

Inducing Predictive Uncertainty Estimation for Face Recognition

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Abstract. Knowing when an output can be trusted is critical for reliably using face recognition systems. While there has been enormous effort in recent research on improving face verification performance, understanding when a model’s predictions should or should not be trusted has received far less attention.

Our goal is to assign a confidence score for a face image that reflects its quality in terms of recognizable information. To this end, we propose a method for generating image quality training data automatically from ‘mated-pairs’ of face images, and use the generated data to train a lightweight Predictive Confidence Network, termed as *PCNet*, for estimating the confidence score of a face image. We systematically evaluate the usefulness of PCNet with its error versus reject performance, and demonstrate that it can be universally paired with and improve the robustness of any verification model. We describe three use cases on the public IJB-C face verification benchmark: (i) to improve 1:1 image-based verification error rates by rejecting low-quality face images; (ii) to improve quality score based fusion performance on the 1:1 set-based verification benchmark; and (iii) its use as a quality measure for selecting high quality (unblurred, good lighting, more frontal) faces from a collection, *e.g.* for automatic enrolment or display.

1 Introduction

There has been tremendous progress in face recognition over the past five years, primarily due to three factors: *First*, the development of neural network architectures, from AlexNet [25], to VGGNet [33], to ResNet [20]; *Second*, the introduction of more sophisticated objective functions, for instance, contrastive loss [11], triplet loss [38], large-margin softmax [27, 13]. *Third*, the large-scale datasets, *e.g.* VGGFace [29], UMDFace [7], MS1M [19], VGGFace2 [9], IMDB-Face [37], that have enabled the data-hungry neural network models to be trained. With these efforts, state-of-the-art face recognition models have demonstrated strong capabilities of learning effective identity embeddings, which are largely invariant to nuance factors, such as pose and age, yet are still discriminative for face identities.

In this paper our objective is face *verification* – the task of determining if two face images are of the same person or not; or, more generally, given two sets of

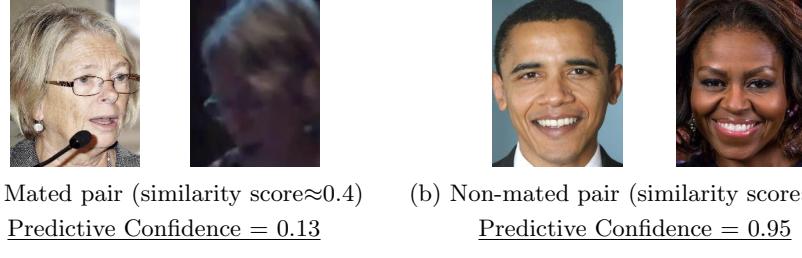


Fig. 1: A face verification model (ResNet101 trained on VGGFace2) gives similar output scores to both pairs, In (a), it refers to a false negative matching, where the low similarity score is most likely due to the inadequate information in the second image. In (b), the similarity score indicates that the identities are different in the pair of images. Predictive confidence is required to decide whether to trust the output from the system or not.

faces, where each set only contains arbitrary number of images from one person, determine if the two sets are of the same person or not. Verification, as is this case for any face recognition task, depends on the assumption that the input image contains sufficient information to be recognizable. During the training stage, this assumption is usually guaranteed, largely due to the bias from the data collection process – that images have been curated by human annotators, and so must be recognizable. Unfortunately, this is not always the case during the inference stage, as the input face images to verification system may be in profile, blurry, or low resolution (or even non-face images if the face detector operating point is for very high recall). As a result, this train-test discrepancy will potentially lead to false positives or negatives during verification. For instance, as demonstrated in Figure 1, a well-trained face recognition model (ResNet101 in this case) is broken by one low-quality image. Conceptually, this challenge can be resolved by augmenting the similarity between the face embeddings with a *predictive confidence*, which is identity-agnostic, and only reflects whether the image contains sufficient discriminative information to be recognizable.

Estimating such confidence scores is a non trivial task, as it is costly and challenging to obtain groundtruth annotations. Indeed, even defining image quality is difficult, despite the early efforts [1, 2] on measuring image quality by pose, expression, illumination, occlusion, and face accessories, some metrics remain extremely subjective. Furthermore, since classifications can be changed by adding perturbations to images (adversarial attacks) that are indistinguishable to human observers [34, 15, 6, 31], human assessments of image quality may be only sub-optimal for network training.

In this paper, we propose a method for generating image quality training data automatically, and use the generated data to train a lightweight network to predict confidences for any face image. The only requirement of the method is to have sets of images of the same person – and such sets are readily available from public face datasets that have identity annotation. Once the Predictive Confidence Network, *PCNet*, has been trained, then it can be applied to any

verification system and any face images. This method is described in Section 3. In Section 4, we systematically evaluate the usefulness of PCNet with error versus reject curves [18]. Experimentally, we demonstrate it can be universally paired with and improve the robustness of other recognition models, including strong models such as SENet50 and ResNet101, and that PCNet outperforms previous quality estimation baselines, while using a significantly lighter architecture (ResNet18 vs ResNet50). We also demonstrate three use cases on the challenging JANUS IJB-C Benchmark [28], (i) PCNet can be used to significantly improve 1:1 image-based verification error rates, such as False Accept Rate (FAR), and True Accept Rate (TAR), of automatic face recognition systems by rejecting low-quality face images; (ii) it can be used for quality score based fusion where a weighted average is used to combine the descriptors of multiple images of the same face into a single descriptor, significantly improve the performance on the 1:1 set-based verification benchmark; and (iii) it can also be used as a quality measure for selecting good (unblurred, good lighting, more frontal) faces from a collection, *e.g.* for automatic enrollment or display.

2 Related Work

Learning set representation. Recent works have proposed architectures for learning face descriptor aggregation [42, 36, 40, 41]. The general idea is to compute a set representation by the weighted average of the individual face, where the weights are treated as a latent variable inferred from the deep networks. While optimizing for classification, the training process implicitly tries to suppress the contribution from low-quality images, and highlight the most discriminative face images. This has later been interpreted as fulfilling the function of quality estimation. Despite the results shown in [41], these methods lead to over-confident predictions, *i.e.* majority of the images will have a high quality score.

Learning with rejection. In the cases of learning with single instance, the problem of classification with a reject option or learning with abstention [16, 43, 12] is highly related, where the classifier is allowed to abstain from making a prediction at a certain cost. Typically such methods jointly learn the classifier and the rejection function. Our paper aims to provide a standalone model that enables to learn the confidence scores independently to any already trained and possibly black-box face recognition systems. Technically, our goal is to learn an appropriate ranking for the confidence scores for the images, but we do not explicitly learn the appropriate rejection thresholds.

Visual quality estimation. In biometric recognition, image or sample quality has long stood out as the obvious way of predicting system performance [26, 32], where poor-quality images pose significant challenges. Traditionally, quality estimation has focused on the image capturing requirements defined by humans, for instance, in ISO/IEC 19794-5 [1], ICAO 9303 [2], the quality is usually measured by pose, expression, illumination, occlusion, and accessories. In the recent literature, learning-based approaches start getting popular, *e.g.* [3, 4, 14, 23, 30, 5, 39, 10, 24, 8, 21, 35]. See [8, 35] for an excellent extended literature review.

3 Approach

In this section we describe the **Predictive Confidence Network** (PCNet), that ingests a face image and outputs a scalar indicating the likelihood of the face being identifiable by a state-of-the-art face verification system. The training method proceeds in two stages: first, there is a simple and scalable approach for generating *pairwise* verification scores using only mated face-image pairs, *i.e.* face images of the same person. Second, we provide an approach to disentangle the pairwise scores to enable training of the PCNet for single faces. We illustrate the method using the VGGFace2 dataset (described in Section 4.1) which is partitioned here into two halves by identities, with the faces of around 4300 identities in each part.

3.1 Generate Pairwise Verification Scores

A standard ResNet34 is trained for face classification on the first half of the dataset, *i.e.* a 4300-way classification. Once trained, verification scores are obtained for all mated pairs in the other half of the dataset, as shown in Figure 2. We also alternate this process (*i.e.* training the ResNet34 on the other half, etc) in this way we obtain pairwise verification scores for all mated pairs in the dataset, ending up with roughly 500 million pairwise scores in total. The scores are obtained in this way, using the two halves of the data, so that the scores are not obtained from the same samples that the network is trained on. Note, the verification score here is obtained as the cosine similarity between the face embeddings, with a score of 1.0 indicating a perfect match.

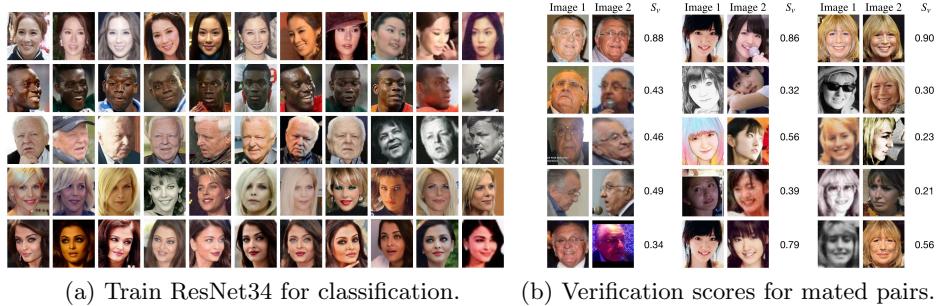


Fig. 2: Generating verification scores for mated pairs.

3.2 Training PCNet

We make the assumption that if the verification score is less than 1.0, then this is due to recognizability information being missing from either of the images forming the pair. We then use a ‘loser takes all’ scheme to obtain the quality measure for the individual images of the pair. That is to say, we assume the

pairwise verification score is fully determined by the image with worst quality (or least discriminative information). This then becomes a training target for the PCNet: it is trained to output a predictive confidence for each image of the pair, such that the minimum of the two confidences equals the verification score of the pair.

Formally, during training, a mated pair of images is selected (*i.e.* both images are of the same identity) and each image is passed through PCNet, parametrized as $\Phi(\cdot)$, and outputs a scalar s , referred as the predictive confidence for the image. For the two images of the pair, if $s_1 = \Phi(I_1; \theta)$ and $s_2 = \Phi(I_2; \theta)$, then the training objective for optimization is defined as the mean square loss, where y is the verification score of the image pair, mathematically, we minimize the following loss:

$$\mathcal{L}(s_1, s_2) = \mathbb{1}\{s_1 < s_2\} \cdot |s_1 - y|^2 + \mathbb{1}\{s_2 < s_1\} \cdot |s_2 - y|^2$$

where $\mathbb{1}\{\cdot\}$ refers to the indicator function. Note that this loss guarantees the permutation invariance between the images in the mated pair. The PCNet is then trained with over 500 million pairwise scores. For simplicity, in this paper, a standard ResNet18 is used as $\Phi(\cdot)$, but the proposed method is not limited to any specific architecture.

4 Experiments

4.1 Datasets

VGGFace2 [9] is used through this paper, to train all face recognition models and PCNet. It contains about 3.31 million images with large variations in pose, age, illumination, ethnicity and profession (e.g. actors, athletes, politicians). Approximately, 362.6 images exist for each of the 9131 identities on average. In order to be comparable with existing models, we follow the same dataset split and only train on the training set (8631 identities).

IJB-C Dataset [28] is used for all the evaluations in this paper, it is a superset of the previous IJB-A and IJB-B datasets. Overall, it contains 3,531 subjects with 31.3K still images and 117.5K frames from 11,779 videos, captured from unconstrained environments with large variations in viewpoints, image quality and distractors (non-face images). It is generally considered as one of the most challenging *public* benchmarks for face recognition.

4.2 Training Details

While generating pairwise predictive confidence and training PCNet, we follow the same strategy, namely, resizing the shorter side to 256, and a region of 224×224 pixels is randomly cropped from each sample. The mean value of each channel is subtracted. Stochastic gradient descent is used with mini-batches of size 256, with a balancing-sampling strategy for each mini-batch due to the

unbalanced training distributions. The initial learning rate is 0.1 for the models learned from scratch, and this is decreased twice with a factor of 10 when errors plateau. As for augmentation during training ResNet34 (in Section 3.1), random transformations are used with a probability of 20% for each image, e.g. monochrome augmentation, horizontal flipping, and geometric transformation. As for generating the pairwise predictive confidence pseudo-groundtruth, each image in the mated pair can potentially have a probability of 0.2 of randomly picking at least one of the degradations from Gaussian blur, motion blur, and jpeg compression, and the degraded images are later used for training PCNet.

4.3 Evaluation Protocol

We benchmark on 1:1 covariate verification and 1:1 verification from JANUS IJB-C. The former refers to the popular image-to-image verification, while the latter refers to set-to-set verification, where each set could potentially contain any number of images of the same identity. For both cases, the performance is reported as the standard True Accept Rate (TAR) vs. False Accept Rate (FAR) (*i.e.* receiver operating characteristics (ROC) curve).

To evaluate the effectiveness of ‘predictive confidence’, we report the error versus reject curves for 1:1 covariate verification (Section 4.5), a metric originally proposed for measuring biometric quality [18], and recently adopted for face recognition [17]. These curves show a verification error-rate over the fraction of ignored face images. Based on the predictive confidences values, these rejected images are those with the lowest confidences and the error rate is calculated on the remaining images. The curves indicate good quality estimation when the verification performance increases (the error decreases) monotonically as more images are rejected (as this indicates that the uninformative images are being rejected first). This process allows a fair comparison to different algorithms for face quality assessment, since it is independent of the range of the quality predictions (only the ordering is used).

As PCNet only provides predictive confidence, but not verification functionality, it is coupled with three different open-source face recognition models that are publicly available, namely, ResNet50, SENet50 and ResNet101, for verification. Although these models have all been trained on VGGFace2, they do behave slightly differently as the training settings vary, *e.g.* data augmentation, learning rate schedule, *etc*, as well as due to the differences in the architectures. Note that, the purpose of this paper is not to benchmark the state-of-the-art face recognition models, instead, we aim to validate the conjecture that the predictive confidence is an effective component for different models, *i.e.* largely model-independent.

4.4 Baselines

We compare with two recent works [41, 21], which propose the idea of using image quality estimation to improve face recognition systems. In [41], the authors propose the Multicolumn Networks (*MNet*), learning a set representation through

a weighted average of all individual images in the set. As a by-product, the networks learn a quality estimation that pays more attention to images with more discriminative information, *e.g.* frontal faces, high-resolution images. In [21], Face-QNet (*QNet*) is trained by comparing images with some ‘golden’ reference images, that were selected by ICAO Compliance Software. We use the official implementation and models [22]. In both works the quality estimation models were trained on VGGFace2 dataset with a ResNet50 architecture; however, in the following sections, we demonstrate that our light-weight PCNet (based on ResNet18) outperforms these strong baseline models on all metrics.

4.5 Results: 1:1 Covariate Verification with Rejection

In this protocol, the goal is to perform still image-to-image verification. In total, there are 140K images with over 7M genuine matches, and 39M impostor matches. During inference, we define the predictive confidence for each pair of images as the minimum score of the two images, and rank these pairwise confidence scores in descending order. By rejecting the bottom $k\%$ pairs, where $k \in [0, 40]$, the obtained TAR and FAR will therefore be informative to understand if the failure cases from modern face recognition systems are indeed predictable from the confidence scores.

Verification Arch.	Predictive Conf.	TAR@FAR=1E-6					TAR@FAR=1E-5				
		r=0.0	r=0.1	r=0.2	r=0.3	r=0.4	r=0.0	r=0.1	r=0.2	r=0.3	r=0.4
ResNet-50	MNet [41]	0.202	0.392	0.446	0.488	0.512	0.433	0.578	0.616	0.638	0.657
ResNet-50	QNet [21]	0.202	0.447	0.502	0.544	0.577	0.433	0.613	0.653	0.693	0.728
ResNet-50	PCNet (Ours)	0.202	0.510	0.536	0.572	0.617	0.433	0.641	0.673	0.718	0.769
SENet-50	MNet [41]	0.317	0.399	0.423	0.455	0.487	0.528	0.595	0.621	0.648	0.670
SENet-50	QNet [21]	0.317	0.453	0.481	0.517	0.539	0.528	0.629	0.660	0.695	0.724
SENet-50	PCNet (Ours)	0.317	0.478	0.508	0.538	0.578	0.528	0.644	0.674	0.715	0.761
ResNet-101	MNet [41]	0.095	0.248	0.366	0.387	0.440	0.249	0.548	0.622	0.659	0.685
ResNet-101	QNet [21]	0.095	0.280	0.352	0.409	0.469	0.249	0.592	0.653	0.700	0.738
ResNet-101	PCNet (Ours)	0.095	0.465	0.490	0.530	0.565	0.249	0.671	0.707	0.752	0.797

Table 1: Error vs rejection on IJB-C 1:1 covariate verification. By only rejecting a small proportion of the low quality image pairs ($r \in [0.0, 0.4]$), significant performance boost can be observed for all different architectures.

As shown in Table 1, we sample five different rejection rates ($[0.0, 0.4]$), where 0.0 refers to the case where no pairs are rejected, *i.e.* the performance from raw verification systems (ResNet50, SENet50 and ResNet101). More complete results are shown in Figure 3, where rejection rates are densely sampled with a gap of 0.01. It is clear that when rejecting the face pairs with lowest predictive confidences, the performance of all face recognition systems has been improved significantly. This claim holds for all the different architectures, demonstrating the generalizability of the PCNet – meaning it is largely recognition model independent. When comparing with baseline models (MNet and QNet), the proposed PCNet shows superior performance on all metrics.

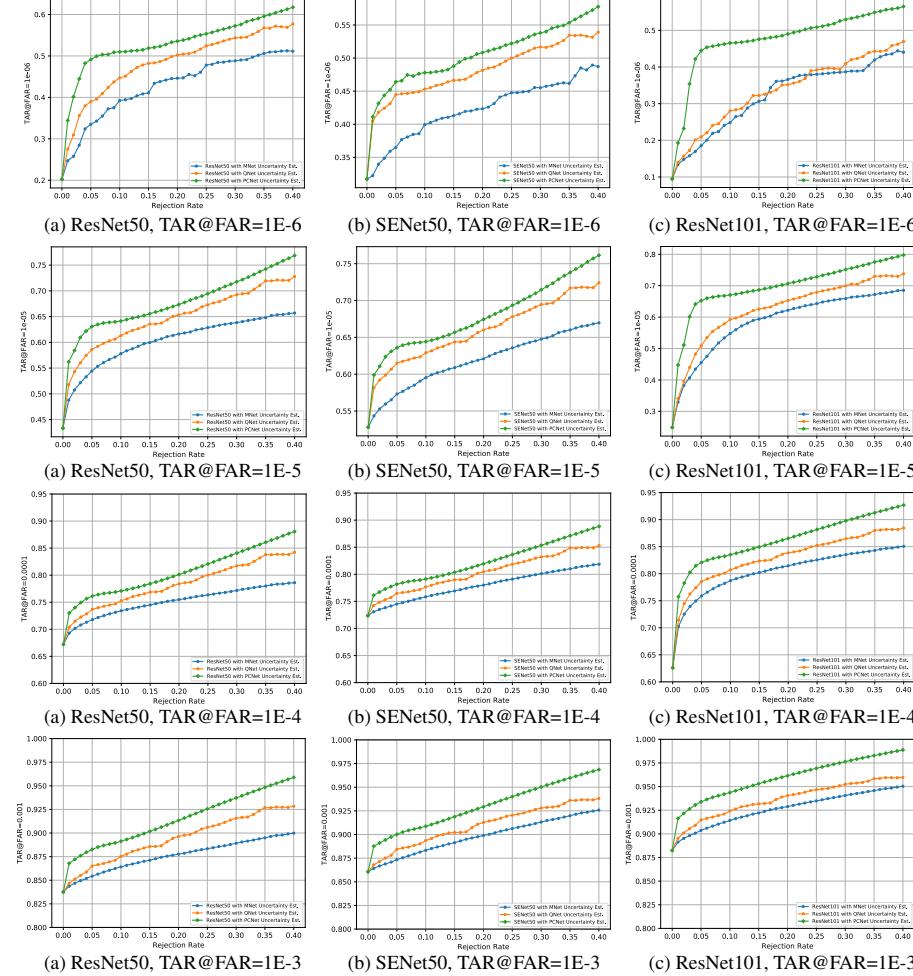


Fig. 3: Error vs rejection curve on IJB-C 1:1 covariate verification, with rejection rate being densely varied.

In Figure 4, we plot the complete ROC curve on 1:1 covariate verification. It is interesting to see that PCNet is already very effective when only rejecting 5% of the pairs with lowest predictive confidences. Remarkably, the verification performance of ResNet101 has been boosted around 20% for TAR@FAR=1E-6 and TAR@FAR=1E-5, suggesting that PCNet is indeed producing informative confidence scores that reflect the potential limitations of modern face recognition systems.

In Figure 5, we plot the correlation between the predictive confidence and the similarity scores from different models, we split the confidence scores into 100 bins, and compute the mean similarity scores falling in each bin. Note that the similarity scores are only generated for the mated pairs in the IJB-C, as

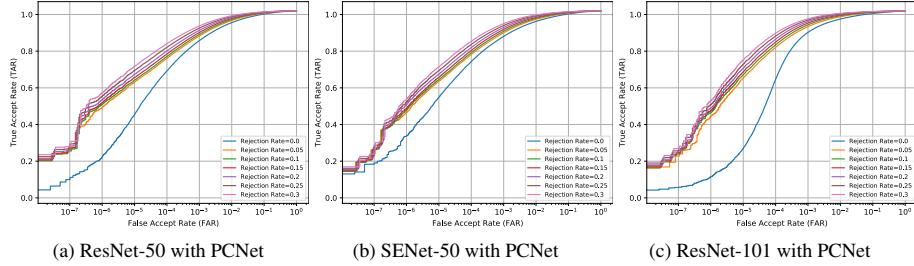


Fig. 4: ROC curves for IJB-C 1:1 covariate verification. Benchmarked for different architectures under different rejection rate. As can be seen, while only rejecting 5% of the pairs with lowest predictive confidences, PCNet can already improve the verification performance significantly.

such curve for non-mated scores will not be informative, because it is expected that all points lying on a narrow band on the very left side, either due to low predictive confidence or high predictive confidence by different identities. From the strong correlations between predictive confidence and matching scores for all models, it shows that the proposed PCNet is effective for avoiding false negatives during evaluation, and also it is model independent, shown from the consistent correlation among different models.

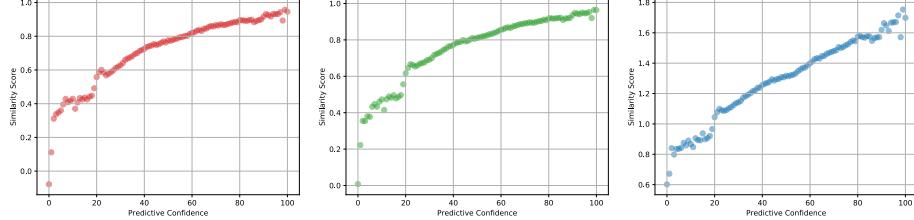


Fig. 5: The correlation between predictive confidence and the similarity scores from different models. The predictive confidences correlate with the similarity scores from different face verification systems – even though it was not trained on them.

Discussion. These results demonstrate that PCNet has indeed learnt a quality measure that correlates with the information content of the face image. Note in particular, the error vs. reject curves have exhibited a monotonic improvement with increasing rejection ratio, meaning that the rejected pairs are of the low visual quality that face recognition systems struggle on. Despite the fact that the PCNet is only trained with mated pairs, verification evaluation suggests that it also successfully orders the non-mated pairs. Examples of the rejected pairs (including mated and non-mated) will be given in the arXiv version.

4.6 Results: Standard 1:1 Verification with Confidence Weighting

This protocol uses set-to-set verification, where each set consists of a variable number of face images and video frames from different sources: each set can

be image-only, video-frame-only, or a mixture of still images and frames. This protocol defines 23124 different sets, with 19557 genuine matches, and over 15M impostor matches. During testing, the set descriptor is computed as a weighted average of individual faces, with the weights obtained from the predictive confidences of the faces as $v = \sum_i s_i \cdot v_i / \sum_i s_i$ where s_i, v_i refers to the predictive confidence and feature embedding for the image (I_i).

Discussion. As shown in Table 2 and Figure 6, using the predictive confidence from PCNet for computing the set representation gives an improvement for all metrics by about 2-8% over the raw ResNet50 and SENet50 on 1:1 mixed verification. The performance improvements are most substantial at low FARs, this is as expected due to the fact that the main issue of average feature aggregation (as used in previous results) is that the set-based representation can be distracted by images of low quality, leading to false matchings. Consequently, the most dramatic improvement is from highlighting the discriminative faces and suppressing the ones with inadequate information.

	Architecture	Predictive Conf.	1:1 Verification				
			TAR FAR=1E-6	TAR FAR=1E-5	TAR FAR=1E-4	TAR FAR=1E-3	TAR FAR=1E-2
Cao <i>et al.</i> [9]	ResNet50	-	0.610	0.742	0.842	0.916	0.958
	ResNet50	QNet [21]	0.641	0.762	0.860	0.929	0.969
	ResNet50	MNet [41]	0.664	0.770	0.864	0.930	0.969
	ResNet50	PCNet (Ours)	0.693	0.803	0.885	0.944	0.970
Cao <i>et al.</i> [9]	SENet50	QNet [21]	0.617	0.753	0.852	0.927	0.971
	SENet50	MNet [41]	0.643	0.768	0.861	0.931	0.972
	SENet50	PCNet (Ours)	0.695	0.800	0.890	0.948	0.974

Table 2: Evaluation on 1:1 verification protocol on IJB-C dataset. Higher is better. The numbers with MNet [41] are based on our re-implementations, and QNet is from the official implementation and model [22].

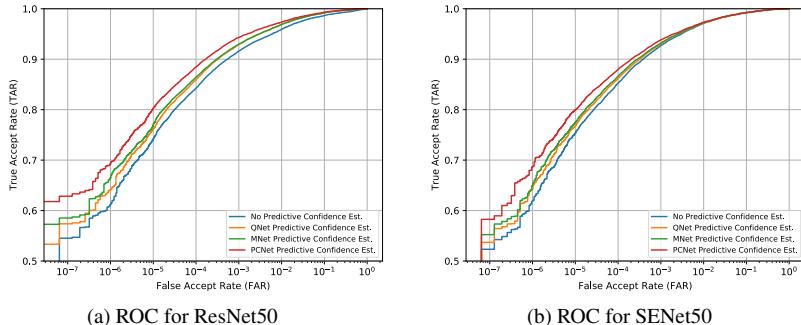


Fig. 6: On 1:1 IJB-C Verification, the PCNet improves the set-based verification for different face verification architectures, and outperform both QNet and MNet.

4.7 Visualization.

In Figure 8, we show the sorted images in ascending order based on the predictive confidences inferred from PCNet. As expected, the low confidence scores for aberrant images are highly correlated with human expectation, *i.e.* blurry, nonface, extreme poses. Note, the images of medium and high quality are not so well separated, though high quality ones are often near frontal.

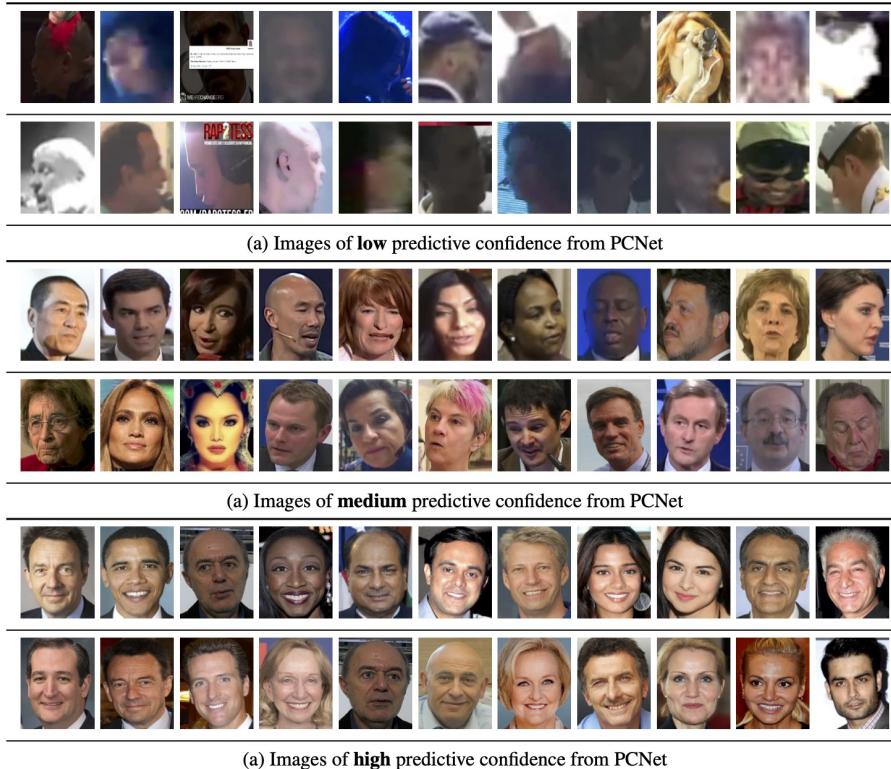


Fig. 7: After ranking all images of the IJB-C datasets, we split the ranking into three different ranges, and randomly sample images from the corresponding range.

5 Conclusions

To summarize, in this paper, we propose a novel training scheme for learning predictive confidence, with the goal of reducing the proportion of errors caused by images with insufficient information, *e.g.* poor visual quality or profile faces, non-face images. While evaluating on the challenging JANUS IJB-C Benchmarks, we

demonstrate three use cases: (i) PCNets can be used to significantly improve 1:1 image-based verification error rates, of automatic face recognition systems by rejecting low-quality face images, (ii) it can be used for quality score based fusion where a weighted average is used to compute set representation, (iii) it can also be used as a quality measure for selecting good (unblurred, good lighting, more frontal) faces from a collection, *e.g.* for automatic enrollment or display. Although we have presented the predictive confidence as essential for face verification, the idea of learning a confidence from true matches is more generally applicable. For example, a predictive confidence could be learnt from a set of ground truth matches between images, and then used to predict a confidence for correspondences between images or video frames.

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Appendix

A Architecture for PCNet

Here, we present the backbone architecture for the proposed PCNet, which is based on the standard ResNet18 with an extra fully connected layer at the end.

Architecture	Input Image ($N \times 224 \times 224 \times 3$)	Output Size
Predictive Confidence Network	conv, 7×7 , 64, stride 2	$112 \times 112 \times 64$
	max pool, 3×3 , stride 2	$56 \times 56 \times 64$
	conv, 3×3 , 64 $\times 2$	$56 \times 56 \times 64$
	conv, 3×3 , 64	
	conv, 3×3 , 128 $\times 2$	$28 \times 28 \times 128$
	conv, 3×3 , 128	
	conv, 3×3 , 256 $\times 2$	$14 \times 14 \times 256$
	conv, 3×3 , 256	
	conv, 3×3 , 512 $\times 2$	$7 \times 7 \times 512$
	conv, 3×3 , 512	
Global Average Pooling		$1 \times 1 \times 512$
FC, 1×1 , 128		$1 \times 1 \times 128$
Predictive Confidence, 1×1 , 1		$1 \times 1 \times 1$

Table 3: Architecture of the proposed Predictive Confidence Network (PCNet).

B More visualization of single-image confidence scores

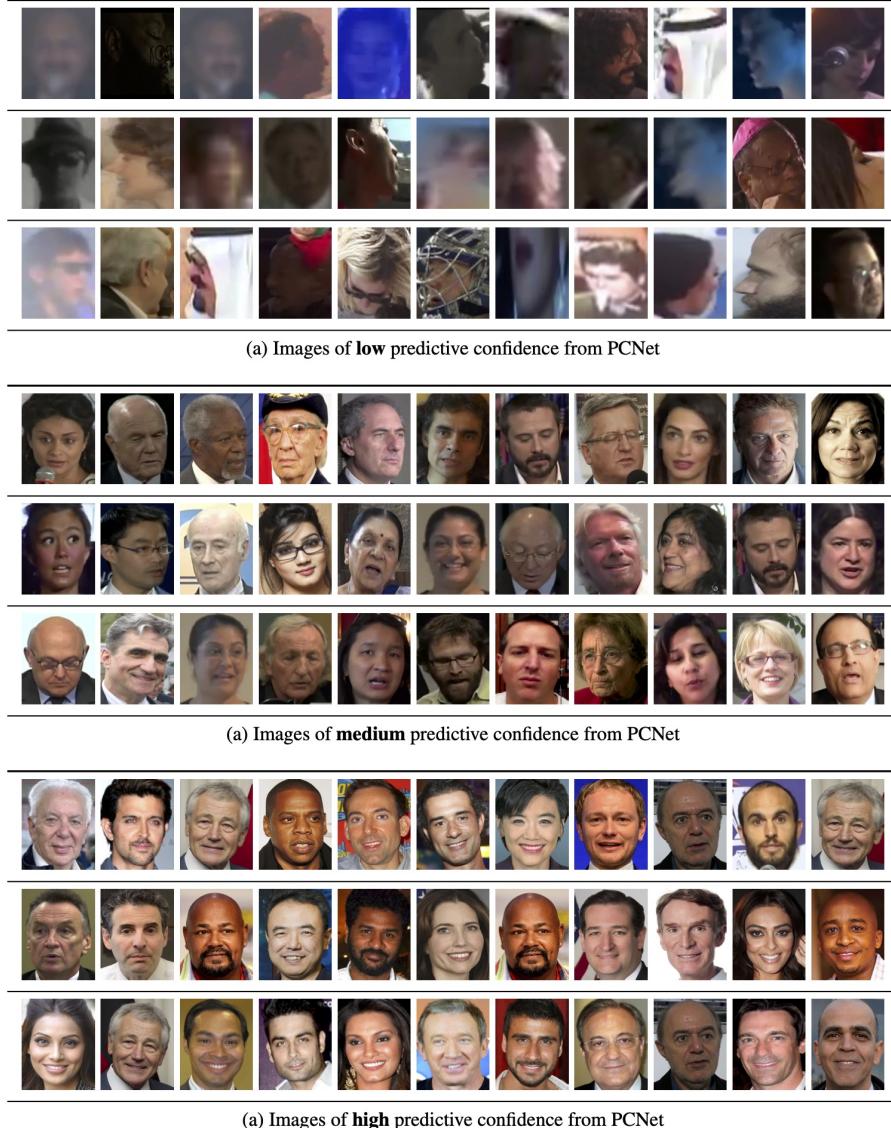


Fig. 8: After ranking all images of the IJB-C datasets, we split the ranking into three different ranges, and randomly sample images from the corresponding range.

C Visualizing the rejected pairs by PCNet

In Figure 9, we show example pairs that have been rejected while plotting the error vs rejection curve, in other words, these pairs are predicted with the lowest predictive confidence from our PCNet. As expected, once single image or both images are of low quality in the sense of insufficient information to be recognizable, the PCNet can indeed alarm the users.

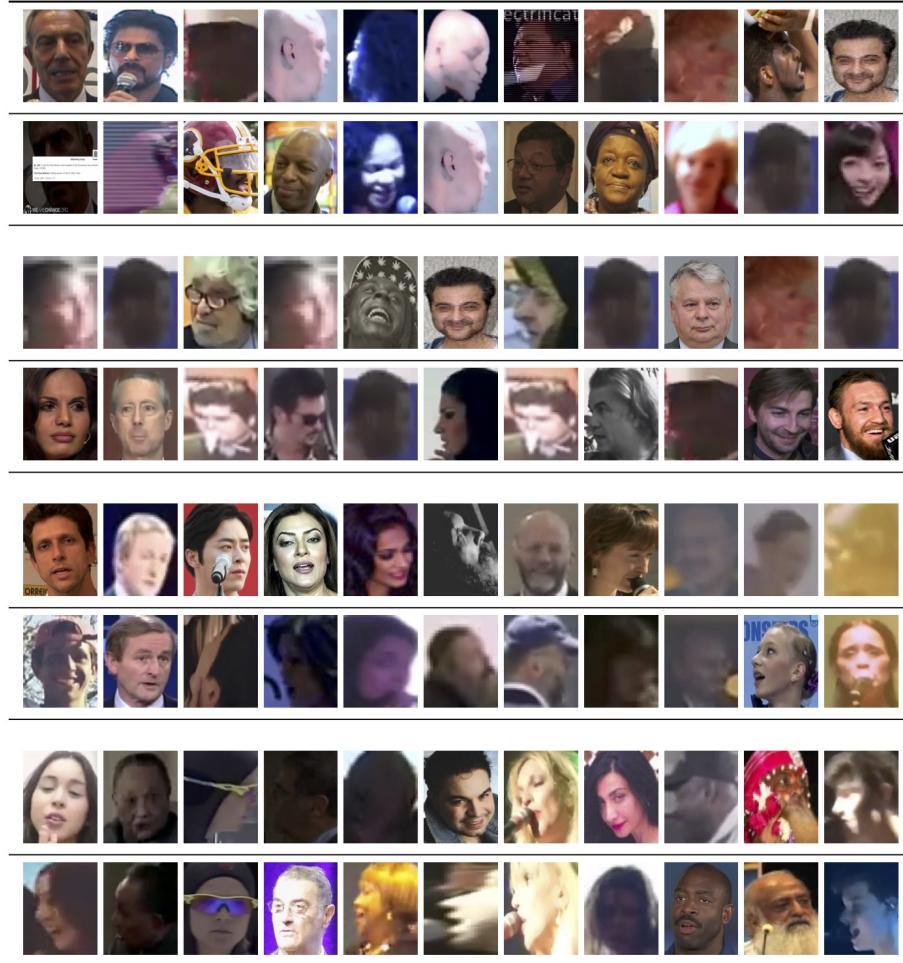


Fig. 9: Visualizing the rejected pairs by PCNet while plotting the error vs rejection curve. Note that, the figures are grouped by pairs in the column, *i.e.* two images are shown in each pairs.