Confidence Preserving Machine for Facial Action Unit Detection

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Abstract

Varied sources of error contribute to the challenge of facial action unit detection. Previous approaches address specific and known sources. However, many sources are unknown. To address the ubiquity of error, we propose a Confidence Preserving Machine (CPM) that follows an easy-to-hard classification strategy. During training, CPM learns two confident classifiers. A confident positive classifier separates easily identified positive samples from all else; a confident negative classifier does same for negative samples. During testing, CPM then learns a person-specific classifier using “virtual labels” provided by confident classifiers. This step is achieved using a quasi-semi-supervised (QSS) approach. Hard samples are typically close to the decision boundary, and the QSS approach disambiguates them using spatio-temporal constraints. To evaluate CPM, we compared it with a baseline single-margin classifier and state-of-the-art semi-supervised learning, transfer learning, and boosting methods in three datasets of spontaneous facial behavior. With few exceptions, CPM outperformed baseline and state-of-the art methods.

1. Introduction

Facial expressions convey varied and nuanced meanings. Small variations in timing and packaging of smiles, for instance, can communicate a polite greeting, felt enjoyment, embarrassment, or social discomfort. To analyze information afforded by facial expression, Ekman and Friesen proposed the Facial Action Coding System (FACS) \([20]\). FACS describes a facial activity in terms of anatomically based Action Units (AUs). AUs can occur alone or in combinations to represent nearly all possible facial expressions. AUs have a temporal envelope that minimally include an onset (or start) and an offset (or stop) and may include changes in intensity. There has been encouraging progress on facial AU detection during the past decades, especially for posed facial actions \([11, 14, 17, 39, 44, 49]\).

Yet, accurate detection of spontaneous facial actions remains challenging \([14, 32, 33, 41]\). A number of sources of error have been identified. They include individual differences in participants \(e.g.,\) gender, ethnicity, video resolution, head yaw, and low intensity. To model these variability, typically a highly non-linear decision boundary is necessary to infer a correct AU. A highly non-linear decision boundary typically lead to over-fitting, and it has been previously shown that existing algorithms generalize poorly to unseen subjects \([10, 40]\). Standard supervised approaches, such as SVM \([21]\) and Boosting \([23]\), use a single hyperplane to separate positive and negative samples. While these classifiers may perform well on samples with high-intensity AUs, frontal head pose or on particular subjects, they often fail with various appearance changes and subtle AUs \(i.e.,\) low intensity. In this paper, we refer to these samples as easy samples and hard samples, respectively.

To reduce errors occasioned above, we propose a two-stage learning framework that combines multiple classifiers...
following an “easy-to-hard” strategy. This approach, which we refer to as a Confident Preserving Machine (CPM), is illustrated in Fig. 1. During training, CPM learns a pair of confident classifiers. One separates easy positive samples from all else. The other does the same for easy negative samples. During testing, CPM then learns a person-specific classifier using a quasi-semi-supervised (QSS) approach to propagate labels from easy samples to hard ones. Labels for QSS come from the confident classifiers and are referred to as virtual labels. In addition, we propose an iterative extension of CPM, termed as iCPM, which iterates between the confident classifiers learning in training and the QSS classifier in testing.

2. Related Work

Here we review related work in error reduction, semi-supervised learning, and transfer learning.

Error reduction: Previous efforts to reduce detection errors have focused on specific sources. To reduce error occasioned by subtle expressions, spatio-temporal directional features extracted by robust PCA [43] and temporal interpolation using {SVM,MKL,RF} classifiers [38] have been proposed. For error involving head pose, particle filters with multi-class dynamics [16] or variable-intensity templates [31] have been proposed. Individual differences in participants also have been considered. [10,40] used a domain-transfer approach. In many cases, however, sources of error can be quite varied and even unknown as to their origin. CPM seeks to minimize error from all potential sources.

Semi-supervised learning (SSL): SSL has emerged as an exciting field of incorporating unlabeled data for training. Such techniques make different assumptions on relationships between input and label space [7]. Smoothness assumption enforces data with same labels to be close to each other, and can be modeled by the prevalent graph-based method [34]. Cluster assumption employs the clustering behaviors of data with same labels. It has shown to be equivalent to low-density separation [8], and can be extended to entropy minimization [26]. Manifold assumption considers that high-dimensional data lie roughly on a low-dimensional manifold. Instead of Euclidean distances used in the smoothness assumption, manifold assumption considers metrics of manifold. Closest to our work is the Laplacian SVM (LapSVM) [3,36], which incorporates the manifold assumption as a regularization for learning an SVM. Some other work explores the combination of the three assumptions in a boosting framework [9]. Interested readers are referred to [7,48] for a more extensive review.

Notwithstanding the progress being made, these assumptions are unsuitable for AU detection, because subjects behave as different distributions in the feature space. Thus, closer data are unlikely to belong to the same label, i.e., smoothness assumptions in SSL could be violated. On the contrary, CPM applies smoothness assumption to unlabeled test samples, where individual differences are excluded.

Transfer learning: Transfer learning also assumes different distributions between some training data and test data. The information between two different domains can be transferred by finding one or multiple intermediate spaces that minimize their ‘mismatch’. Given each domain represented as a linear subspace, their similarities can be evaluated on aligned subspaces [22], or as their geodesic distances on a Grassmann manifold [24,25]. The discrepancy between raw features can be alleviated by learning a transformation [29,37]. Some seeks to the idea of importance reweighting to adapt one or multiple training domain(s) to a test domain [5,28,42]. Following this direction, Selective Transfer Machine (STM) [10] was proposed to remedy individual differences in facial AU detection by treating each subject as a domain. Recently, there have been several studies that describe a training domain as classifier parameters, and assume that an ideal classifier for the test domain can be represented as a combination of the learned classifiers [18,19,45]. Merging into this direction, STM was extended by transferring from source classifiers, and reduced training time complexity [40].

CPM differs from transfer learning in three ways. One, most transfer learning methods emphasize individual differences in subjects. CPM assumes that error has multiple sources. Individual differences are only one. Other sources include head pose and AU intensity. Two, CPM includes spatial-temporal smoothness that is absent in most transfer learning approaches. Three, CPM is more efficient, because it avoids the selection from multiple sources domains [19,40] or re-weighting each sample [10,42].

3. Confidence Preserving Machine (CPM)

3.1. Overview

Facial AU detection typically deals with data in the form of videos. i.e., each subject has at least a clip of video instead of a single image. Among these videos, some frames are easier to tell an AU presence than others. Fig. 2 shows the easy and hard frames from a particular video. Because hard samples are intrinsically inseparable, treating easy and
hard samples equally would degrade the performance of a standard single-hyperplane classifier (e.g., SVM [21]).

To address these issues, we propose the CPM, a two-stage framework that exploits multiple classifiers with an easy-to-hard strategy. Fig. 3 illustrates the CPM framework. The first stage, training confident classifiers, aims to find a pair of classifiers that distinguish easy and hard samples in training subjects. We define the easy samples as the ones on which the predictions of the confident classifiers agree with each other, and the hard samples otherwise. Compared to standard approaches that use a single classifier, each of confident classifiers focuses on predicting one class. The confident classifiers, therefore, are able to identify whether an unseen sample is easy or not, and predict confidently on it. In the second stage, training a QSS classifier, we first identify easy test samples by applying the trained confident classifiers. With confident predictions on easy test samples, a quasi semi-supervised (QSS) approach is introduced to train a person-specific classifier. The QSS classifier determines the label of the hard samples by propagating consistently the predictions in space and time.

### 3.2. Train confident classifiers

The first stage in CPM is to train the confident classifiers, a pair of classifiers that aims to cooperatively identify and separate easy and hard samples in the training set \( \{x_i, y_i\}_{i=1}^n \) with index \( D = \{1, 2, \ldots, n\} \), where \( y_i \in \{+1, -1\} \) denotes a label and \( n \) is the size of training set.

In this paper, we cast the AU detection problem as a binary classification problem, although multi-label formulations have been proposed (e.g., [47]). We formulate CPM in the context of maximum margin learning extending the support vector machine (SVM), but it can be applicable to any other supervised learning paradigm. The intuition behind the confident classifiers is to learn two classifiers, one for the positive class, represented by a hyperplane \( w_+ \), and will predict confidently positive samples; similarly \( w_- \) is for the negative class. We will consider easy samples \( \mathcal{E} \) as the sub-set of the training samples where both classifiers make the same prediction and hard samples \( \mathcal{H} \) otherwise. It is important to note that \( w_+ \) and \( w_- \) will classify the easy positive and negative samples respectively and they do not necessarily need to be parallel. Mathematically speaking,

\[
\begin{align*}
\mathcal{E} &= \{ i \in D | y_i w_+^\top x_i > 0, \forall y_i \in \{+, -\} \}, \\
\mathcal{H} &= D \setminus \mathcal{E},
\end{align*}
\]

where \( \mathcal{E} \) and \( \mathcal{H} \) denote the index sets of easy samples and hard samples, and we denote the confident classifiers \( \{w_+, w_-\} \), or \( w_y \).

Learning the confident classifiers can be done iteratively by maximizing the margin as:

\[
\min_{w_y, \mathcal{E}} ||w_y||^2 + \sum_{i,j} (\xi_i^+ + \xi_j^-) \\
\text{subject to} \quad y_i w_y^\top x_i \geq 1 - \xi_i, \forall i \in \mathcal{E}, \\
\eta_j^+ w_y^\top x_j \geq 1 - \xi_j, \forall j \in \mathcal{H},
\]

where \( y_i \) is the ground truth label, \( \eta_j^+ \) is a relabel of a hard training sample \( x_j \) (explained below). \( \xi_i \) and \( \xi_j \) are non-negative slack variables for easy samples and hard samples respectively, to take into account misclassification. The easy samples, will preserve the original labels \( y_i \), whereas we will relabel the hard samples as \( \eta_j^+ \) for \( w_+ \) and \( \eta_j^- \) for \( w_- \), to make the classifiers as confident as possible.

We present Alg. 1 to solve (2). Because the partition of hard samples \( \mathcal{H} \) and easy samples \( \mathcal{E} \) should be learned at the same time as confident classifiers, Alg. 1 updates \( \mathcal{H} \), \( \mathcal{E} \) and the confident classifiers \( \{w_+, w_-\} \) alternatively. Note that we cannot guarantee a convergence of this process, thus a maximum iteration is set. The set of hard samples is initialized as empty. In the later iterations, hard samples are updated as those misclassified by both \( w_+ \) and \( w_- \). The relabeling strategy enables \( w_+ \) and \( w_- \) to preserve confident prediction in each class by adjusting the labels for hard samples. Here, we explore two relabeling strategies:

![Figure 3](image1.png)

Figure 3. The proposed two-stage CPM framework: Given training videos, the confident classifiers are first trained, and then passed to train a QSS classifier, which makes the final prediction on a test subject. In iterative CPM, easy test samples are selected to iteratively augment the training set.

![Figure 4](image2.png)

Figure 4. Illustration of two relabeling strategies. Data A and B are two synthetic data without and with noisy instances, respectively. (a)∼(c) show the confident classifiers learned on the relabeled data using holistic relabeling on A, holistic relabeling on B, and localized relabeling on B, respectively.
Algorithm 1 Train confident classifiers

Input: Data \( \{(x_i, y_i)\}_{i=1}^{n} \) and its index set \( D = \{1, 2, \ldots, n\} \)

Output: Confident classifiers \((w_+, w_-)\), easy samples \(E\) and hard samples \(H\)

1. Initialization: \( E \leftarrow D; H \leftarrow \emptyset \);
2. repeat
3. \((w_+, w_-) \leftarrow \text{solve (2)}\) with fixed \(E\) and \(H\);
4. Update easy and hard samples \((E, H)\) using (1);
5. Update relabels \(\eta_j^+ \forall j \in H\);
6. until convergence or reach maximum #iteration

1) Holistic relabeling: The most straightforward strategy is to relabel all hard samples as +1 when training \(w_+\), and -1 when training \(w_-\), i.e., \(\eta_j^p = -y_j, \forall x_j \in H\). We term this strategy holistic relabeling. The main advantage of holistic relabeling is its low computational complexity.

2) Localized relabeling: Holistic relabeling may result in some unnecessary hard samples if signal noise exists. To gain more robustness to signal noise, we relabel an hard sample \(x_j\) as +1 only when there exists a neighboring support instance \(x_k\) with positive ground truth label, and similarly for relabeling \(x_j\) as -1. We term this localized relabeling. Denote the set of instances with support instances as \(S_y = \{j \in H | \exists k \in H : d(x_j, x_k) \leq r, y_k = y\}\), where \(r\) is a threshold and \(d(x_j, x_k)\) is the distance between \(x_j\) and \(x_k\). The relabeling is formulated as

\[
\eta_j^+ = \begin{cases} 
-1 & x_j \in S_- \\ \ y_j^+ \\
y_j & \text{otherwise}
\end{cases}
\quad \eta_j^- = \begin{cases} 
+1 & x_j \in S_+ \\ \ y_j^-
\end{cases}
\quad \text{for} \quad y_j \neq 0.
\tag{3}
\]

For simplicity, both strategies use binary labels. Note that other relabeling strategies are directly applicable, e.g., weighting the relabels similar to those in DA-SVM [5], or introducing the concepts of bags as in MIL [1]. Fig. 4 illustrates the two relabeling strategies on synthetic examples. (a) and (b) illustrate the confident classifiers learned using holistic relabeling on A and B, respectively. As can be seen, the confident classifiers move toward the noisy instances in (b), showing that the holistic relabeling is improper for the presence of noise. Fig. 4(c) illustrates the result using localized relabeling, which is more robust to noisy instances.

3.3. Train a quasi-semi-supervised (QSS) classifier

In the previous section, we have discussed how to train the confident classifiers. As pointed out first by Chu et al. [10], a generic classifier trained on many subjects is unlikely to generalize well to an unseen subject because the training and test distributions could vary due to camera model, intra-personal variability, illumination, etc. Chu et al. [10] showed that person-specific and personalized models outperformed existing methods. Following this motivation, in this section, we train a quasi-semi-supervised (QSS) classifier with virtual labels provided by the confident classifiers. We term it QSS instead of semi-supervised because the labels are not provided in ground truth.

Recall our goal is to train a person-specific classifier \(f_t(x) = w_t^\top x\) for the test subject. To obtain such classifier, labels for the test subject are required. CPM collects such labels from the prediction of confident classifiers \(w_+\) and \(w_-\). Because confident classifiers are trained with many subjects, they are likely to generalize well to easy samples. However, on the other hand, there remains hard samples that CPM find difficult to identify. To disambiguate the hard samples, CPM adopts a quasi-semi-supervised (QSS) classifier that uses Laplacian similarity to enforce label smoothness on spatially and temporally neighboring samples.

Suppose we are given a test video with \(m\) frames denoted by \(X^{te} = [x_1, x_2, \ldots, x_m]^\top\) with index \(D^{te} = \{1, 2, \ldots, m\}\). CPM will first identify the easy test samples \(E_t\) as the ones on which both \(w_+\) and \(w_-\) agrees in the label prediction, i.e., \(E_t = \{i \in D^{te} | \text{sign}(w_+^\top x_i) = \text{sign}(w_-^\top x_i)\}\). \(y_i = \text{sign}(w_+^\top x_i)\) is a virtual label for an easy test sample. Once these virtual labels are obtained, CPM will propagate labels to the hard samples with a semi-supervised strategy minimizing:

\[
\min_{w_t} \sum_{i \in E_t} \ell(y_i, w_t^\top x_i) + \gamma_s \|w_t\|^2 + \gamma_t S(w_t, X^{te}), \tag{4}
\]

where \(\gamma_s, \gamma_t\) control the importance of regularizations. \(S(w_t, X^{te})\) is defined as the smoothness term that enforces the neighboring instances in both the feature space and the temporal space to have similar predictions:

\[
S(w_t, X^{te}) = (X^{te} w_t)^\top D^\top D X^{te} w_t, \tag{5}
\]

where \(D\) is a smoothness matrix that penalizes differences in the predictions of temporally and spatially adjacent instances. Specifically, \(D_{ij} = -1/\lambda_{ij} e_{ij}, |i - j| \leq T, i \neq j\); \(\lambda\) is a Gaussian-like weight, such that closer frames have more similar predicted labels (see Fig. 5(a) for an illustration with \(T = 5\)). \(e_{ij}\) is 1 if \(|x_i - x_j|_2 \leq \epsilon\), and 0 otherwise. It excludes the smoothness between the frames that are far away in feature space. \(Z_t \) is a normalization factor such that \(\sum_{i=1}^{T} \sum_{j=1}^{T} \lambda_{ij} e_{ij} = 1\). \(D_{ij} = 0\) elsewhere. We provide more derivation details in the supplementary material. Note that \(D^\top D\) assembles Laplacian matrix by imposing smoothness on neighboring samples and are both positive semi-definite. However, \(D^\top D\) considers both temporal and spatial constrains with Gaussian-like weight \(\lambda_{ij}\) and ejected factor \(e_{ij}\), respectively.

Fig. 5 shows the effectiveness of the smoothness term \(S\) on 3 AU's in the BP4D dataset. To start the label propagation, 2.5% frames were randomly selected from each video as the estimated labels of easy instances. We compare the prediction on the rest 97.5% frames by training a
linear SVM only using the labeled frames, and one with the 
smoothness term $S$ over all the labeled and unlabeled data.
As can be seen, compared to the ground truth, the prediction 
with the smoothness term performs more consistent result 
across 3 AUs. Although being rare, in some cases, it is pos-
sible that easy test samples are unavailable. Consequently, 
Eq. (4) fails to learn a QSS classifier $w_1$. In this case, we 
simply assign $w_t = \frac{1}{2}(w_+ + w_-)$.

3.4. Iterative CPM

CPM learns in sequential fashion the confident classifi-
cers (Sec. 3.2) and the QSS classifier (Sec. 3.3). So, the 
PS classifier learned in a QSS fashion depends indirectly 
on video data, and the QSS classifier labels the hard samples (green 
diamonds), and learns the hyperplane (black line). At the 
third iteration, the easy and hard samples are 
again updated to train $(w_+, w_-)$ and QSS classifier achieving 
100% of classification accuracy.

Complexity: As in standard transfer learning meth-
m 
ods [18, 42], iCPM incorporates all the training data to 
compute a QSS classifier for each test clip. Despite so, 
iCPM is relatively efficient in training due to the learning 
of linear classifiers. In Alg. 2, solving (2) with fixed $E$ and $H$ and solving (4) are both linear with complexity $O(\max(n, d) \min(n, d)^2)$ [6], where $d$ is the dimension of features; $n$ is the number of samples in $E \cup H$ in (2), or the number of test samples in (4).

3.5. Comparison with alternative methods

Besides CPM and iCPM, concepts similar to easy and hard samples have presented in other methods. Boosting methods learn a strong classifier after combining a set of weak classifiers. However, it fits a classifier for completely labeled data without coping with unlabeled data. CPM or iCPM also seems to be like co-training [4], which alternatively trains two or more classifiers so that the most confi-
dent samples from one classifier are used to train another. But in co-training, labeled data and unlabeled data are sup-
posed to have a same distribution.

As a component of CPM, confident classifiers are simi-
lar to SVM with reject options (RO-SVM) [27, 27], which 
designs new loss functions where data in reject region have a loss value between 0 and 1. We can think of RO-SVM as learning two parallel hyperplanes between which lie the hard samples. Unlike RO-SVM, hyperplanes in the pro-
posed confident classifiers are not necessarily paralleled. Twin SVM (TW-SVM) [30] also has two hyperplanes, where each plane is close to one class and far from the other. Confident classifiers are different from TW-SVM due to their different purposes. TW-SVM aims to make more accurate predictions on all the samples but cannot tell hard samples from easy ones, while confident classifiers are obligated to distinguish hard and easy samples, and only predict on easy ones.

4. Experiments

4.1. Datasets

GFT [12] are recorded when three previously unacquainted young adults sat around a circular table for 30-min conversation with drinks. Moderate out-of-plane head motion and occlusion are presented in the videos which makes the AU detection challenging. In our experiments, 50 subjects are selected and each video is about 5000 frames.

BP4D [46] is a spontaneous facial expression dataset in both 2D and 3D videos. The dataset includes 41 participants aging from 18 to 29 associating with 8 tasks, which are covered with an interview process and a series of activities to elicit eight emotions. Frame-level ground-truth for facial actions are obtained using the Facial Action Coding System. In our experiments, we only use the 2D videos.

DISFA [35] recorded 27 subjects’ spontaneous expressions when they were watching video clips. DISFA not only codes the AUs, but also labels the intensities. In our experiments, we use the frames with intensities equal or greater than A-level as positive, the rest as negative. The dataset consist of 27 videos with 4845 frames each.

4.2. Settings

All the experiments were conducted using same protocol for fairness. Each dataset was divided into 10 splits, where each split designated several (5 in GFT, 4 or 5 in BP4D, 2 or 3 in DISFA) subjects as test data and the remaining as training data. Each subject served as test data once during the ten splits. 49 landmarks in the face were tracked by IntraFace [13]. For each AU, SIFT descriptors around the associated landmarks were extracted, e.g., the landmarks around the mouth for AU12. The same feature were used throughout the experiments.

We evaluated the performance using frame-based F1-score (F1-frame), which is prevalent in binary classification problems, and event-based F1 (F1-event) [15], which evaluates detection at event-level. An event is defined as a maximum continuous period that an AU is present. F1-Event is similar to F1-frame but applying event-based precision $EP$ and recall $ER$, i.e., $F1-event = \frac{2EP \cdot ER}{EP + ER}$.

4.3. Objective evaluation on CPM components

Recall that two major components in CPM are the confident classifiers and the PS classifier learned with QSSL. In order to validate their effectiveness, we conducted comparisons with a baseline linear SVM [21], confident classifiers only (Conf), and CPM (Conf+PS classifiers). In Conf, we trained confident classifiers using Alg. 1, and then passed them to train a PS classifier without a smoothness assumption. Thus, Conf checks the effectiveness of confident classifiers when compared with a standard single-hyperplane SVM. CPM differs from Conf by learning the PS classifier with the spatial-temporal smoothness as discussed in
Table 1. Comparison on GFT. (“H” stands for an extra post-processing with HMM)

<table>
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Table 2. Comparison on BP4D. (“H” stands for an extra post-processing with HMM)

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Figure 7. Results on GFT, DISFA and BP4D datasets. Note that the scales in each dataset are different for display purpose.

Sec. 3.3. In this way, CPM verifies the QSS classifier’s effectiveness on propagating labels with smoothness assumptions. We also conducted iCPM to validate the iterative integration in CPM.

Fig. 7 illustrates the results on GFT, BP4D and DISFA datasets, respectively. The values of F1-frame and F1-event were reported as the average over all AUs. Comparing the results between SVM and Conf, confident classifiers showed positive affects on the performance. The effectiveness of applying smoothness assumptions was indicated by the results between Conf and CPM. Out of the results, iCPM outperformed CPM in most cases, validating the effectiveness of the proposed iterative integration.

4.4. Comparisons

This section compares the proposed CPM with alternative methods, including baseline single-hyperplane classifiers, semi-supervised learning (SSL), and transfer learning approaches. For baselines, we used LibLinear [21] and Matlab toolbox for Adaboost [23]. For SSL, we implemented a linear version of Laplacian SVM (Lap) [36]. Its kernel version is computationally prohibitive because our experiments contain more than 100,000 samples. For transfer learning, we compared to state-of-the-art methods including Geodesic Flow Kernel (GFK) [24], Domain Adapt-
Table 3. Comparison on DISFA. (“H” stands for an extra post-processing with HMM)

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MDA had a smooth assumption over test data. GFK performed similarly to SVM, although it did not provide a way to deal with multiple sources. Across three datasets, iCPM consistently outperformed three transfer learning methods.

With few exceptions, iCPM consistently outperformed the alternative methods in both metrics. Because iCPM incorporated the spatial-temporal smoothness term (as described in Sec. 3.3), it showed an obvious increase on F1-event compared to F1-frame. Recall that AU detection aims for detecting temporal events, we believe this spatial-temporal smoothness would significantly improve the detection result. Note that the experiments with HMM did not show consistent improvements on either F1-frame or F1-event as iCPM did. A possible explanation is that a trivial enforcement of temporal consistency is likely to make some frames similar to their misclassified neighbors, or over-smooth some short events. It indicated that the performance edge of iCPM was given by both separating easy/hard samples and its temporal-spatial smoothness.

5. Conclusion

We have presented the CPM for facial AU detection. Unlike standard methods with assumptions on sources of error, CPM censors hard-to-recognize samples that could be ascribed to low intensities, head motion, or individual differences. CPM exploits an easy-to-hard framework that incorporates the proposed confident classifiers and a quasi semi-supervised classifier regularized with spatial-temporal smoothness. We also introduce iCPM, an iterative extension of CPM, that gradually adds easy test samples to update the confident classifiers. Experiments on three spontaneous datasets showed the effectiveness of CPM against semi-supervised learning and transfer learning methods. Future work includes a non-linear extension of CPM.

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