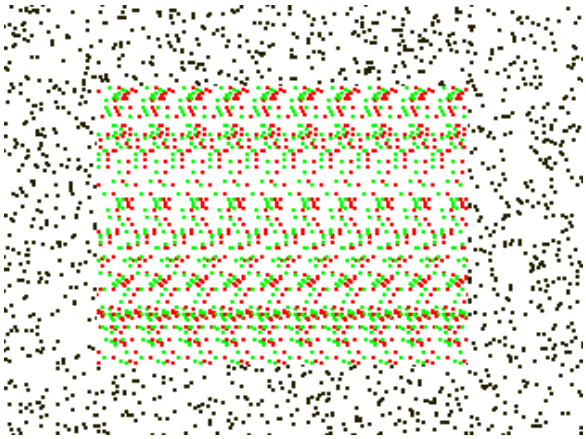


Figure 3: Randum Dot Stereogram with Ambiguous Depth Perception

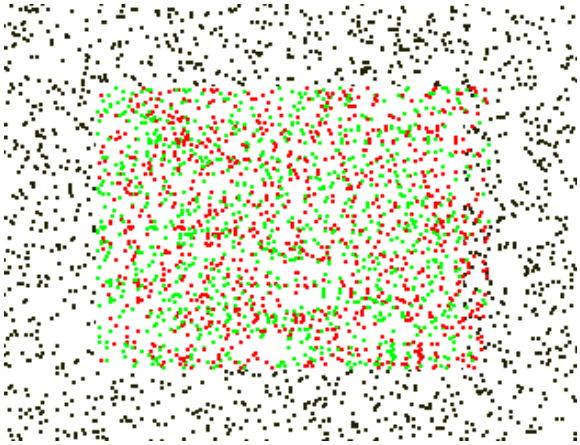
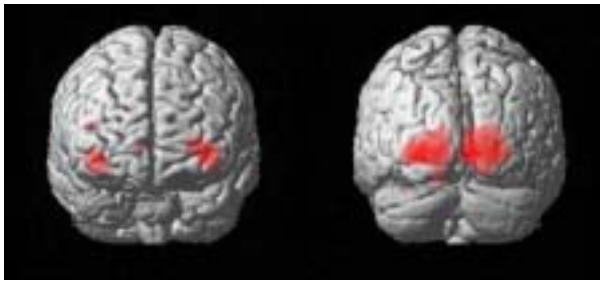


Figure 4: Randum Dot Stereogram with No Ambiguous Depth Perception



F **R**

Figure 5: Neural activity related to ambiguous depth resolution (fMRI Image)
F: Front View, and **R**: Rear View

Results of the Experiment

Figure 5 shows the result of fMRI measurement. Major neural activities detected as increases in the regional cerebral blood flow (rCBF) relating to depth perception of the ambiguous stereoscopic image were observed in bilateral visual field (Brodmann's Area (BA) 17 and 18) and bilateral prefrontal area (BA10).

ISSN: 1727-1983

Discussion

The proposed model explains the three characteristics of biofeedback. Actually, (1) addition of the informational pathway made it possible to learn the input-output relation of the target BFN, and (2) if the learning converges, the input-output characteristic of LS is the inverse characteristic of BFN. It is proved as follows.

We denote the Laplace transform of each signal and each transfer function as shown in Table 1 and Figure 1. Here, we have the following equations according to the system configuration.

$$\begin{cases} z(s)=C(s)[x(s)-y(s)] \\ y(s)=K(s)[z(s)+u(s)] \\ u(s)=L(s)y(s) \end{cases}$$

When the learning converges, z(s) tends to 0. Therefore,

$$[1-L(s)K(s)]y(s)=0.$$

This leads to

$$L(s)=K^{-1}(s),$$

showing that the characteristic of LS is equal to the inverse characteristic of BFN, namely, LS has become the inverse system of BFN at this stage.

Thus, after convergence of the learning, (3) the cascade combination of LS and BFN forms a feedforward system, and when VCS is applied to LS, the output of BFN directly follows it without OFB, *i.e.* voluntary control is made possible.

However, convergence of the learning is not necessarily expected for two possible reasons: failure in finding a relevant module and existence of complexity in the evaluating function. First, there might be many feedback control modules working on the subconscious level, and in order for the training to succeed, LS must be bound to the relevant control module including the target BFN (Figure 6). Secondly, even if relevant binding is achieved, there might be cases the learning process does not terminate when the evaluation function is too complex, such as when it contains local minimum/maximum structure.

Search for the relevant binding would be made on the trial and error basis and when the binding is made, the consciousness alteration would be experienced. Situation in the visual experiment is analogous to that in the consciousness alteration because both processes include intentional shift from a stable neural state to another stable state overcoming a barrier between them. Therefore, the process of interpretation change in depth perception is considered to be a model of the consciousness alteration.

Results of the fMRI measurement show increase in rCBF in bilateral visual field and bilateral prefrontal area in the ambiguous stereoscopic vision. Since the increase in rCBF in the visual field was caused by the visual task itself, the increase in rCBF in the bilateral prefrontal area would be related to the mental process of interpretation change. Neural activation in prefrontal area is related to working memory including binding control of various kind of memories [4]. Therefore, the result shows that the activity in the prefrontal area has a close relationship to the binding process in the biofeedback model.

Conclusion

Mathematical model of biofeedback was proposed and its behavior was discussed. The model could explain many aspects of biofeedback. In addition, using fMRI, neurophysiological activity was measured relating to binding process between the learning system on the conscious level and the module corresponding to the target biological function. It revealed neural activity in bilateral prefrontal area as well as bilateral visual field.

The present study was supported in part by the Grant in Aid for Scientific Research, Scientific Research (C) (2) 11680851 and (C) 15500331, Japan.

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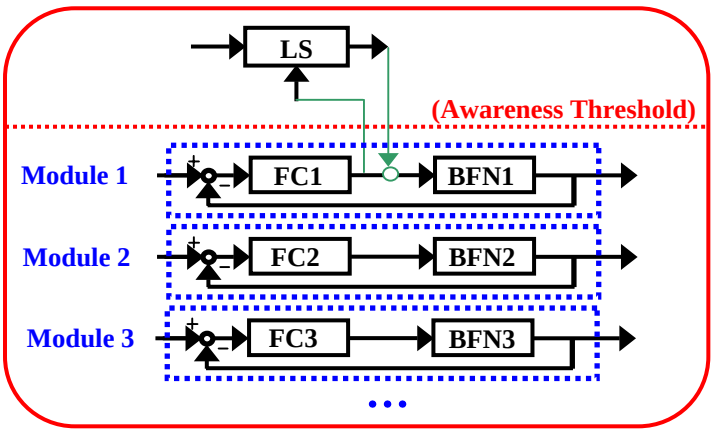

Figure 6: Block Diagram of Biofeedback in the binding process
LS: Learning System, **FC**: Feedback Controller, and **BFN**: Biological Function

ISSN: 1727-1983