19 Evaluation Criteria for BCI Research

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19.1 Abstract

To analyze the performance of BCI systems, some evaluation criteria must be applied. The most popular is accuracy or error rate. Because of some strict prerequisites, accuracy is not always a suitable criterion, and other evaluation criteria have been proposed. This chapter provides an overview of evaluation criteria used in BCI research. An example from the BCI Competition 2005 is used to display results using different criteria.

Within this chapter, evaluation criteria for BCI systems with more than two classes are presented, criteria for evaluating discrete and continuous output are included, and the problem of evaluating self-paced BCI operation is addressed. Special emphasis is put on discussing different methods for calculating the information transfer rate. Finally, a criterion for taking into account the response time is suggested.

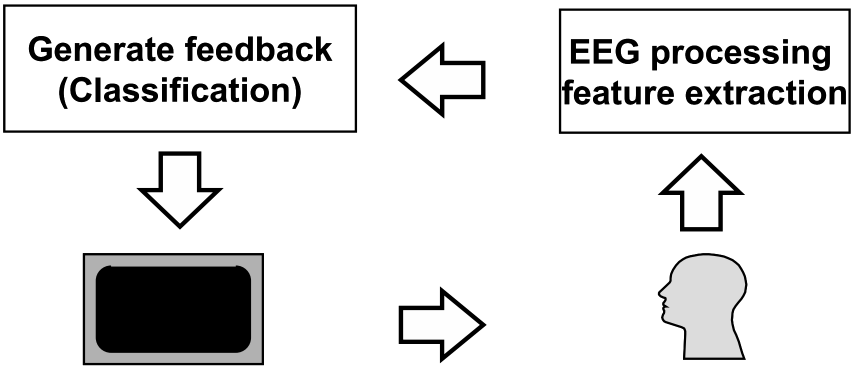

Figure 19.1 Scheme of a BCI. A typical BCI consists of the data acquisition, the feature extraction, a classification system for combining the feature and generating the feedback, the actual presentation of the feedback, and a (ideally motivated and cooperating) subject. The subjects receive real-time feedback to train their own strategy for generating repeatable patterns.

19.2 Introduction

At present, the communication capacity (i.e., information rate) of current BCI systems is not sufficient for many real-world applications. To increase the information rate, possible improvements in signal processing and classification must be investigated and compared. It is reasonable to assume that the quest for the best methods requires efficient evaluation criteria.

The performance of BCI systems can be influenced by a large variety of methodological factors: experimental paradigms and setups that include trial-based (system-paced) or asynchronous (self-paced) modes of interaction; the type and number of EEG features (e.g., spectral parameters, slow cortical potentials, spatiotemporal parameters, nonlinear features); and the type of classifier (e.g., linear and quadratic discriminant analysis, support vector machines, neural networks, or a simple threshold detection) and the target application as well as the feedback presentation. BCI systems can consist of almost any arbitrary combination of these methods. To compare different BCI systems and approaches, consistent evaluation criteria are necessary.

Which criterion to use depends on what is being evaluated. The highest-level evaluation studies the operation of useful BCI applications, like the evaluation of a spelling device or a controlled wheelchair. Here, application-specific tests must be applied. For example, the operation of a spelling device could be assessed by "letters per minute." However, a criterion of "letters per minute" has a different meaning depending on whether the speller includes word prediction.

The evaluation of BCI systems is also complicated by the fact that most systems include a feedback loop (see figure 19.1). Each component within this feedback loop can fail. If one component fails (e.g., bad EEG features, bad classifier, low subject motivation, or poor feedback presentation), the whole BCI system may not work. If this happens, it can be very difficult to determine which component caused the problem. To address these

Class	Y	N
Y	Hits (TP)	Misses (FN)
N	FA (FP)	CR (TN)

Table 19.1 Example of a confusion matrix with two states. If a two-class problem consists of one active and one passive state, the terms *true positives* (TP), *false negatives* (FN), *false positives* (FP), and *true negative* (TN) are used for *hits*, *misses*, *false activation* (FA), and *correct rejection* (CR), respectively.

Class	1	2	3	4	Total
1	73	17	7	8	105
2	10	87	3	5	105
3	6	13	74	12	105
4	2	4	7	92	105
Total	91	121	91	117	420

Table 19.2 Example of a Confusion matrix for $M = 4$ classes. The result is one submission in the BCI Competition 2005 for Data Set IIIa. More results are available in table 19.3.

difficulties, online and offline analysis must be performed. All of these analyses use criteria for measuring the performance.

In this chapter, an overview of evaluation criteria used in BCI research is presented and discussed. Three methods of estimating the information transfer are presented. Cue-paced BCI data from the last BCI competition is used as an example. The shortcomings of the most frequently used evaluation criterion—the error rate or accuracy—is discussed and alternative criteria presented. Evaluation criteria of the response speed of BCIs and the evaluation of asynchronous BCI data are presented, too. Note, the BioSig project at http://biosig.sf.net provides a software library that contains the software implementation of the evaluation criteria presented below.

19.3 The Confusion Matrix

For a M-class classification problem, the results are best described by a confusion matrix. The confusion matrix shows the relationship between the output classes the user intended (the true classes) and the actual output of the classifier (i.e., the predicted class). Two examples of confusion matrices are shown in tables 19.1 and 19.2. If a two-class problem consists of one active and one passive (no control) state, the terms *true positives* (TP), *false negatives* (FN), *false positives* (FP), and *true negative* (TN) are used for *hits*, *misses*, *false activation* (FA), and *correct rejection* (CR), respectively (see table 19.1). If the classes all represent intentional control states, for example, *1* and *2*, *left* and *right*, or more than two classes, no special denotation is used for the fields of the confusion matrix (see table 19.2).

The elements n_{ij} in the confusion matrix indicate how many samples of class i have been predicted as class j. Accordingly, the diagonal elements n_{ii} represent the number of correctly classified samples. The off-diagonal n_{ij} represent how many samples of class i have been incorrectly classified as class j. The total number of samples is $N = \sum_{i=1}^{M} \sum_{j=1}^{M} n_{ij}$. Asymmetrical confusion matrices can be used to reveal a biased classifier. Despite its advantages, the confusion matrices are rarely presented; usually some summary statistic (see section 19.4) is calculated and presented. Partly, this can be explained by the difficulty of comparing two confusion matrices.

19.4 Classification Accuracy and Error Rate

The classification accuracy (ACC) or the error rate (ERR = 1-ACC) are the most widely used evaluation criteria in BCI research. Nine out of fourteen datasets in the BCI competitions 2003 and 2005 used the accuracy or the error rate as the evaluation criterion. One possible reason for its popularity is that it can be very easily calculated and interpreted.

However, it is important to note that the accuracy of a trivial (random) classifier is already $100\%/M$, (e.g., for $M = 2$ classes 50% are correct just by chance). If the ACC is smaller than this limit, an error occurred and further exploration is required. On the other hand, the maximum accuracy can never exceed 100%. Sometimes, this could be a disadvantage, especially when two classification systems should be compared and both provide a result close to 100%.

$$ACC = p_0 = \frac{\sum_{i=1}^{M} n_{ii}}{N} \tag{19.1}$$

The ACC also can be derived from the confusion matrix and has been called the overall accuracy. Some limitations of accuracy as evaluation criterion are based on the facts that (1) the off-diagonal values of the confusion matrix are not considered and (2) classification accuracy of less frequent classes have smaller weight.

19.5 Cohen's Kappa Coefficient

Cohen's kappa coefficient κ addresses several of the critiques on the accuracy measure. The calculation of κ uses the *overall agreement* $p_0 = ACC$, which is equal to the classification accuracy, and the *chance agreement* p_e

$$p_e = \frac{\sum_{i=1}^{M} n_{:i} n_{i:}}{N^2} \tag{19.2}$$

with $n_{:i}$ and $n_{i:}$ are the sum of the ith column and the ith row, respectively. Note, $n_{:i}/N$ and $n_{i:}/N$ are the a posteriori and a priori probability. Then, the estimate of the kappa coefficient κ is

$$\kappa = \frac{p_0 - p_e}{1 - p_e} \tag{19.3}$$

and its standard error $\sigma_e(\kappa)$ is obtained by

$$\sigma_e(\kappa) = \frac{\sqrt{(p_0 + p_e^2 - \sum_{i=1}^{M} [n_{:i} n_{i:} (n_{:i} + n_{i:})]/N^3)}}{(1 - p_e)\sqrt{N}}. \tag{19.4}$$

The kappa coefficient is zero if the predicted classes show no correlation with the actual classes. A kappa coefficient of 1 indicates perfect classification. Kappa values smaller than zero indicate that the classifier suggests a different assignment between output and the true classes.

Sometimes, the specific accuracy $specACC$ for each class i is calculated, too.

$$specACC_i = \frac{2n_{ii}}{n_{i:} + n_{:i}} \tag{19.5}$$

For more details on Cohen's kappa coefficient, see also Cohen (1960); Bortz and Lienert (1998); Kraemer (1982). Cohen's kappa coefficient addresses several of the criticisms of the accuracy measure: (1) it considers the distribution of the wrong classifications (i.e., the off-diagonal elements of the confusion matrix); (2) the frequency of occurrence is normalized for each class—classes with less samples get the same weight as classes with many samples; and (3) the standard error of the kappa coefficient easily can be used for comparing whether the results of distinct classification systems have statistically significant differences.

If the actual (or the predicated) number of samples are equally distributed across classes, the chance expected agreement is $p_e = 1/M$, and the Kappa coefficient and the accuracy are related by the following equalities:

$$\kappa = \frac{p_0 - p_e}{1 - p_e} = \frac{Mp_0 - 1}{M - 1} \tag{19.6}$$

$$ACC = p_0 = \frac{M\kappa - \kappa + 1}{M}. \tag{19.7}$$

The kappa coefficient has been used in Schlögl et al. (2005) and was also the evaluation criterion for dataset IIIa of the BCI competition 2005 (BCI Competition III (2005a)). The result of one submission is shown in figure 19.3; the kappa coefficient was calculated for every point in time across all trials of the test set.

19.6 Mutual Information of a Discrete Output

One of the ultimate goals of a BCI system is to provide an additional communication channel from the subjects' brains to their environment. Therefore, the communication theory of Shannon and Weaver (1949) can be applied directly to quantify the information transfer. Based on this idea, several attempts have been suggested.

Farwell and Donchin (1988) calculated the information transfer for M classes as

$$I = \log_2(M). \tag{19.8}$$

For example, a two-class system can provide one bit, a four-class system can provide two bits. This information rate assumes an error-free system; it provides an upper limit for a discrete M-class system. Therefore, this suggestion is not useful for comparing different BCI systems.

Based on Pierce (1980), Wolpaw et al. (2000a) suggested the following formula for calculating the information transfer rate for M classes and $ACC = p_0$:

$$B[bits] = \log_2(M) + p_0 \cdot \log_2(p_0) + (1 - p_0)\log_2(1 - p_0)/(M - 1). \tag{19.9}$$

The formula holds under the following conditions:

(1) M selections (classes) are possible,
(2) each class has the same probability,
(3) the specific accuracy (see section 19.4) is the same for each class, and
(4) each undesired selection must have the same probability of selection.

Often these assumptions are not fulfilled. In the example in table 19.2, the conditions (3) and (4) are not fulfilled.

The information transfer rate can also be derived from the confusion matrix, which provides a transition matrix of a communication channel between the input X and the output Y. The random variable X models the user intention and can take M possible values according to the selected tasks. The random variable Y models the classifier output and can take M possible values, or M+1 if the clasifier supports trial rejection. The entropy $H(X)$ of a discrete random variable is defined as

$$H(X) = -\sum_{j=1}^{M} p(x_j) \cdot log_2(p(x_j)). \tag{19.10}$$

Nykopp (2001) derived the information transfer for a general confusion matrix:

$$I(X;Y) = H(Y) - H(Y \mid X) \tag{19.11}$$

$$H(Y) = -\sum_{j=1}^{M} p(y_j) \cdot log_2(p(y_j)) \tag{19.12}$$

with

$$p(y_j) = \sum_{1=1}^{M} p(x_i) \cdot p(y_j \mid x_i) \tag{19.13}$$

$$H(Y \mid X) = -\sum_{i=1}^{M}\sum_{j=1}^{M} p(x_i) \cdot p(y_j \mid x_i) \cdot log_2(p(y_j \mid x_i)) \tag{19.14}$$

$$I(X;Y) = \sum_{i=1}^{M}\sum_{j=1}^{M} p(x_i) \cdot p(y_j \mid x_i) \cdot log_2(p(y_j \mid x_i)) - \sum_{j=1}^{M} p(y_j) \cdot log_2(p(y_j)) \tag{19.15}$$

where $I(X;Y)$ is the mutual information, $p(x_i)$ is the a priori probability for class x_i, and $p(y_j \mid x_i)$ is the probability to classify x_i as y_j.

While the definition in (19.15) is more precise than (19.9), it is not frequently used in practice because it requires the confusion matrix and the a priori class probabilities. The prerequisites for (19.9) say $p(x_i) = 1/M$ (classes have the same a priori probability), $p(y_i \mid x_i) = p_0$ (accuracy for each class is equal), and for $j \neq i$ is $p(y_j \mid x_i) = (1 - p_0)/(M - 1)$ (each undesired selection is equally distributed); accordingly, the entropies are $H(Y) = log_2(M)$ and

$$H(Y \mid X) = -\sum_{i=1}^{M} 1/M[p_0 \cdot log_2(p_0) + \sum_{j \neq i} (1 - p_0)/(M - 1) \cdot log_2((1 - p_0)/(M - 1))].$$

It follows that $I(X;Y) = log_2(M) + p_0 \cdot log_2(p_0) + (1 - p_0) \cdot log_2((1 - p_0)/(M - 1))$, which is equivalent to (19.9). Thus, equation (19.15) is a general version of equation (19.9) (Kronegg and Pun (2005); Kronegg et al. (2005)).

These criteria have been applied mostly to BCI systems operating on a trial-by-trial basis. In figure 19.3, these criteria were applied to each sample within the trial, providing a time course of these criteria.

19.7 Mutual Information of a Continuous output

The criteria in section 19.6 are based on discrete magnitudes of the BCI output. Evaluation criteria are also needed for continuous magnitudes such as those to move a cursor in the horizontal or vertical direction. The information content of such continuous output will affect the subject's training. BCI experiments with continuous (in time and magnitude) feedback have been described in Neuper et al. (1999), BCI Competition III (2005b), and Schlögl (2000a). Thus, quantifying this information content is of crucial interest.

Shannon's communication theory (Shannon and Weaver (1949)) also is applicable to these continuous signals. It is reasonable to assume that the BCI output Y is a stochastic process. Moreover, the output can be decomposed into a *signal* component X and a *noise* component Z. The signal component X is due to the *will* or *deliberate action* of the

Criterion	Measure	Class 1	Class 2	Class 3	Class 4
Error	22.4 %				
Accuracy	77.6 %				
Specific Accuracy		74.5	77.0	75.5	82.9
Kappa	0.70 ± 0.05				
I(Wolpaw)	0.88 bit				
I(Nykopp)	0.92 bit				
I(Continous)	1.24 bit	0.30	0.28	0.31	0.35
max. STMI	0.64 bit/s	0.21	0.18	0.14	0.14
SNR		0.51	0.48	0.53	0.63
Parametric correlation		0.67	0.69	0.68	0.77
Rank correlation		0.67	0.69	0.68	0.77
AUC		0.85	0.87	0.87	0.88

Table 19.3 Summary results. The results are derived from the time point with the largest κ at $t = 6.80s$. The one-versus-rest results for each class are presented for the two-class criteria. The time courses are shown in figure 19.3.

user, as it contains the user's intention; the second component contains all uncorrelated (noise) terms Z including the background brain activity, amplifier noise, etc. Implicitly, it is assumed that the subject was motivated and deliberately performed the mental task. If the subject was not cooperative, the subject's activity would be counted as background noise. The signal component can be obtained from the correlation between the output and the actual class labels (intentional state); the noise is the component of the output that does not contain any class-related information. Note, the signal and the noise are uncorrelated and provide an additive noise model (see also Schlögl et al. (2002, 2003)).

According to communication theory, the entropy of the output $H(Y)$ is the sum of the entropy of the input $H(X)$ and the entropy of the (additive) noise $H(Z)$. In other words, the difference between the entropies of the output and the noise is the entropy of the input. This entropy difference is also the mutual information between the input and the output, also called the information transfer $I(X;Y)$. That is, the mutual information is the amount of information that can be interfered with from the output.

The mutual information is

$$I(X;Y) = H(X) - H(X|Y) \tag{19.16}$$

and can be alternatively written as

$$I(X;Y) = H(Y) - H(Y|X). \tag{19.17}$$

The next step consists of estimating the entropy $H(X)$ of a stochastic process X. The entropy of a stochastic process with the probability distribution $p(x)$ is

$$H(x) = \int_x p(x)log(p(x)). \tag{19.18}$$

Accordingly, the probability density of X must be known. The probability density can be obtained empirically from the histogram of X. However, if the number of samples is too small, it is reasonable to use second order statistics only; in this case, only the mean and variance have to be estimated, assuming all higher order moments are zero. This corresponds to the assumption of a Gaussian distribution.

The entropy of a Gaussian process with variance σ_x^2 is (Rieke et al. (1999) Appendix 9, pp. 316–317)

$$H(X) = \frac{1}{2}\log_2(2\pi e\sigma_x^2). \tag{19.19}$$

The entropy of the noise component $H(Y \mid X)$ is based on within-class variance $\sigma^2_{withinclass}$ (the variance when the input X, i.e., the class c, is fixed) of the system output. The entropy of the total process $H(Y)$ is based on the total variance σ^2_{total} of the output. The difference in entropy indicates the information of the *input* X transferred to the output Y.

$$I(X,Y) = H(Y) - H(Y \mid X) \tag{19.20}$$

$$= \frac{1}{2}\log_2(2\pi e\sigma^2_{total}) - \frac{1}{2}\log_2(2\pi e\sigma^2_{withinclass}) \tag{19.21}$$

$$= \frac{1}{2}\log_2\left(\frac{\sigma^2_{total}}{\sigma^2_{withinclass}}\right) \tag{19.22}$$

The mutual information indicates the input information that passes through a noisy communication channel and can be obtained at the output.

The above formula can be rewritten such that the total variance is the sum of the noise (i.e., within-class) variance and the signal variance, assuming that noise and signal are uncorrelated. Accordingly, we get

$$I = H(Y) - H(Y \mid X) = \frac{1}{2}\log_2\left(\frac{\sigma^2_{signal} + \sigma^2_{noise}}{\sigma^2_{noise}}\right) = \frac{1}{2}\log_2(1 + SNR) \tag{19.23}$$

whereas

$$SNR = \frac{\sigma^2_{signal}}{\sigma^2_{noise}} = \frac{\sigma^2_{total}}{\sigma^2_{noise}} - 1 \tag{19.24}$$

indicates the signal-to-noise ratio.

Intuitively, the SNR also can be obtained visually, comparing the means and the variances of the output for each class. This approach has been proposed for evaluating cue-based BCI with two classes (i.e., intentional control states) with a continuous output (Schlögl (2000a); Schlögl et al. (2002, 2003)). For the interpretation of M-states, M discriminant functions are obtained (using a one-versus-rest scheme), and each provides a continuous output for which the mutual information can be obtained. The total amount of information can be obtained by summing up the mutual information of the M one-versus-rest outputs. This approach has been used in figure 19.3 for four-class data. Accordingly, it is also possible to extend this approach toward M classes.

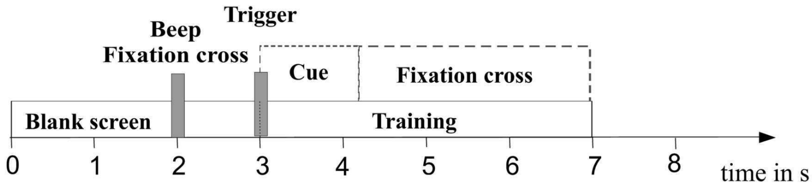

Figure 19.2 Paradigm used for the experiment in BCI Competition III (2005a). Results are shown in figure 19.3.

19.8 Criteria for Evaluating Self-Paced BCI Data

The previous criteria usually are applied to system outputs obtained in individual trials sychronized to an external "go-now" cue. As such trial-based analysis has been referred to as *synchronous*, *cue-paced*, or *intermittent* analysis. The results in figure 19.3 and tables 19.2 and 19.3 were obtained in this way.

For certain applications, we want subjects to operate the BCI in a self-paced (or asynchronous) mode. To support this, the BCI system is specially designed to produce outputs in response to intentional control as well as periods of no control (Mason and Birch (2000)). For investigations of self-paced control, we need to identify the subject's intention to control at arbitrary times and distinguish it from periods of no control. Thus, we need to evaluate the continuous (nonstop) data stream produced by the BCI. The terms *asynchronous*, *self-paced*, and *continuous* analysis have been used for this kind of evaluation. (Remark: In this context the term *continuous* is used differently than in section 19.7, where we used the terms *continuous in magnitude* and *continuous in time within a trial*).

Unlike intermittent analysis, where the timing of intended control is tied to experimental cues, the identification of the intended output in continuous (nonstop) analysis is more problematic. The intended output is often estimated from observations of the subject's behavior in relation to the experimental protocol or through subject self-report. This can result in fuzzy time estimates, which impact the analysis. There is no strict algorithm for defining the intended output sequence, and it remains up to the experimenter how to do this. In any case, the method used to define the intended output sequence is essential information and should be accurately reported in research papers.

19.8.1 HF-Difference

The University of Michigan group has developed a validation criterion for continuous analysis called the *HF-difference* (Huggins et al. (1999)). The HF-difference is a cost function that combines the likelihood of event detection and the accuracy of detected events. The HF-difference has been used only in a single-event state-versus-idle/no-control state discrimination task. The HF-difference is created by subtracting a false detection percentage (F) from a hit percentage (H). H is the percentage of events that are detected within specified timing constraints. F is the percentage of detections that are not correct and therefore is a measure describing the trustworthiness of the detections produced by

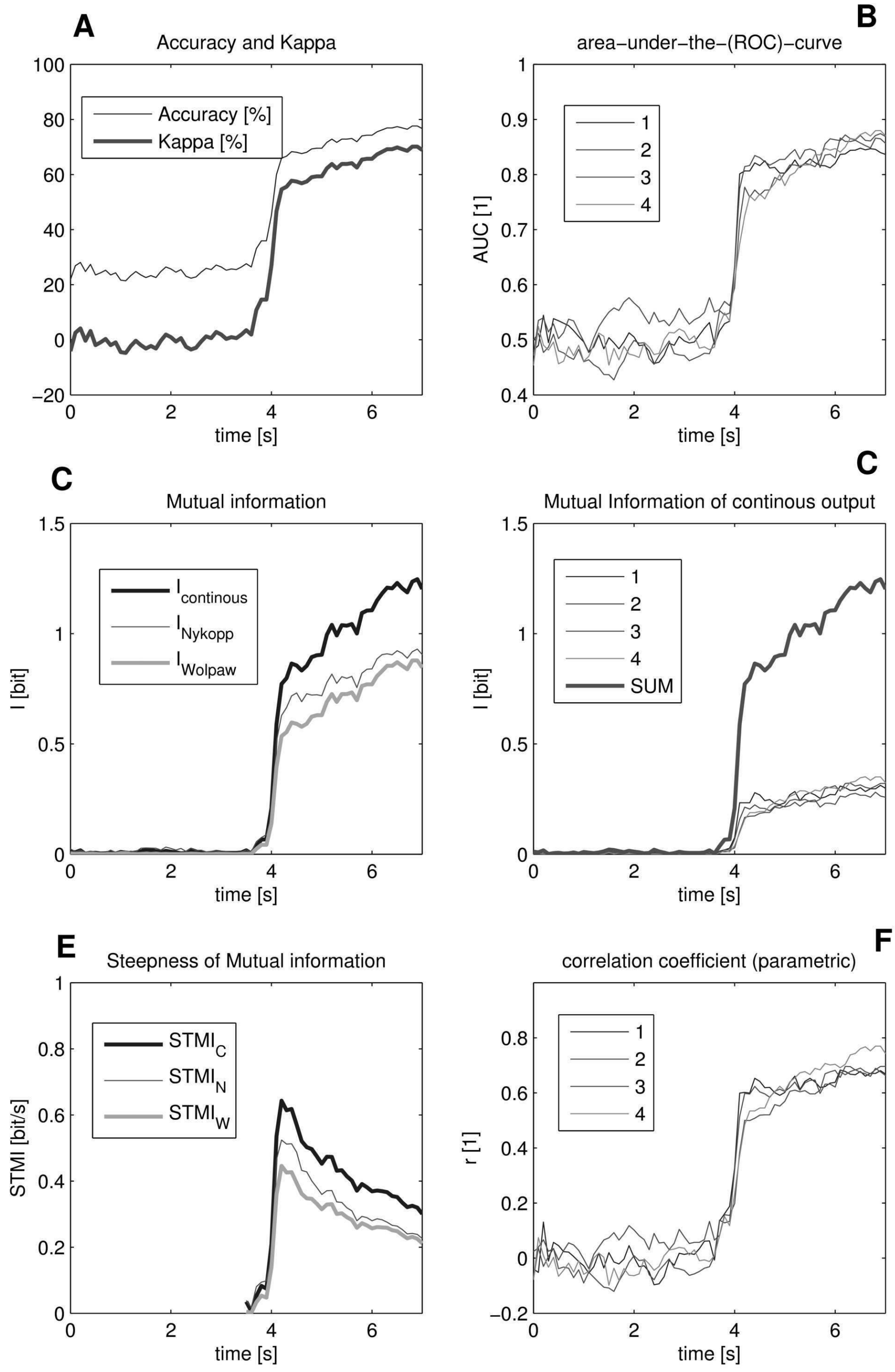

Figure 19.3 Time course of various evaluation criteria. The accuracy and kappa (a), the area-under-the-curve for each of the four one-versus-rest evaluation (b), Wolpaw's and Nykopp's discrete mutual information together with the sum of the continuous mutual information (c), and the continuous mutual information for each of the one-versus-rest evaluation together with its sum (d), the "steepness of mutual information" $I(t)/(t - t_0$, for the continuous "C," Nykopp's "N" and Wolpaw's "W" formula (e), and finally the parametric correlation coefficient (f) are shown. Before cue-onset (at $t_0 = 3s$), no separability is observed, the accuarcy is 1/4=25%, kappa is 0, AUC is 0.5, I=0 bit, and the correlation is 0. After the cue onset, the separability increases.

the method. The H and F percentages are subtracted to produce the HF-difference, which varies between 100 percent for perfect detection and -100 percent. Equal weighting of the H and F metrics are used typically.

The hit rate H (also called Sensitivity Se or Recall) is defined as

$$H = Se = \frac{TP}{TP + FN}. \tag{19.25}$$

The false detection rate F is defined as

$$F = \frac{FP}{TP + FP}. \tag{19.26}$$

Note, $1 - F$ (also called the positive predictive value or Precision Pr) is not the same as the specificity ($Sc = \frac{TN}{TN+FP}$). In asynchronous mode, the specificity Sc cannot be obtained because the number of true negatives TN is not defined. In the field of information retrieval (Rijsbergen (1979)), the harmonic mean of $Precision$ and $Recall$ is called the F_1-measure

$$F_1 = 2\frac{Se \cdot Pr}{Se + Pr} = \frac{2 \cdot TP}{2 \cdot TP + FN + FP}. \tag{19.27}$$

In the field of BCI research, the Hit/False–difference has been more used widely and is defined as

$$HFdiff = H - F = \frac{TP}{TP + FN} - \frac{FP}{TP + FP} = Se + Pr - 1. \tag{19.28}$$

Computing false detections in this way emphasizes the operational cost of false positives (to the user of the interface) more than sample-based metrics. For example, suppose a 100-second segment of data sampled at 200 Hz and containing 20 event triggers was used as the test data and a detection method produced 20 detections, of which 10 were wrong. With a sample-by-sample classification, 10 false detections in 100 s would yield a false positive rate of 10/(100 * 200) = 0.05%, giving a false sense of confidence in a method that was wrong half the time. However, the HF-difference calculation would produce an H of 50% (half of the events detected), an F of 50% (half of the detections incorrect) and an HF-difference of 0.

On the other hand, the HF-difference ignores important timing characteristics such as the time over which the measurement was made and the time between events. So, while the same HF-difference may describe the performance for 5 events over a 10 second period and over a 10 minute period, this level of performance over the longer period means a much larger number of correctly classified nonevent samples. Further, the HF-difference formula does not specify the criteria by which a detection is classified as a hit or a false detection, allowing the adjustment of these criteria for the particular application under consideration.

As a cost function, the HF-difference provides a user-centered evaluation criteria. However, HF-difference values can be directly compared only when the criteria used to define a hit are the same and over data with similar event spacing.

19.8.2 Confusion Matrix for Self-Paced Data

Because of the limitations of the HF-difference and the lack of an alternative, there is currently no commonly accepted criterion available for evaluating self-paced BCI data. An important step toward such a standard is the paper of Mason et al. (Submitted) defining the relevant terms and providing some cornerstones for such criterion. Currently, there are two approaches under consideration—both are confusion matrices (Mason et al. (2005b)). In the first approach, the confusion matrix is obtained on a sample-per-sample basis. Each sample of the BCI output is compared with the label of the intended output for that sample. The second approach is a transition-based confusion matrix. Each transition of the BCI output is compared to the intended output to determine whether it is a desired or undesired transition. Currently, there is no consensus on how to create the confusion matrix and the issue is an ongoing research topic.

19.9 Other Criteria

19.9.1 Receiver-Operator Characteristics (ROC)

There are several other criteria that can be used; one is the receiver-operator characteristics (ROC) curve. The ROC curve obtained by varying the detection threshold and plotting the *Sensitivity* (fraction of true positives) versus $1 -$ *Specificity* (fraction of false positives). Several summary statistics can be derived from ROC curves. A-prime (A') and d-prime (d') describe the separability of the data and are based on a detection threshold (Pal (2002)), whereas no detection threshold is needed for the area under the (ROC) curve AUC. ROC curves also have other interesting properties (for more details, see Stanislaw and Todorow (1999)). ROC-based criteria have been used for evaluating different artifact detection methods (Schlögl et al. (1999a,b)), in the BCI competition 2005 for feature selection (Lal et al. (2005a)), and by Rohde et al. (2002) for *self-paced* evaluation using AUC for comparing different detectors and for selecting detection thresholds.

19.9.2 Correlation Coefficient

The correlation coefficient is used sometimes for feature extraction or for validation. The Pearson correlation (i.e., the parametric correlation) is defined as

$$r = \frac{\sum_i (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{(\sum_i (y_i - \bar{y})^2)(\sum_i (x_i - \bar{x})^2)}} \tag{19.29}$$

where x_i is the class label, y_i is the output value, and $\bar{x_i}$ and $\bar{y_i}$ denote the mean values of x_i and y_i, respectively. Alternatively, the rank correlation is computed by replacing the sample values x_i and y_i by its ranks $rank(x_i)$ and $rank(y_i)$ (19.29). The rank correlation should be used for non-Gaussian data, while for Gaussian data the parametric correlation is recommended. The correlation coefficient r can range from -1 to 1 with an $r = 0$ indicating no correlation between the output and the class label. The time courses of the parametric and the rank correlation are presented in figure 19.3. The squared correlation coefficient r^2 has been used by Wolpaw's group (Wolpaw et al. (2000b)) for selecting the electrode position and the frequency band. The correlation coefficient can be computed for two classes, and also for more classes if the classes are ordered (e.g., if more than two target classes are available on a one-dimensional scale). The dataset used in table 19.2 and figure 19.3 does not provide such an ordering; therefore, the results of the two-class correlation coefficient are presented only for each of the individual one-versus-rest comparisons.

19.9.3 Evaluation of continuous-input and continuous-output systems

So far, all the presented evaluation criteria require a discrete target class for reference. However, BCI systems with continuous output information have been developed recently by groups such as Donoghue et al. at Brown University (Gao et al. (2003b); Wu et al. (2004a, 2005)). Within the evalution of these systems, the task of the subject is to track a target in a two-dimensionsional space. The reference information (the 2D position of the target) as well as the BCI output are continuous variables. For the evaluation of this type of BCI system, the mean squared prediction error (MSE)

$$MSE = 1/N \cdot \sum_{t=1}^{N} ((x_t - \hat{x_t})^2 + (y_t - \hat{y_t})^2) \tag{19.30}$$

and the correlation coefficient in the x and y direction have been used

$$CC_x = \frac{\sum_i (x_i - \bar{x})(\hat{x_i} - \bar{\hat{x}})}{\sqrt{(\sum_i (x_i - \bar{x})^2)(\sum_i (\hat{x_i} - \bar{\hat{x}})^2)}} \tag{19.31}$$

$$CC_y = \frac{\sum_i (y_i - \bar{y})(\hat{y_i} - \bar{\hat{y}})}{\sqrt{(\sum_i (y_i - \bar{y})^2)(\sum_i (\hat{y_i} - \bar{\hat{y}})^2)}} \tag{19.32}$$

in several works (Gao et al. (2003b); Wu et al. (2004a, 2005)) for comparing different decoding algorithms. Here, (x, y) and $(\hat{x}, \hat{y})$ indicate the position target and the output, respectively. Note, the correlation coefficient here is the same in (19.29), only the symbols are used differently. Here, the two-dimensional input and output are denoted by (x, y) and $(\hat{x}, \hat{y})$, respectivly; in (19.29), the one-dimensional input and ouput are denoted by x and y, respectively.

However, they recommend the MSE over the correlation coefficients, because "MSE is more meaningful for prosthetic applications, where the subjects need precise control of cursor positions; [they] observed decoding results with relatively high correlation coefficients that were sometimes far from 2D hand trajectory" (Wu et al. (2005)(pp. 93–94)).

19.9.4 Response Time

The previous paragraphs were dedicated to evaluation criteria that measure the separability of the data (through accuracy, mutual information, etc.). However, what happens if the perfect data processing method has been developed, but the result is obtained one hour after the subject actually performed the action? Even if we could speed up the method to a one-minute delay, the BCI will not be accepted by users. In other words, the response time is also a crucial parameter in assessing the performance of a BCI.

To take into account not only the separability but also the response time, the maximum *steepness of the mutual information* has been used as the evaluation criterion in BCI Competition III (2005b).

$$STMI(t) = \frac{I(t)}{t - t_0} \tag{19.33}$$

whereas t_0 is the time for the cue onset and $I(t)$ is the continuous mutual information. The maximum mutual information is the slope of that tangent on the curve $I(t)$ that goes through point $(t, I) = [t_0, 0]$.

The results in figure 19.3 provide some information about time course of the detection accuracy. The data were recorded according to a cue-based paradigm (figure 19.2) with the cue presented at time $t_0 = 3s$; afterward the separability (figure 19.3) increases up to a maximum time $t = 7.0s$ giving a response time of $4.0s$ for optimum accuracy. However, the maximum steepness of $0.64bit/s$ is obtained at $t = 4.2s$.

The steepness can also be calculated for any other criterion; for the BCI competition, the steepness of the mutual information was chosen because the mutual information provides a smooth curve and is, therefore, most suitable.

The BCI system with the largest maximum steepness provides the fastest and most accurate feedback at the output. The steepness will be especially useful for investigating signal processing and feature extraction methods. For example, it can be used to identify the optimum window length (trade-off between estimation accuracy and delay time). Furthermore, the steepness of the mutual information also provides an upper limit of the theoretical information transfer rate (amount of information per time unit) of a specific BCI design.

19.10 Discussion

Three approaches (19.9), (19.15), and (19.23) for estimating the mutual information have been described. The first approach uses the (overall) accuracy, the second approach uses the confusion matrix to estimate the mutual information, and the third approach evaluates the information content of the continuous output. All approaches were derived from the communication theory of Shannon and Weaver (1949). The differences in the results (see figure 19.3 and table 19.3) are due to different a priori assumptions, which are not always fulfilled. Especially (19.9) has some strong preconditions (e.g., equal distribution of wrong classifications), which are rarely fulfilled. Consequently, methods taking into account the whole confusion matrix should be preferred in case of a discrete output. For the evaluation of continuous BCI output, the mutual information for continuous output is recommended; it does not require thresholding, and the magnitude information is taken into account. The derivation of the equations also points out the possibility of a more refined analysis, for

Criterion	Units	# classes	min/chance/max	Threshold required
ERR	%	M	0/$\frac{M-1}{M}$100%/100%	YES
ACC	%	M	0/$\frac{100\%}{M}$/100%	YES
Kappa	[1]	M	-1/0/1	YES
I_{Wolpaw}	[bit]	M	$0/0/\log_2(M)$	YES
I_{Nykopp}	[bit]	M	$0/0/\log_2(M)$	YES
$I_{Continuous}$	[bit]	$2, M^1$	$0/0/\inf$	NO
$STMI$	[bit/s]	2	$0/0/\inf$	NO
SNR	1	2	$0/0/\inf$	NO
Correlation r	[1]	$2, M^2, cont.^4$	$-1/0/1$	NO
AUC	[1]	2	0/0.5/1	NO
A'	[1]	2	0/0.5/1	YES
d'	[1]	2	$-\inf/0/\inf$	YES
F_1	[1]	2	0/0.5/1	YES
HF-diff	%	1^3	-100%/-/100%	YES
MSE	$[cm^2]$	$cont.^4$		NO

Table 19.4 Overview of evaluation criteria. The # classes column indicates whether the criterion is suitable for a two-class or for an M-class problem. Nevertheless, the two-class criteria also can be applied to each class of an M-class problem if each class is evaluated against the rest (one-vs.-rest scheme). The column min/chance/max indicates the range (min/max) and the result of a chance classification. The threshold column indicates whether a known threshold value is necessary (YES) or if the performance can be computed without determining a certain threshold (NO).
[1]The mutual information for continuous output is defined by two classes, and can be extended to M classes by summing up the information of each 1-vs.-rest output. [2]The correlation coefficient r can be applied to $M > 2$ classes only if the classes can be ordered such that $c_1 < c_2 < \cdots < c_M$. [3]The $HF-diff$ is used for evaluating one active state versus a resting state. [4]The reference information is not discrete but continuous, no class information but, e.g., target trajectory is provided.

example, the assumption of Gaussianity can be replaced by more accurate estimates of the actual output distribution.

Although evaluation criteria have not received much attention in BCI research, complete definitions, further discussion, and sound application of these criteria will improve the overall evaluations of BCI systems. To simplify the usage of various criteria, the software implementation of the evaluation criteria is available through the BioSig project http://biosig.sf.net/.

Notes

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