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Feature extraction from EEGs associated with emotions

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Abstract The state of mind of a person is supported by the brain activity, and hence features of the state of mind appear in the scalp potentials, as seen on an electroencephalogram (EEG). The EEG features have been extracted into a set of 135 state variables of cross-correlation coefficients of EEGs collected with ten scalp electrodes in the θ, α, and β frequency bands corresponding to *anger*, *sadness*, *joy*, and *relaxation*. An emotion matrix is defined which transforms the set of 135 state variables into a four-element emotion vector of which the components are indexes corresponding to the four elementary emotional states. The maximum time resolution of the emotion analysis is 0.64 s and it is done in real time. This new technique has a wide variety of applications in both medical and nonmedical areas, and the technology suggests the possibility of direct control of systems by the human emotional state.

Key words Emotion · EEG · Brain function · Emotional state

Introduction

Scalp potentials, measured by an electroencephalograph (EEG), are rich in information about brain activity, and proper signal processing would allow us to collect global information about mental activities and emotional states. Such a technique would open up new ways of controlling robots or making robots behave more like human beings. The mental control of robots would also be possible.

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There are several reports of research into the relationship between psychological states and EEGs. Emotions are recognized from facial expressions, although there is criticism about the universality of this method. There have been several proposals about how any state of mind can be broken down into more elementary emotional components. Eckman and Friesen[1] described the six basic facial expressions of *happiness*, *anger*, *surprise*, *fear*, *disgust*, and *sadness*, and combined these components to explain 33 more complex emotions. Izard[2] added another three, namely, *interest*, *shame*, and *contempt*, to give nine elementary emotional components. Schlosberg[3] introduced two orthogonal axes lying on a plane, each of which is spanned by two extremes (love, mirth, happiness) versus (anger, determination), and (surprise, fear, suffering) versus (contempt, disgust), and another axis of tension versus sleep, which is orthogonal to this plane, was added. Thus a state of mind is expressed as a point in this 3D space. Another set of six elementary emotional components was proposed by Tomkins.[4] A recent positron emission tomography (PET) study[5] revealed that transient *sadness* significantly activates bilateral limbic and paralimbic structures as well as the brain stem, thalamus, and caudate/putamen, while transient *happiness* is associated with significant, widespread reductions in cortical cerebral blood flow in the right prefrontal and bilateral temporal–parietal regions. According to Dawson,[6] the type of emotion expression in infants is associated with asymmetries in frontal EEG activity which reflect specific regulation strategies. The left frontal region is specialized for regulation strategies involving action schemes that serve to maintain the continuity and stability of the organism–environment relationship, and of motor schemes such as those involved in language and the expression of happiness and interest. On the other hand, the right frontal region processes *fear*, *disgust*, and *distress*. It is said that emotions are better recognized by the right hemisphere, and the right hemisphere is specialized for dealing with negative emotions.[7] Cerebral blood flow (CBF) increases during *sad* and decreases during *happy* mood induction. The only region that shows specific lateralized changes in CBF which differentiate *sad* states from *happy* states is the frontal pole, with left CBF being higher during *sad* mood induction and lower during *happy* mood induction relative to right CBF.[8] The type of emotion expression has been found to be associated with asymmetries in frontal EEG activity, and the intensity of emotion expression was found to be associated with generalized activation of both the right and left frontal regions.[9] Moreover, *intention*, *aggression*, and *joy* are found to be mainly characterized by an increase of alpha-coherence, whereas a decrease of alpha-coherence is seen for *anxiety* and *sorrow*.[10] The left frontal brain region is specialized for approach to emotions, such as *joy*, whereas the right frontal region is specialized for withdrawal emotions, such as *distress*. Furthermore, depression reduces brain activity in the left frontal region. We have been successful in extracting features in EEGs associated with some particular emotional states, and in quantifying the level of the features associated with the emotional states.

Mental and emotional brain activities strongly depend on synaptic connections, and the state of mind is partly manifested in the spatial correlation of EEGs. Features of EEGs associated with emotional states have been extracted in terms of cross-correlation coefficients of EEGs collected with ten scalp electrodes. Features of the state of mind, however, are buried in the spontaneous EEGs generated by other brain activities, and sophisticated mathematical manipulations will be required to separate required features from unwanted ones. Such event-related potentials are usually obtained by synchronous averaging of EEGs obtained by repeating the same events. However, synchronous averaging is not possible in the present case. Therefore, feature extraction needs to be done using single events.

The present technique is similar to spectral analysis in that the magnitudes of EEG features for a given emotional state are broken down into features of the four elementary emotional states; this is similar to spectral analysis of optical signals, and the technique is called the emotion spectrum analysis method, or ESAM.

The behavior of a robot is controlled by means of telemetry; now that features of human emotions can be expressed as electric signals, it is technically possible to control a robot directly by means of emotional states, or an emotional state can be monitored through the corresponding electric signals processed by the ESAM. It is also possible to extract features in EEGs of animals, and in future we should be able to communicate with animals directly through electric signals.

Method of analysis

Ten disk electrodes were placed on the scalp at positions FP1, FP2, F3, F4, T3, T4, P3, P4, O1, and O2 according to the International 10–20 Standard, and EEGs were recorded with a reference electrode on the right earlobe. The electric potentials were sampled at 100 Hz, and then separated into their θ (5–8 Hz), α (8–13 Hz), and β (13–20 Hz) frequency components by means of fast Fourier transforms (FFT). The frequency range below 5 Hz is very often affected by artifacts such as eye blinking, while the contribution from the frequency range above 20 Hz is small. The values of the cross-correlation coefficients on 45 ($= {}_{10}C_2$) channel pairs were evaluated every 5.12 s (it is possible to shorten this time to 0.64 s); a total of 135 such variables were obtained. The cross-correlation coefficient $c(\alpha; jk)$ between potentials collected with electrodes j and k for the α band, for instance, is given by

$$c(\alpha;jk) = \frac{\sum_{\alpha} X_j(f_n) X_k^*(f_n)}{\sqrt{\sum_{\alpha} |X_j(f_n)|^2} \sqrt{\sum_{\alpha} |X_k(f_n)|^2}} \tag{1}$$

where $X_j(f_n)$ is a Fourier transform of EEG at the jth electrode site and nth frequency bin, and the summation is over the frequency bins in the α frequency band. The set of these 135 variables forms the input vector $\boldsymbol{y}$, and this is linearly transformed into the 4-vector $\boldsymbol{z} = (z_1, z_2, z_3, z_4)$ by operating a transformation matrix $\boldsymbol{C}$ on $\boldsymbol{y}$. The magnitudes of these components indicate the levels of features corresponding to these emotional states. We call $\boldsymbol{C}$ the emotion matrix and $\boldsymbol{z}$ the emotion vector, and these are related by

$$\mathbf{C} \cdot \mathbf{y} + \mathbf{d} = \mathbf{z} \tag{2}$$

where $\boldsymbol{d}$ is a constant vector.

Numerical values for the emotion matrix elements were obtained in the following way. Seven people who were well trained in mental imaging participated in preparing the emotion matrix. They first imaged *anger*, and 5.12-s EEG segments were cut out from their ten-channel EEGs; this process was repeated for the other three elementary emotional states of *sadness*, *joy*, and *relaxation*. The numerical values of the matrix elements were determined in such a way that $\boldsymbol{z} \approx (1, 0, 0, 0)$, $(0, 1, 0, 0)$, $(0, 0, 1, 0)$, and $(0, 0, 0, 1)$, corresponding to the four elementary emotional states, respectively, and $(0, 0, 0, 0)$ was considered to be the control state in which no special emotion was activated in the subjects. The features for these emotional states were made approximately orthogonal to one another. Now we let each vector component be the index of the related emotional state, and its magnitude was regarded as its level. In preparing the emotion matrix from the observed EEG data, the so-called purification process was applied. EEG data for each basic emotional state were divided into two groups, A and B, of almost equal size. The matrix was prepared from EEG data Group A, and was applied to Group B. Any EEG data which gave incorrect results were removed from Group B and a new matrix was prepared based on the remaining data in Group B. This matrix was then applied to Group A, and the same process was repeated. Usually two or three repetitions are enough to remove incorrect EEG data, and a more reliable emotion matrix is thereby obtained. When the emotion matrix is prepared with N subjects, it includes all the EEG features of the elementary emotions. However, if the emotion matrix is prepared for a particular person, the good correspondence of EEG features to the given emotional state is limited to that person only, and these correspondences are lost in general subjects.[11]

Noise reduction

The emotion vector should have positive components only, according to the definition. In the real situations, however, it shows negative as well as positive values. This can be explained in the following way. Some of the EEG features of a certain subject feeling *anger*, for instance, will be in the region *anger* for all subjects participating in preparing the matrix, while other features may be outside it. These features will disturb the mutual orthogonality of the vector components. The brain's activities are not limited to these four elementary emotional states, but include many others with features which are not related the ones for the elementary emotions but which will project state points spread over the emotion space spanned by $\mathbf{z}$. It is conjectured that these components will project points randomly over the origin of the z space producing noise; one then obtains negative indexes. From fluctuations in the negative parts of the emotion vector components the standard deviation σ, the noise amplitude, can be estimated.

The index level estimated on the positive side is the sum of the noise and the signal. The noise part is compressed by multiplying the estimated level by a factor $f(z)$. This factor is defined for $z > 0$ as

$$f(z) \equiv \tanh\left(\frac{z}{4\sigma}\right) = \frac{\exp\left(\frac{z}{4\sigma}\right) - \exp\left(-\frac{z}{4\sigma}\right)}{\exp\left(\frac{z}{4\sigma}\right) + \exp\left(-\frac{z}{4\sigma}\right)} \quad (3)$$

and should be zero for $z < 0$. The smaller part of the emotion index that is comparable to the noise level is suppressed by this factor. These processes are carried out after recording the EEG data off-line. The noise standard deviation σ is estimated over the period of the task or over the whole EEG record, and the noise reduction is uniform over that period. Although the noise offset is reduced by factor of $f(z)$, noise is still superimposed on the signal. This effect is removed by a moving average

$$\bar{z}_n = 0.1(z_{n+2} + z_{n-2}) + 0.2(z_{n+1} + z_{n-1}) + 0.4z_n \quad (4)$$

where $\bar{z}_n$ is the smoothed signal at the nth time point.

When a subject is feeling *anger*, the index for *anger* reaches a high level. However, an *anger* index does not always mean that the subject feels *anger*. It seems more reasonable to interpret it as indicating mental stress. In the same way, the *sadness* index seems to indicate mental depression. Consequently the indexes of EEG features for *anger*, *sadness*, *joy*, and *relaxation* have been named N1, N2, P1, and R, respectively.

Reliability of the ESAM

Currently it is difficult to evaluate how reliable the ESAM is because there is no absolute scale against which results can be calibrated. Therefore, we applied the ESAM to evaluate mental operations in which subjects were doing calculations solving pattern-matching problems, or doing nothing. The emotion matrix was developed from EEG data collected from five subjects by purification, and it was then applied to the same five subjects. The scores are shown in Table 1, in which a "correct" mark is given when the subject gets a target task mark larger than 0.5, while "incorrect" means less than 0.5. The mean rate of correct scores was 86.8%, 78.2%, and 88.3% for calculations, pattern matching, and doing nothing, respectively. We assume that a similar level

Table 1. Ratios of correct answers in mental calculations, geometrical pattern matching, and in an idle state for five subjects.

Long trials	Correct/incorrect/total	% correct/% incorrect
Subject No. 1 (Yu93)		
Calculations	25/0/25	100.0/0.0
Spatial task	46/2/48	95.8/4.2
Idleness	21/6/27	77.8/22.2
Subject No. 2 (Ot93)		
Calculations	30/6/36	83.3/16.7
Spatial Task	31/14/45	68.9/31.1
Idleness	78/5/83	94.0/6.0
Subject No. 3 (Sh93)		
Calculations	38/11/49	77.6/22.4
Spatial Task	30/14/44	68.2/31.8
Idleness	90/1/91	98.9/1.1
Subject No. 4 (Ar93)		
Calculations	27/7/34	79.4/20.6
Spatial Task	31/5/36	86.1/13.9
Idleness	51/14/65	78.5/21.5
Subject No. 5 (NN93)		
Calculations	31/2/33	93.6/6.1
Spatial Task	24/9/33	72.2/27.3
Idleness	58/5/63	92.1/7.9

The EEG analysis was made by the emotional spectrum analysis method (ESAM).

of reliability can be expected in cases featuring the four emotional states.

As state variables we also examined power spectra and channel powers in the three frequency bands, but the percentages of correct answer were almost the same as for the ESAM; however, the number of state variables in the power spectral density depends on the time resolution. This is a disadvantage of this method, although if the nonlinear transformation is included, as in a mathematical neural network, the percentages are slightly better. The neural network is suitable for identifying an emotional state, but the linear matrix transformation is more convenient for estimating the levels of the four indexes.

Results of emotion analysis

A female subject did algebraic tasks for one hour. After she stopped this work, emotion analysis was started and the results are shown in Fig. 1. The indexes shown in this figure are N1, N2, P1, and R, and their levels were evaluated every

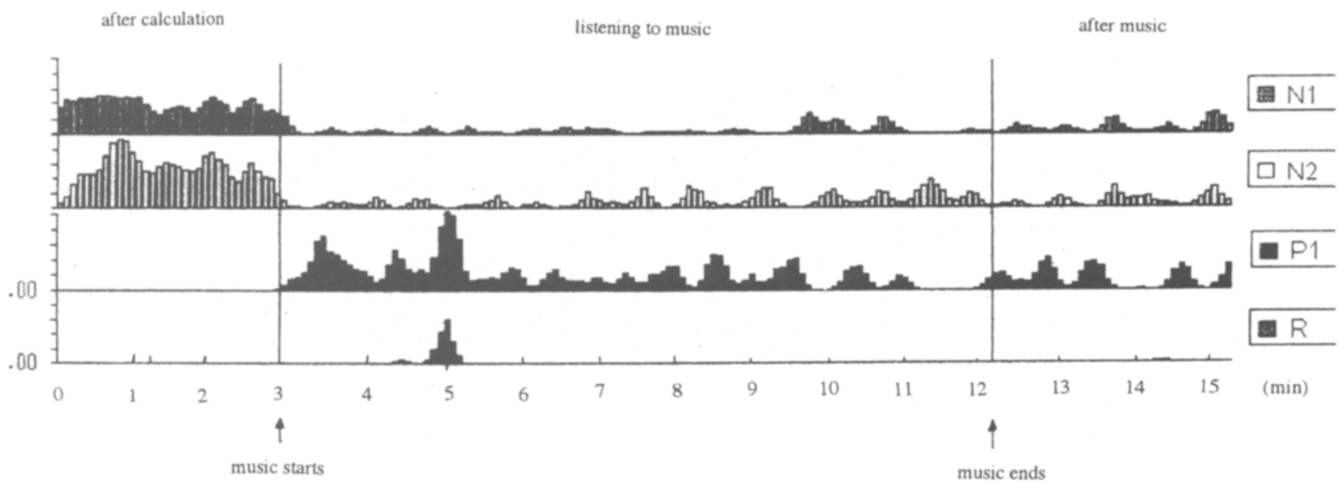

Fig. 1. A subject was involved in algebraic tasks for 1 h and then listened to music. The mental stress indicated by indexes N1 and N2 was released by the music, which the subject loves, and after the music stopped it did not return

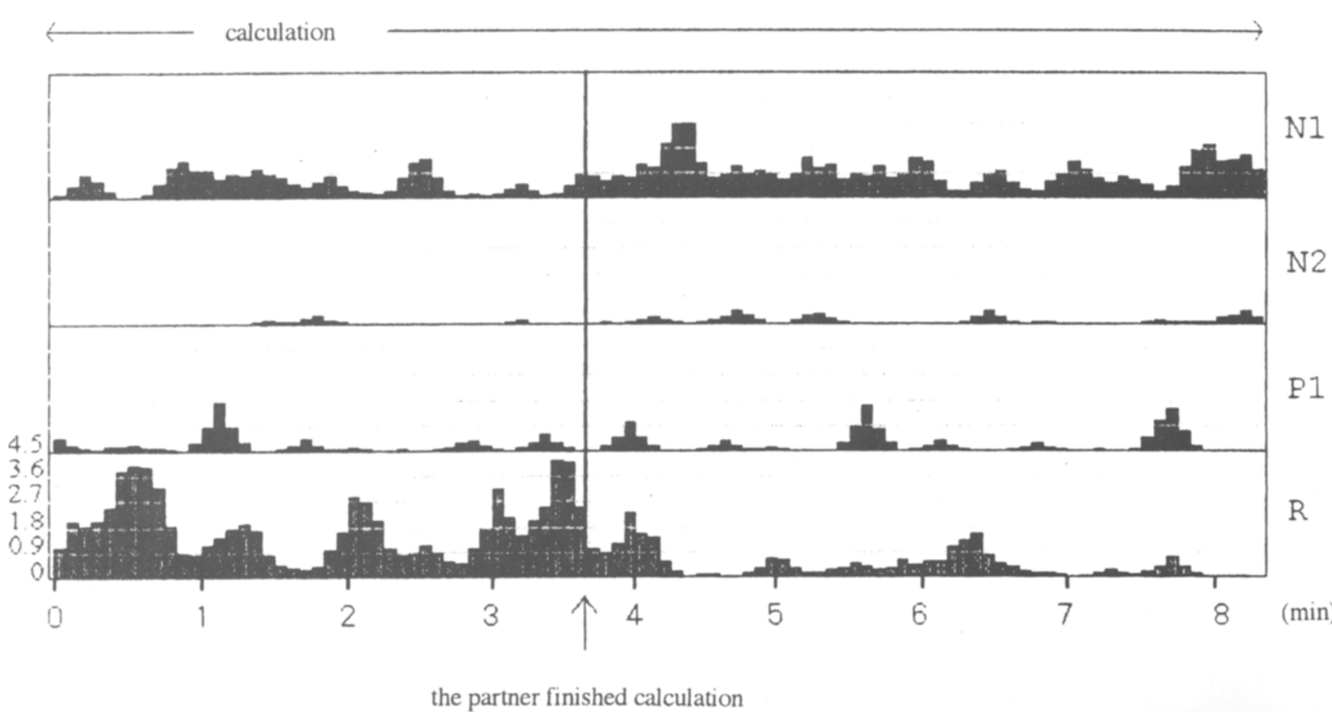

Fig. 2. Two subjects were involved in calculations. One subject was doing the calculations in a relaxed way (R is excited). When he knew that his partner had finished the task, his stress (N1) was increased and the relaxed mood was reduced

5.12 s. Initially the subject showed signals mainly in N1 and N2. N1 indicates mental stress/anger; when a subject is psychologically tired this index is usually accompanied by N2. However, when a subject is excited and interested in something, N1 is accompanied by P1. In the present case, the subject was psychologically tired of mathematical work. She then began to listen to her favorite music, a piano sonata of Chopin. Immediately indexes N1 and N2 decreased to low levels and at the same time index P1 (characterizing *joy*) increased, although it was reduced after only two or three minutes, probably because of habituation. Interestingly, indexes N1 and P1 were fluctuating in opposite phases. After the music finished, the same state continued. A similar tendency was observed in a slightly demented female subject of 79 years old when she started music therapy. In this case the reduction in N1 took place more slowly, and was accompanied by an increase in P1 and R. After the music therapy, mental stress (N1) gradually came back. If the music had been one of her favorite pieces, the reduction in N1 would have occurred more rapidly.

A second example is shown in Fig. 2. Two male subjects, A and B, did algebraic tasks. Subject B finished the work earlier and said he had finished. Subject A showed a relatively high relaxation index, R, and a low stress index, N1, before he heard that subject B had finished his work. When he found that he was behind his partner in finishing the work, his relaxation level decreased and his stress index increased.

Discussion

The ESAM cannot measure a person's state of mind just like a voltmeter. The control state depends on the subject, and varies from day to day depending on his/her physical and mental condition. A complex mental state is expressed as a combination of the four indexes corresponding to the EEG features for the four elementary emotional states. The ESAM has been applied to the state of mind of people receiving counseling. Psychological analyses of people viewing TV commercials have been successful. Emotion analysis by means of ESAM is also done in real time, although noise reduction is not so complete. This technique will open up a way to make possible direct control of robots by the human mind, and also to allow communication with patients who cannot express their feelings by means of voice or bodily movements. Communication with animals should also be possible.

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