A Bio-Signal-Based Control Approach to Building a Comfortable Space

Junzo Watada, Chee Peng Lim and Yung-chin Hsiao

Abstract It is difficult to define a comfortable space for people. This is partly because comfort relates to many attributes specifying a space, partly because all people have different preferences and also because even the same person changes his or her preference according to the state of health, body conditions, working state, and so on. Various parameters and attributes should be controlled in order to realize such a comfortable space according to the database of past usages. Information obtained from human bodies such as temperature, blood pressure, and alpha waves can be employed to adjust the space to the best condition. The objective of the paper is to present the possibility that a space is able to be adjusted to a human condition based on human brainwaves.

Keywords Affective engineering • Living body measurement • Fuzzy control • Neural network • Comfortable space

J. Watada (✉) · Y. Hsiao
Graduate School of Information, Production and Systems, Waseda University, 2-7 Hibikino, Wakamatsu, Kitakyushu 808-0135, Japan
e-mail: junzow@osb.att.ne.jp

Y. Hsiao
e-mail: eugenehs@hotmail.com

C. P. Lim
Centre for Intelligent Systems Research, Deakin University, Geelong Waurn Ponds Campus Locked Bag 20000, Geelong Victoria 3220, Australia
e-mail: chee.lim@deakin.edu.au

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1 Introduction

In today's stressfull society, comfortable space and life are important to eliminate intense stress on us. We should create a suite of new technological tools to realize a comfortable space. In this chapter, the comfortable space means one where a person feels at ease and free from stress when he/she stays there although each person has a different feeling about being comfortable. It is hard to realize a comfortable space for all humans. Therefore, we should build a comfortable space from each person's viewpoint. It is hypothesized that a machine or a system is able to recognize and evaluate the state of a person from his/her behavior, voice, and other measurements by automatically gathering data and recognizing patterns from the collected data. If we can measure an electroencephalogram (brainwaves, heart beats, sweat, saliva, etc.) by an instrument, the obtained information can be employed to realize a comfortable space.

The objective of this chapter is to show the possibility that the measurement of human senses enables us to realize a comfortable space for any person even if the person changes his/her comfortable feeling toward the changing environment or condition [1, 2].

2 Affective Engineering

Affective information means total information of human senses. Affective engineering is "a technology, method, or theory to translate human affective information or image to production of real things or to design of objects." It is vague and uncertain that a customer has an image or expectation about some product. Again, affective engineering is a technology to build such affective information or vague image in product design in some way [3]. The objective of this paper is to employ brainwaves obtained from a person to adjust the environment of a space to the most comfortable state that he/she feels. There are many measurements from a human body which can be used for the control of a space, for instance, heart beats, sweat, saliva, etc.

In [4] bio-potential signals, which included electroencephalographic (EEG), electrooculargraphic (EOG), and electromyographic (EMG) signals from psychological experiments were collected. The EEG signals were analyzed in three different frequency bands, namely a low-frequency band including δ and θ waves, a middle-frequency band including the *alpha* wave, and a high-frequency band including the *beta* wave. The aim of the experiment was to recognize different types of emotions based on bio-potential signals, which included joy, anger, sadness, fear, and relax. To stimulate the emotions, a number of commercial films were broadcasted on TV. The support vector machine (SVM) was used as the emotion classifier. The results showed that multi-modal bio-potential signals were useful for emotion recognition, and the SVM was deemed suitable as the underlying classifier for the emotion recognition tasks. In another experiment [5] with a similar experimental setting, the aim was to recognize pleasure and unpleasure emotions. To generate pleasure and unpleasure, A bio-signal-based control approach to building comfortable space three stimuli, classical music as well as music mixed with noise (e.g., industrial noise) were played. The SVM and a neural network were used for the classification tasks. The experimental outcome showed that both methods produce similar results.

A Bayesian network was deployed for emotion recognition using EEG signals [6]. Audio and visual pictures were used to induce emotions, such as joy, neutral, anger, sad, and surprise. EEG signals were transformed into power spectrum using the fast Fourier transform method, while low-frequencies EEG artifacts were eliminated. The results showed that, while the probability values for many different emotions were different, those of anger and sadness were similar. On the other hand, machine learning techniques were employed to predict a learner's emotions in an intelligent tutoring system based on EEG signals [7]. The emotion states that were of interest included anger, boredom, confusion, contempt, curious, disgust, eureka, and frustration. The best classification accuracy yielded by the k-nearest neighbor algorithm was above 82 %.

A wavelet-chaos-based method was applied to detection of seizure and epilepsy using EEG signals and sub-bands [8]. Specifically, the δ, θ, α, β, and γ sub-bands of EEG signals were examined, and quantified in terms of correlation dimension (CD) and the largest Lyapunov exponent (LLE). It was found that, subject to a large number of EEG segments, the average values of CD were useful for differentiating three groups of subjects (healthy subjects, epileptic subjects during a seizurefree interval, and epileptic subjects during a seizure) based on β and γ sub-bands, while those of LLE was useful for differentiating these three groups of subjects using α sub-band. EEG signals were also used as a source to detect deceptive and truthful responses [9]. The main objective was to extract joint time-frequency EEG features through wavelet analysis. During the experiment, EEG signals were recorded from four electrode sites when five subjects went through a modified version of the guilty knowledge test. The results from the wavelet analysis revealed significant differences between deceptive and truthful responses.

Another application of EEG signals as a source for biometric identification was investigated [10]. Gaussian mixture models and the maximum a posteriori model adaptation were deployed for person authentication, that is, accepting or rejecting a person claiming an identity. A series of experimental simulations was performed to demonstrate the potential of the proposed method. Nevertheless, the database used was too small to render any conclusive lessons in regard to person authentication.

3 Brainwaves

In affective engineering, physiological measurement is widely employed such as impression method, psychological measure, and so on to quantize affective information. In physiological measurement, emotional quantity includes automatic nerve responses or brainwaves against an external stimulus. In this chapter, we employ the measurement of brainwaves.

3.1 Electroencephalogram

The electroencephalogram is explained in its operations and functions shortly in the following.

3.1.1 Spontaneous Electroencephalogram

It is not easy to interpret the cognitive meaning of an electroencephalogram (brainwave). Nevertheless, some characteristics of the electroencephalogram have been explained quantitatively. The electroencephalogram is a kind of oscillated brainwaves. Such brainwaves can be characterized using amplitude and frequency. Specifically, in many researches, electroencephalograms are classified according the difference of frequencies and compared with consciousness states (wake levels).

3.1.2 Electrical Voltage Related to Events

In order to find the meaning of an electroencephalogram, it is significant to analyze brainwaves recorded in an electroencephalograph when a stimulus is given, for example, when an experimenter gives light flash or large sound to a test subject. Such brainwaves are named event-related potential (ERP) or evoked potential since they come out from a specific stimulus or event. Comparing with the resulted brainwaves, an electroencephalogram a brain produces spontaneously is named a spontaneous or freely electroencephalogram or back brainwave.

The electroencephalograph is obtained by duplicating various amplitudes of frequencies. It is hard to clarify their characteristics by observing and measuring an electroencephalogram obtained by giving a stimulus sound to a test subject because the effects would be buried under such a spontaneous electroencephalogram. It is possible to abstract the effect from duplication of electroencephalographs at the same timing because the same kind of results by the same strength of stimuli removes the influence of the spontaneous electroencephalograms. Such spontaneous electroencephalograms are leveled by duplicating such noises. Then, the ERP can be clearly obtained. The widely adapted interpretation of the electroencephalogram is to understand as electronic activities of a brain and the duplication of many small voltages from synapses.

The 10/20 method is widely employed as the positions of electrodes, which is the standard of International Electroencephalogram Society. But it is not necessary to measure all of them. Both sides of the frontal part, whole temporal, centered temporal, and central portions are used widely [3].

3.1.3 Types of Electroencephalograms

Brainwaves are categorized into four groups such as δ brainwaves, θ brainwaves, α brainwaves, and β brainwaves. Brainwaves with lower frequencies than α

brainwaves are named slow brainwaves and ones with higher frequencies than α brainwaves are fast brainwaves.

The frequency of α brainwaves is from 8 to 13 Hz. The brainwaves emerge in the brain of a person who is in the rest state such as concentrated state, meditation state and relaxed state.

β brainwaves are from 15 to 40 Hz, and they show the characteristics of a strongly engaged mind. When a person is engaged in some activities, he/she shows β brainwaves.

δ brainwaves are from 0.5 to 4 Hz. These brainwaves are obtained in unconscious and deep sleep states. They never go down to zero, which implies a brain-dead state. But, a deep dreamless sleep would take a person down to the lowest frequency, typically 2–3 cycles a second.

θ brainwaves are from 4 to 8 Hz. A person who has daydream shows θ brainwaves. A person who is driving on a freeway, and then discovering that he/she cannot recall the last five miles, is often in a θ state.

It is not easy to adjust the temperature itself directly by measuring an electroencephalogram. In this research, the measurement of an electroencephalogram is employed to distinguish the objective person's state at work or at rest.

3.2 Illustration of Experimental Environment

The brainwaves, body temperature, blood pressure, and heart beat are measured according to the response of various stimuli changes when a person is in a space where various attributes of the space can be changed including light intensity, light color, an air condition system, image media, and a massage system. The space is named an affective space.

Figure 1 shows the environment of an experiment that a test subject puts on the electroencephalogram electrodes. He undergoes the measurement of brainwaves in a relaxed state. The affective space is shown in Fig. 2 too.

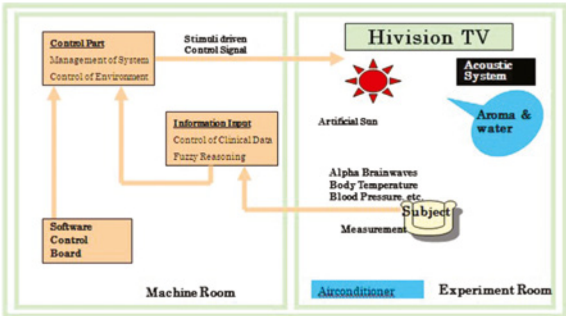
4 Fuzzy Control

Fuzzy control is widely employed in industries in early days since the proposal of a fuzzy system in 1965. Fuzzy control is a kind of intelligent control methods. Rules employed in the fuzzy control are written in the if-then format, and they are approximately reasoned to provide a suitable control signal. As one rule can cover a wide range of control, it is possible to appropriately control the controlled object using few rules so as that it mimics human operations [11].

In addition, when the rules are overlapping with each other, the plural rules can compensate the action of control with each other. Even if some rules do not work well, other plural rules can compensate these rules and produce the expected control signal.

Fig. 1 An experimental space and a test subject

Fig. 2 Illustration of an experimental space



It is not necessary in a fuzzy controller to model a controlled object precisely. In other words, if it is possible to obtain response results, an object can be adjusted perfectly without understanding the controlled object. Of course, it is not possible to provide the if-then rules without understanding basic response and actions of the controlled object. In this chapter, we employed fuzzy control to adjust the room temperature according to the measurement of brainwaves from a test subject.

5 Building a Fuzzy Control System Using Brainwaves

It is possible to know the present state of a test subject by measuring his/her brainwaves and analyzing the characteristics of brainwaves. In this paper, a fuzzy controller is employed to adjust an environment to the most comfortable state based on the measurement.

In this chapter, we select one attribute out of various features that represent a comfortable space. That is, in building a comfortable space, room temperature is employed as a controlled parameter and the most comfortable space will be

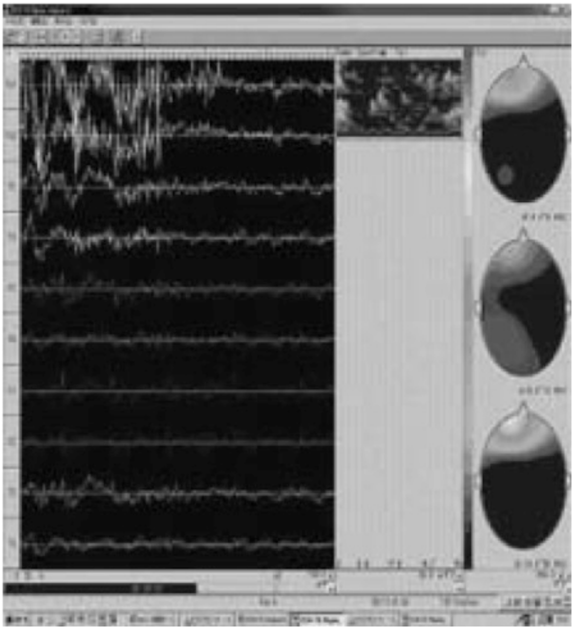


Fig. 3 Measurement result of α waves

realized for a test object by adjusting the room temperature. This means to build the affective information system realizing that a person in a space will be made most comfortable by controlling the temperature of the space.

5.1 Method to Select Characteristic Features

Brainwaves were measured with an interval of 5.12 s for 1,200 times, that is, about 100 min (=5.12 × 1200). In the experiment, a subject repetitively carried out works and rests for a certain interval. In the experiment, his/her α brainwaves were measured as shown in Fig. 3.

Each step is accomplished as in Table 1. But, each step is not conducted strictly because it takes 1 or 2 min to move one interval to another (see Fig. 4). He/she should prepare to change from the current state of works. It can be supposed for 1 or 2 min. Let us denote numerical data of the brainwaves as $X_j^1, (i = 1, \ldots, n)$ where $i =$ step number.

5.2 Procedure of Obtaining Brainwaves

The procedure of obtaining brainwaves is illustrated as follows.

Table 1 Table of brainwave frequency

1	−360	Step 1: Working interval (30 min)
361	−540	Step 2: Rest interval (15 min)
541	−900	Step 3: Working interval (30 min)
901	−1,080	Step 4: Rest interval (15 min)
1,081	−1,200	Step 5: Working interval (30 min)

(1 Step = 5.12 s)

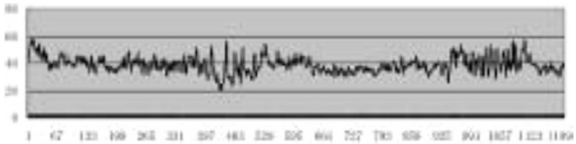


Fig. 4 Graph of measured brainwaves

Step 1. Calculate the mean using all numerical data and shift the mean of all sample voltages so as to become 0. Calculate the absolute value as shown in Fig. 5a. The calculation is as follows:

$$X_j^2 = |X_i^{(1)} - X_{ave}| \tag{1}$$

Step 2. The resulting measurement of the brainwaves shows that the amplitude of brainwaves becomes larger. Calculate the mean of every 40 steps where one step means 10 ms in order to remove random errors. The calculation is shown as follows:

$$X_j^3 = \frac{1}{S} \sum_{T=T(j-1)+1}^{T(j)} \left(X_j^{(2)} (j = 1, \cdots, n), T(j) = S_j \right) \tag{2}$$

Step 3. Calculate the mean value of the results obtained in Step 2. The result is shown in Fig. 5b. The calculation can be written as follows:

$$X_j^{(4)} = |X_j^{(3)} - X_{ave}| \tag{3}$$

Step 4. A total of 33 % of the maximum value obtained in Step 3 is set as the threshold of full stop θ; Set each step value to 1 when the value is greater than θ and 0 when the value is less than the threshold θ, respectively. The result is as shown in Fig. 5c. The calculation is shown as follows:

$$X_j^{(5)} = \begin{cases} 1 : X_j^{(4)} \geq \theta \\ 0 : X_j^{(4)} \leq \theta \end{cases} \tag{4}$$

5.3 Result of Selection of Characteristic Features

Figure 5c shows three characteristic terms, that is, (1) between steps 1 and 10, (2) between steps 11 and 14, and (3) between steps 24 and 218.

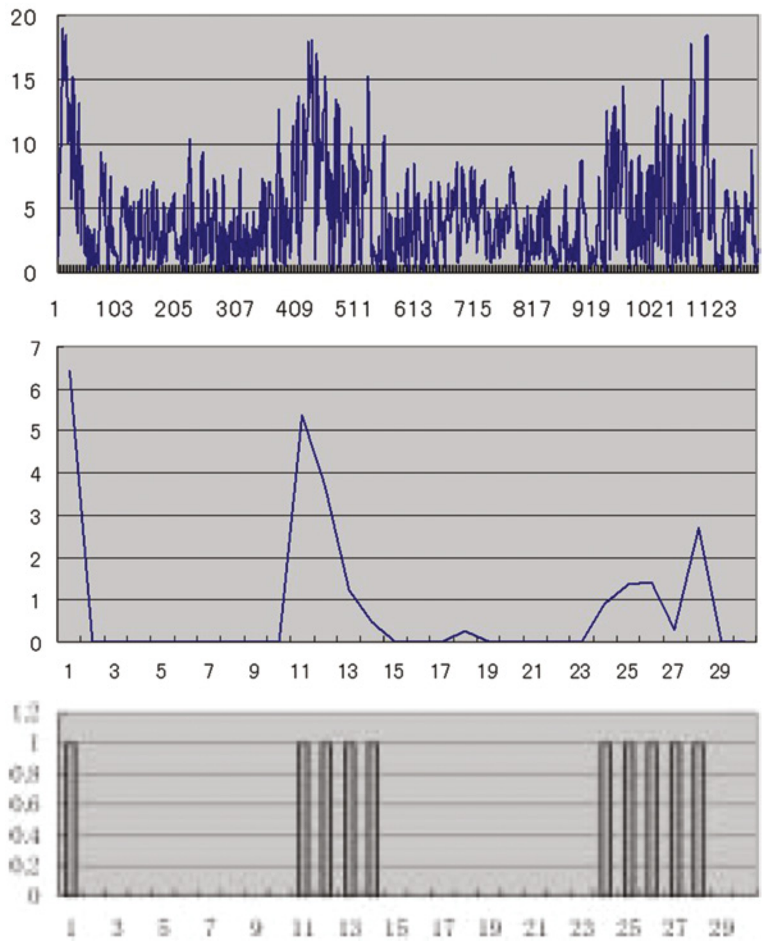


Fig. 5 Value obtained at each step in the procedure of brainwaves. (**a**) Graph obtained by Step 1. (**b**) Graph obtained by Step 3. (**c**) Graph obtained by Step 4

1. The interval between steps 1 and 10 can be explained as the interval of starting to work and the object did not feel any stress during working. As such, the brainwaves were not yet decreasing sufficiently.
2. The interval between steps 11 and 13 can be explained as the subject had rest and the α brainwave is appropriate. On the other hand, in step 14, the subject started working. In this state, the subject just started the work so the α brainwaves did not decrease from the relaxed state to the stressed state.
3. The interval between steps 24–28 can be explained as the subject had appropriate α brainwaves between steps 24 and 27, as similar to that in the interval between steps 11 and 13. But in step 28, the subject just started rest so the state of the subject was not changed sufficiently from the relaxed state to the stressed state. Therefore, the α brainwaves did not decrease as it was expected.

Table 2 Table of control rules

		Δx_1				
		PB	PS	ZO	NS	NB
	NB			PB		
	NS			PS		NS
x_1	ZO	PB	PS	ZO	NS	NB
	PS	PS		NS		
	PB			NB		

5.4 Rule Table Employed

In the experiment, a fuzzy controller is employed to adjust the temperature in the room. The fuzzy controller is configured as follows:

The rule table employed is shown as in Table 2, where x_1 denotes the present temperature and Δx_1 denotes the change of the present temperature.

In a rule table employed, notations *N*, *P*, *B,* and *S* denote negative, positive, big, and small, respectively. The words are expressed using membership functions. In other words, *NB* means big in the negative value and *PS* means small in the positive value. *ZO* means about zero. In this paper, the detail of fuzzy control is not explained. Please refer to books such as Ref. [11].

In the experiment notation, *a* means 25 and 18 for rest and working of the subject, respectively. The detail explanation will be given in Sect. 5.6.

5.5 Membership Function

Parameters of membership functions employed in the experiment are shown in Fig. 6a–c. In the experiment notation, 25 and 18 indicate the rest and working of the subject, respectively. A detailed explanation is given in Sect. 5.7.

5.6 Algorithm of Control System

Step 1. Input the degree of the present temperature.
Step 2. Change the value into 1 and 0 according to working and rest of the subject using the characteristic abstraction of brainwaves.
Step 3. Using data obtained in Step 2,

(a) As value 1 shows that the subject is in the rest state, set the optimum temperature to 25 °C in order to make the subject relaxed. So the temperature of the space is controlled as it becomes 25 °C by a fuzzy controller. Value α in Fig. 5a–c is set to 25.

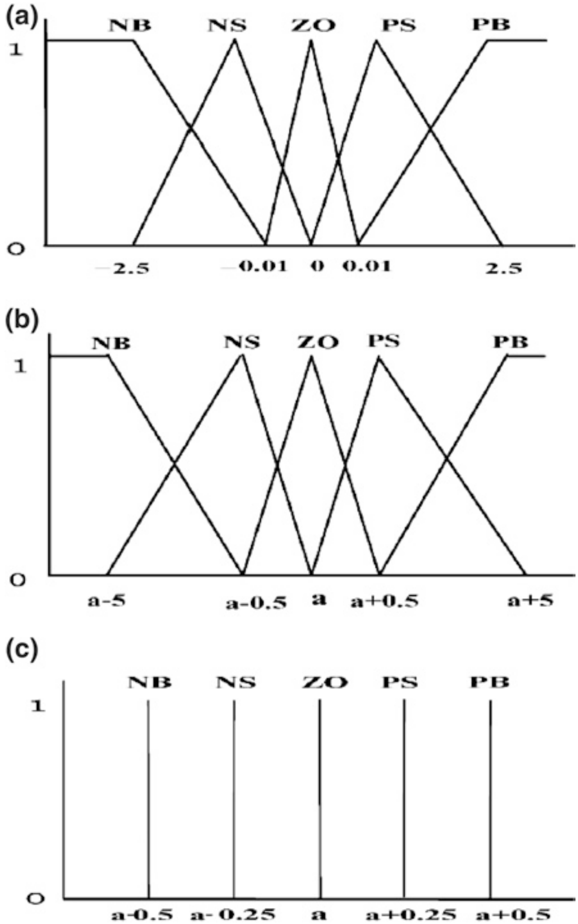


Fig. 6 Fuzzy Control. (**a**) Membership function of a temperature. (**b**) Membership function for the change in temperature. (**c**) Membership function of the output temperature

(b) As value 0 shows that the subject is in the working state, set the optimum temperature to 18 C degree in order to make the subject work comfortably. So the temperature of the space is controlled as it becomes 18 C degree by a fuzzy controller. Value α in Fig. 6a–c is set to 18.

5.7 Simulation Results

The simulation is pursued according to the algorithm of a control system shown in Sect. 5.6. Figure 7 shows the results. The temperature of the room started from 20 °C and the temperature of the room is optimally adjusted according to the state of the subject using the measurement of the α brainwaves. As Fig. 7 shows, the temperature of the room is optimally controlled according the state of the subject.

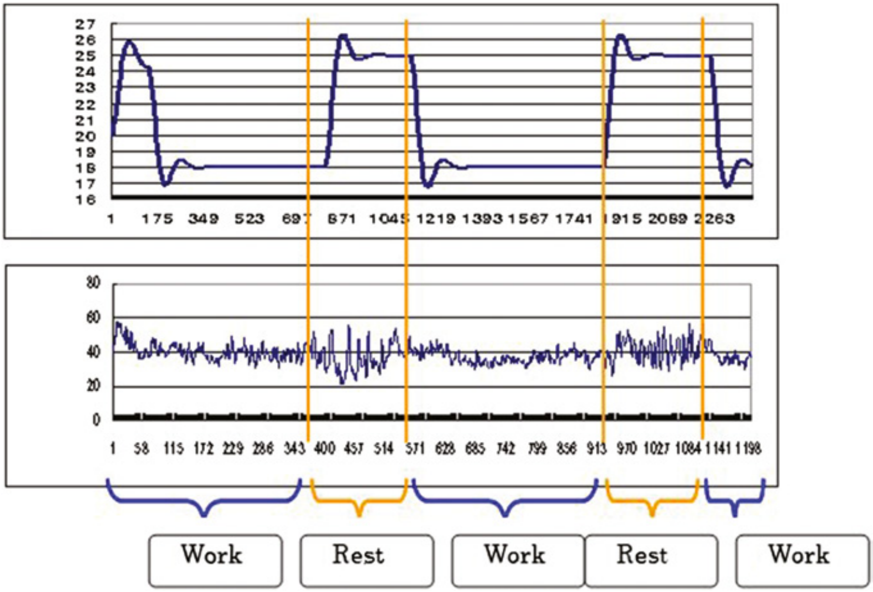


Fig. 7 Comparison between result and α brainwaves

In the interval between steps 0 and 100, the temperature of the room was adjusted to 25 °C because the subject just started the work and the α brainwaves did not decrease before feeling stress.

Section 5.4 explains how the space temperature is adjusted to the same value according to the subject state. In this section, the optimal temperature is obtained from database which contains the historical change of the temperature in the condition of a day such as time, weather, and the state of a person. It should be explained how to decide an appropriate value with the lack of data. A neural network is employed to compensate the lack of data. The smart house adjusts the room temperature to some optimal value which is obtained from a database. When the database does not have appropriate value, the neural network compensates the unavailable value using the neighboring values.

6 Control on the Basis of Database

In temperature control by fuzzy controller, it is possible to employ the database of temperature in order to simply the input of the objective temperature. In this chapter, we employed the neural network to complement the lack of the data in the database.

6.1 Features of a Neural Network

Neural network is a parallel processing model with many processing units that perform computation simultaneously. Each processing unit is an artificial neuron. A human brain consists of 14 billion neurons which process information in parallel. The neural network has the learning ability. It adjusts its connecting weights according to the outside environment. This is also known as the self-organizational ability.

6.1.1 Neuron Model

An artificial neural network model has physiological features of a biological network consisting of multiple input nodes and one output node. Each neural network has units that are connected with each other, as the retina. Units are connected by a line corresponding to nerve fiber. As a real neuron, the connection between neurons is one way such as a signal flows to one direction as a synaptic connection. Some weight (connection weight:w_i) is multiplied with the connected unit. The weight shows the strength between two units.

Weighted inputs ($w_i u_i$) are summed to produce U and transformed by response function (f), then the output (y) is obtained as follows:

$$y = f(U), \quad \text{where } U = \sum_i w_i u_i \tag{5}$$

Furthermore, the output (y) shows positive for a stimulus signal and is negative for an inhibitive signal. The weighted value is positive for a stimulus signal and is negative for an inhibitive signal. According to the adjustability of synaptic connection, the weight value can be learned.

6.2 Back Propagation

The back propagation algorithm is a learning algorithm with a teacher proposed by D.E. Rumelhart in 1986 for a neural network with hierarchical structure consists of input, hidden, and output layers. The backpropagation algorithm is a special case of learning methods for minimizing an evaluation criterion which was known as the probabilistic descent method proposed by Amari in 1967 and Ya.Z. Tsypkin in 1966. The backpropagation algorithm is employed to have neighboring values in order that the neural network can compensate an unavailable value.

Table 3 Database of neural temperature for each sex and each month (°C)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Male	21.8	22.0	22.2	22.3	n.d.	23.1	23.5	23.6	22.8	22.2	n.d.	22.4
Female	23.2	23.4	23.6	23.7	n.d.	24.2	24.8	25.6	24.3	23.6	n.d.	23.6

n.d. denotes "not defined."

6.3 Algorithm of Control Method Using Database

First, we build the database of objective temperature for each sex, and for each month. Table 3 shows the database of neutral temperature for each sex and each month (°C). The parameters of a neural network employed in the experiment are as follows:

1. The number of units in the hidden layer = 4
2. The number of units = 10.
3. The initial weighted value is between −1 and 1.
4. The initial threshold value is between −1 and 1.
5. Learning rate = 0.2
6. Total number of learning cycles = 100,000
7. The condition of learning termination is till the error is less than 0.001.

We employed the teaching data illustrated in Table 3 as the neural temperature for each sex and each month. The input is sex and month. Man is 1 and woman is 0, and month is denoted by 1 January–12 December.

Excluding months 5 May and 11 November, the objective temperature is set to 2. But, for months 5 May and 11 November, there are no values in Table 3. Therefore, we employed the neural network to compensate the value of the objective temperature using the database.

6.4 Results

Figure 8 shows the error rate in the computation where the vertical axis is the error rate and the horizontal axis is the number of learning cycles. Figure 8 shows that even in May and November where data are not available, the temperature is properly obtained through the neural network compensation. Even if we have few data on some features, we can compensate such missing data through the backpropagation learning of a neural network and the compensation by the neural network allows effective and efficient controlling of the comfortable space within a short time.

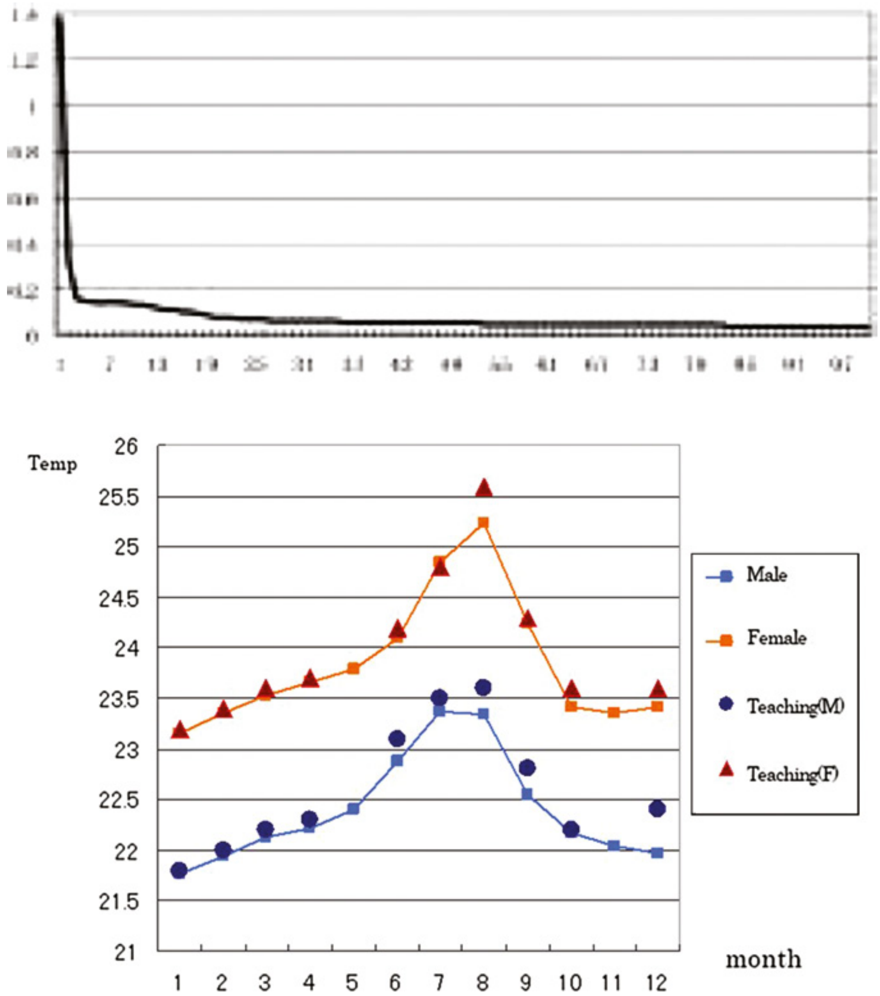


Fig. 8 Result obtained by neural network

7 Conclusions

The temperature of the space is effectively controlled using the measurement of α brainwaves of a test subject according to his/her state such as in a working state or in a rest state. The proposed method can be extended to other human parameters such as humidity, smell, and so on. We may also use other parameters of a human body including electrocardiogram, sweat analysis, saliva analysis, and so on. This system enables us to control a human environment according to the state of a person.

Nevertheless, there are several issues that should be considered. One issue is how the temperature should be set for plural persons in a room. One solution is to set the mean value for all persons there. In this case, it will have the possibility that all people would not be satisfied. In the measurement of brainwaves, many people may not be able to produce clear brainwave signals.

The brainwaves, body temperature, blood pressure, and heart beat are measured according to the response of various stimuli changes when a person is in a space where various attributes of the space can be changed, including light strength, light color, an air-conditioning system, image media, and a massage system. The space is named affective space.

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