Image-Quality-Based Adaptive Face Recognition

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Abstract—The accuracy of automated face recognition systems is greatly affected by intraclass variations between enrollment and identification stages. In particular, changes in lighting conditions is a major contributor to these variations. Common approaches to address the effects of varying lighting conditions include pre-processing face images to normalize intraclass variations and the use of illumination invariant face descriptors. Histogram equalization is a widely used technique in face recognition to normalize variations in illumination. However, normalizing well-lit face images could lead to a decrease in recognition accuracy. The multiresolution property of wavelet transforms is used in face recognition to extract facial feature descriptors at different scales and frequencies. The high-frequency wavelet subbands have shown to provide illumination-invariant face descriptors. However, the approximation wavelet subbands have shown to be a better feature representation for well-lit face images. Fusion of match scores from low- and high-frequency-based face representations have shown to improve recognition accuracy under varying lighting conditions. However, the selection of fusion parameters for different lighting conditions remains unsolved. Motivated by these observations, this paper presents adaptive approaches to face recognition to overcome the adverse effects of varying lighting conditions. Image quality, which is measured in terms of luminance distortion in comparison to a known reference image, will be used as the base for adapting the application of global and region illumination normalization procedures. Image quality is also used to adaptively select fusion parameters for wavelet-based multistream face recognition.

Index Terms—Biometrics, face recognition, illumination, quality measures, wavelet transforms (WTs).

I. INTRODUCTION

AUTOMATIC face image analysis has received a considerable amount of attention by the computer vision research community. Much progress has been made in developing robust algorithms and technology to transfer face image analysis from theory to successful automated identification systems for various applications. Continued research in this field is motivated by the need for convenient, reliable, efficient, pervasive, and universal person identification methods as proof of entitlement to services, to counter identity theft, crime, and international terrorism and as a tool in forensic investigations. The unobtrusive nature and the relative ease of obtaining face biometric samples from a distance make face recognition systems very desirable. The availability of low-cost devices have enabled

face identification systems to move from centralized control rooms to portable handheld person identification systems. Such *fieldable* biometric systems are an ideal person identification tool for street/city policing, crowd control at large venues, and border control.

However, automatic face recognition remains a challenging task when presented with uncooperative users as well as in uncontrolled environments. Intraclass variations due to changes in lighting conditions, facial expressions and pose, occlusion, and poor sensor quality cause identification errors. In the literature, there is a tendency to associate these variations as distortions from "standard" reference images, giving rise to measures of image quality [1], [2]. This paper is concerned with face recognition under varying illumination.

Discrete wavelet transforms (DWTs), which are multiresolution image analysis tools that decompose an image into low and high frequencies at different scales, have been successfully used in a variety of face recognition schemes as a dimension reduction technique and/or as a tool to extract a multiresolution feature representation of a given face image [3]–[8]. The multiresolution property of DWT enables one to efficiently compute a small-sized feature representation that is particularly desirable for face recognition on constrained devices such as mobile phones.

Sellahewa and Jassim [7], [9] have shown that the low-frequency approximation subband is a suitable face descriptor for recognition under controlled illumination, but it is significantly affected by varying illumination. On the other hand, the detail subbands (e.g., horizontal and vertical face features) are reasonably robust against varying lighting conditions, but they are affected by geometrical changes such as varying facial expressions and pose. Accurate identification of faces, imaged under poor and uncontrolled lighting conditions, is still a challenge for both subband representations. This is commonly addressed by normalizing the illumination of both enrolled and test images. However, a recent study [9] shows that normalizing well-lit face images could lead to a decrease in identification accuracy and suggests that an adaptive approach to illumination normalization could improve the identification accuracy of face recognition systems.

Jassim and Sellahewa [8] combine the use of low- and high-frequency subbands in face recognition by means of score level fusion. The identification accuracy of the fused *multistream* approach is higher than that achieved by any of the individual subbands. However, the effective selection of fusion parameters remains unresolved.

Here, we propose a quality-based adaptive approach to face recognition. The contribution of this paper is threefold: 1) an objective measure of illumination quality of a given face image is used to decide if the image should be preprocessed to

normalize its illumination; 2) the *global* quality-based normalization scheme is extended to a *regional* quality-based approach to adaptive illumination normalization; 3) the illumination quality measure is used as a means to adaptively select the weighting parameters of the fused wavelet-based multistream face recognition scheme.

The rest of this paper is organized as follows. Section II presents a review of approaches to face recognition in the presence of varying lighting conditions. The illumination quality measure used in this study and the proposed adaptive approach to face recognition is presented in Section III. Section IV evaluates the suitability of the illumination quality measure for the proposed adaptive face recognition scheme. Recognition experiments are presented and discussed in Section V. Conclusions and future work are presented in Section VI.

II. LITERATURE REVIEW

Changes in lighting conditions during enrollment and identification stages contribute significantly to intraclass variations of face images. Typical methods employed to address varying illumination conditions could be categorized as follows: 1) *feature-based methods*; 2) *generative methods*; and 3) *holistic methods*. In feature-based approaches, faces are represented by illumination invariant features. Typically, these are geometrical measurements and relationships between local facial features such as the eyes, mouth, nose, and chin [10], [11]. Feature-based methods are known to be robust against varying illumination conditions. However, they rely on accurate face and facial feature point detection, which is a challenging task on its own right.

Generative methods [12]–[15] have been proposed to address the problem of varying illumination based on the assumption of the Lambertian model. It has been demonstrated that the variability of images under a fixed pose, consisting of only diffuse reflection components and varying illumination conditions can be represented by a linear combination of three basis images [16], [17]. Belhumeur and Kriegman [18] demonstrated that a set of images of an object under fixed posed, consisting of diffuse reflection components and shadows under arbitrary lighting conditions, forms a convex cone (called the illumination cone) in the image space and that this illumination cone can be approximated by a low-dimensional subspace. Experimental results show that these generative methods perform well under varying illumination conditions. However, they require a number of training samples that represent extreme illumination conditions. It may be possible to acquire such images for certain applications (e.g., identification cards and physical access control systems), where individuals are cooperative, but not so for surveillance- and counter-terrorism-related applications where only one or few images of an individual are available for training.

In holistic approaches, the entire face image is considered for face representation without taking into account any specific geometrical features of the face. A face image could be thought of as a point in a high-dimensional image space. To avoid computational complexities and to reduce redundant data, a face image is first linearly transformed into a low-dimensional subspace before extracting a feature vector. The most commonly used dimension reduction technique in face recognition is the principal components analysis (PCA) [19]. PCA is known to retain intraclass variations due to changes in illumination. It has been demonstrated that leaving out the first three eigenfaces that corresponds to the three most significant eigenvalues could reduce the effect of variations in illumination [20]. However, this may also lead to the loss of information that is useful for accurate identification. An alternative approach to PCA-based linear projection is Fisher's linear discriminant, or the linear discriminant analysis (LDA), which is used to maximize the ratio of the determinant of the *interclass* scatter to that of *interclass* scatter [20], [21]. Like generative approaches, the downside of the holistic approaches is that a number of training samples from different conditions are required to identify faces in uncontrolled environments.

A more common approach to address the effects of varying lighting conditions is to preprocess face biometric samples to normalize illumination before extracting facial features for identification. Widely used normalization techniques include histogram equalization (HE), histogram matching, gamma intensity correction, and quotient image. These normalization techniques can be applied to an image either globally or regionally. Shan *et al.* [22] proposed a region-based approach to illumination normalization where an image is first partitioned into four regions. The selected normalization technique (e.g., HE) is applied to each region separately (i.e., RHE). The region-based normalization leads to higher identification accuracy than the traditional global normalization.

It is commonly accepted that illumination normalization techniques help in improving recognition accuracy [22], [23]. However, the improvements depend on the extent of variation in illumination present between enrolled and test images and are often not repeatable on different data sets [7], [24]. In a recent study, Sellahewa and Jassim [9] show that normalizing well-lit face images could lead to a decrease in identification accuracy and highlight the need for a quality-based adaptive approach to illumination normalization as an alternative to existing approaches where all images, irrespective of their lighting conditions, are normalized prior to feature extraction.

This paper focuses on wavelet-based face recognition in the presence of varying illumination. A brief description of WTs and their use in face recognition is given below in Section II-A and B.

A. Wavelet Transforms (WTs)

A WT hierarchically decomposes a signal into low- and high-frequency components, providing a multiresolution analysis of the signal. The DWT is a special case of the WT that provides a compact representation of a signal in time and frequency that can be efficiently computed [25], [26].

The most commonly used wavelet decomposition of an image, which is the one adopted here, is the pyramid scheme (also known as the nonstandard decomposition). At a resolution level of k, the pyramid scheme decomposes an image I into $3k + 1$ subbands $(\mathrm{LL}_k, \mathrm{HL}_k, \mathrm{LH}_k, \mathrm{HH}_k, \ldots, \mathrm{HL}_1, \mathrm{LH}_1, \mathrm{HH}_1)$, with LL_k being the subband with the lowest pass. The subbands

LH$_1$ and HL$_1$ contain finest scale wavelet coefficients that get coarser, with LL$_k$ being the coarsest. The LL$_k$ subband is considered as the k-level approximation of I.

B. WTs in Face Recognition

A subband of a wavelet transformed face image can be used as face feature descriptor [4], [5], [7]. Typically, sub-band coefficients (i.e., LL$_k$, HL$_k$, and LH$_k$) are normalized by Z-score normalization (ZN) in terms of its mean and standard deviation. The ZN has shown to improve the recognition accuracy, particularly under varying illumination [7]. Two feature vectors from the same stream are typically compared by calculating a distance score, and the subject's identity is classified according to the nearest neighbor.

In [4] and [5], WTs are used to reduce image dimension prior to using statistical dimension reduction techniques such as PCA and LDA. The wavelet-based schemes are computationally efficient, and their identification accuracy is comparable, if not better than the PCA- and LDA-only approaches [5], [24]. The advantage of using only the wavelet coefficients as the feature representation over methods such as PCA and LDA is that the wavelet only approach does not require a training stage to create a low-dimensional subspace.

Different decomposition levels and/or wavelet filters yield different face feature vectors, giving rise to different face recognition schemes and providing opportunities for a multistream (multichannel) identification. In the multistream approach [7], [8], a face image is represented by multiple feature vectors at a given scale (e.g., LL and LH subbands). Two images are compared by first calculating a distance score for each subband representation, followed by a score fusion that can be performed by calculating a weighted average of the scores. The fused score is then used to classify the identity of the individual. The selection of fusion weights is an important task as it influences the accuracy of the system. This paper presents an adaptive approach to select fusion weights based on the illumination quality of the given probe image.

III. Image-Quality-Based Adaptive Face Recognition

Real-time computation of a quantitative objective image quality measure is an essential tool for biometric-based identification applications. Such measures can be used as a quality control to accept, reject, or reacquire biometric samples, as quality-based processing to select a biometric modality, algorithm, and/or system parameters, and as confidence estimators of reliability of decision.

This paper investigates the use of an image quality measure as a base for an adaptive approach to face recognition in the presence of varying illumination. Naturally, the illumination quality of a given face image is to be defined in terms of its luminance distortion in comparison to a known reference image. The mathematically defined quality measure proposed by Wang and Bovik [27], i.e., the universal image quality index (Q), incorporates the necessary ingredients that fits our needs. The Q aims at providing meaningful comparisons across

different types of image distortions by modeling any image distortion as a combination of the following three factors: 1) loss of correlation; 2) luminance distortion; and 3) contrast distortion. Here, the luminance distortion factor of Q is used to measure global or regional illumination quality of images. This will be called the luminance quality (LQ) index.

A. Universal Quality Index

Let $x = \{x_i | i = 1, 2, \ldots, N\}$ and $y = \{y_i | i = 1, 2, \ldots, N\}$ be the reference and the test images, respectively. The universal quality index in [27] is defined as

$$Q = \frac{4\sigma_{xy}\bar{x}\bar{y}}{\left(\sigma_x^2 + \sigma_y^2\right)\left[(\bar{x})^2 + (\bar{y})^2\right]} \quad (1)$$

where

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$$

$$\sigma_x^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \qquad \sigma_y^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \bar{y})^2$$

$$\sigma_{xy} = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y}).$$

Statistical features in (1) are measured locally to accommodate space-variant nature of image quality and then combine them together to a single quality measure for the entire image. A local quality index Q_j is calculated by sliding a window of size $B \times B$ pixel by pixel from the top-left corner until the window reaches the bottom-right corner of the image. For a total of M steps, the overall quality index is given by

$$Q = \frac{1}{M}\sum_{j=1}^{M} Q_j. \quad (2)$$

B. Global LQ (GLQ) and Region LQ (RLQ) Indexes

The universal quality index Q can be written as a product of three components, i.e.,

$$Q = \frac{\sigma_{xy}}{\sigma_x\sigma_y} \cdot \frac{2\bar{x}\bar{y}}{(\bar{x})^2 + (\bar{y})^2} \cdot \frac{2\sigma_x\sigma_y}{\sigma_x^2 + \sigma_x^2}. \quad (3)$$

LQ, which is the luminance distortion factor in Q, is defined as

$$\text{LQ} = \frac{2\bar{x}\bar{y}}{(\bar{x})^2 + (\bar{y})^2}. \quad (4)$$

With a value range of [0, 1], LQ measures how close the mean luminance is between x and y. LQ equals 1, if and only if $\bar{x} = \bar{y}$. The window size used in this paper is the default 8×8 pixels.

GLQ is calculated similarly to the calculation of a single Q value in (2). RLQ represents the LQ of a region of an image resulting from a 2×2 partitioning of the image. The LQ of a region of an image is calculated by partitioning the local quality

Fig. 1.   Illumination subsets of Extended YaleB.

index map [resulting from the blockwise calculation of (4)] into four regions.

C. Image-Quality-Based Adaptive Normalization

The proposed image-quality-based adaptive normalization works by first calculating the GLQ of a given image and then normalizing only if its GLQ is less than a predefined threshold.

Inspired by the work of Shan *et al.* [22] and the fact that the images tend to exhibit regional variation in image quality as a result of the direction of the light source, the *global* quality-based adaptive normalization is extended by introducing a *region* quality-based adaptive approach to normalization. A region of an image is normalized only if the RLQ score is lower than a predefined threshold.

The commonly used HE is adopted here for illumination normalization. Hence, the two proposed approaches to adaptive normalization will be referred to as global quality-based HE (GQbHE) and regional quality-based HE (RQbHE). The threshold can be determined empirically, depending on the objectives of the applications under consideration.

D. Image-Quality-Based Adaptive Fusion

The idea is to select fusion weight parameters to adaptively suit the condition of probe images. The quality-based fusion (QbF) works by first calculating the LQ of the input image, and if its LQ score is higher than a predefined fusion threshold, then the approximation subband is given a higher weight than the detail subbands during score fusion. If the LQ score is less than the threshold, the approximation subband gets a very low weight (to indicate that the face descriptor is unreliable for the given image).

IV. EVALUATION OF THE LQ INDEX

A. Evaluation Data

1) Extended Yale Face Database B (Extended YaleB): Extended YaleB [13], [15] consists of 38 subjects, each imaged under 64 illumination conditions in frontal pose, capturing a total of 2414 images. These images can be divided into five illumination subsets according to the angle θ of the light source with respect to the optical axis of the camera. The number of images, the range of the angle θ, and an example image of each subset are shown in Fig. 1. The 168×192 pixel cropped images in the database are resampled to a fixed size of 128×128 for the experiments reported in this paper.

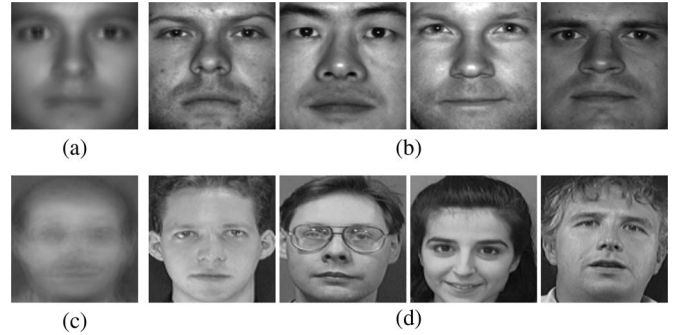Fig. 2.   Example images of the AT&T database.

Fig. 3.   Reference face images used to calculate LQ and a sample of gallery images from each database. (a) Reference. (b) Example gallery images from Extended YaleB. (c) Reference. (d) Example gallery images from the AT&T database.

2) AT&T (ORL) Face Database: The AT&T (formerly ORL) [28] database consists of 40 subjects, each with ten face images captured against a dark homogeneous background. Images of some subjects were captured at different times. Variations in pose (frontal images, with tolerance to some side movements), facial expressions (open/closed eyes, smiling/not smiling), and facial details (glasses/no glasses) are captured in this collection of face images. Sample images of the database are shown in Fig. 2. The original 92×112 pixel images are resampled to 128×128 for the experiments in this paper. The AT&T database is used to find a suitable threshold for the adaptive normalization as well as to demonstrate that the reference image used to calculate the illumination quality of a face image can be selected independently of the gallery images of a face recognition system.

3) Reference Image: The calculation of the LQ index for a given face image relies on the use of a reference image, preferably one that is independent of subject and gallery face images. The reference image used in the evaluation of the LQ index as well as for face recognition experiments is the average face image of the 38 individual faces, each one captured in frontal pose and under direct illumination (i.e., the average image of the P00A+000E+00 image of each subject). The same 38 images are commonly used as gallery images for face recognition experiments using Extended YaleB. The Yale reference image and a sample of individual faces are shown in Fig. 3(a).

B. Evaluation

The illumination condition of each image and of each subset of Extended YaleB is well defined. To demonstrate the appropriateness of LQ index for our purposes, we determined the distribution of GLQ values in different subsets of this database. The subject-independent reference image [see Fig. 3(a)] based on Extended YaleB data is used to calculate the LQ scores.
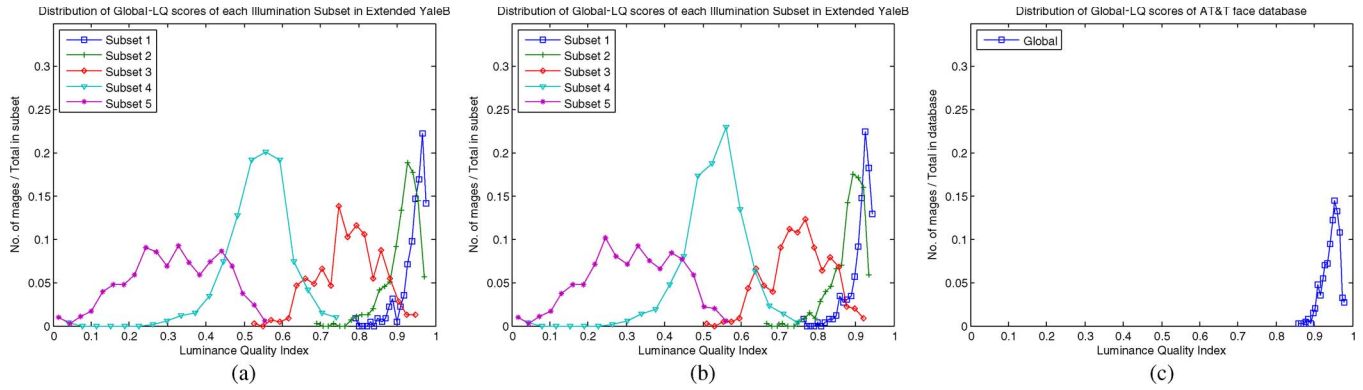
Fig. 4. Distribution of global quality index scores for images in Extended YaleB and AT&T. (a) Reference and evaluation: Extended YaleB. (b) Reference: AT&T; evaluation: Extend YaleB. (c) Reference and evaluation: AT&T.
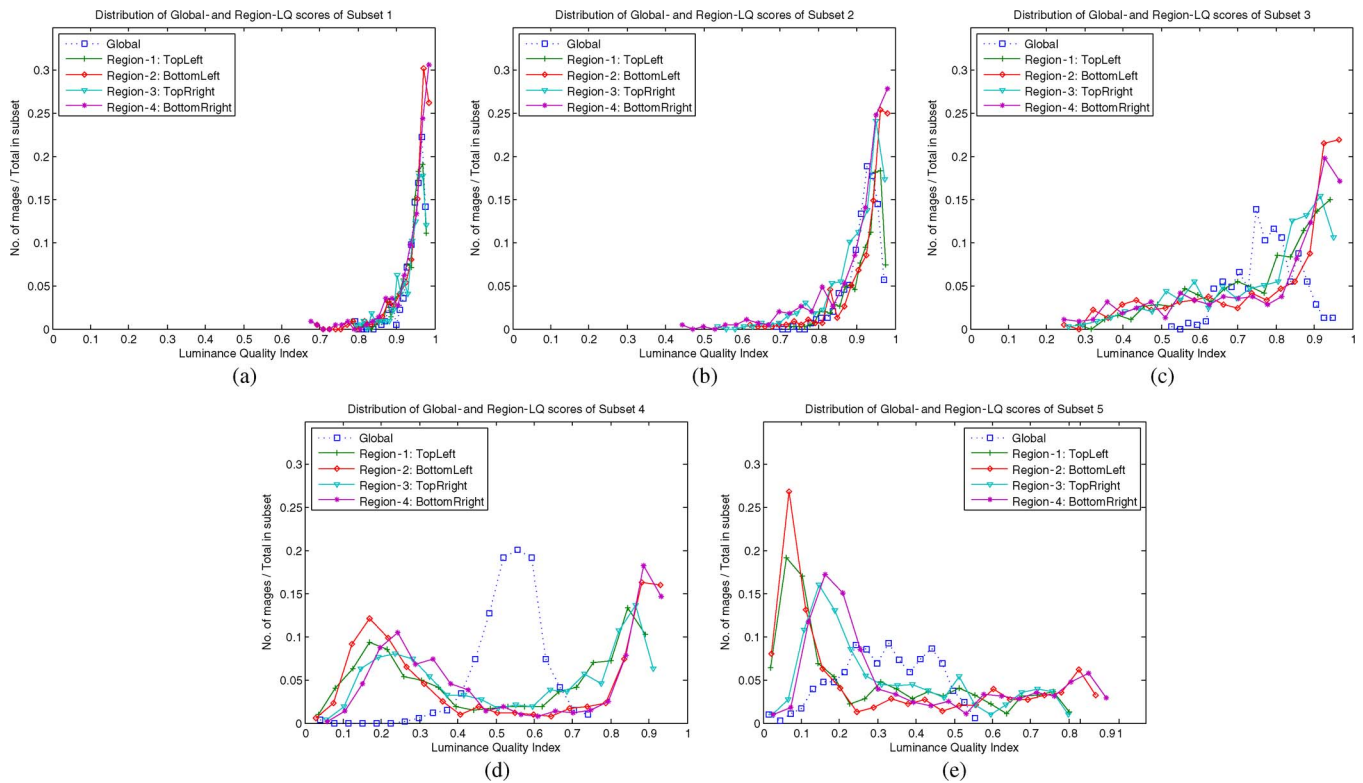

Fig. 5. Distribution of GLQ and RLQ index scores of the five illumination subsets of Extended YaleB. (a) GLQ versus RLQ: subset 1. (b) GLQ versus RLQ: subset 2. (c) GLQ versus RLQ: subset 3. (d) GLQ versus RLQ: subset 4. (e) GLQ versus RLQ: subset 5.

The P00A+000E+00 image of each subject was excluded in the evaluation since these are used to calculate the reference image. The distribution of GLQ scores of the images in each illumination subset is shown in Fig. 4(a).

A close examination of the distributions reveals that 60% of the 225 images in subset 1 have a GLQ score of 0.95 or higher, compared to only 19% of the images of subset 2 with such high illumination quality. Furthermore, 91% and 73% of the images of subsets 1 and 2, respectively, have a GLQ score of 0.9 or higher. This demonstrates that the GLQ measure correctly quantifies the illumination quality of images in subsets 1 and 2 to be very near that of the reference image while also recognizing that the images in subset 1 are nearer the reference image than the images in subset 2. Only 4% of images in

subset 3 have a GLQ score of 0.9 or higher, while 33% of its images have a GLQ value range of [0.8, 0.9]. This indicates a noticeable variation in illumination of subset 3 images. Nearly 82% of the images of subset 4 have a GLQ value less than 0.6, while the highest GLQ score of its images is only 0.76. Nearly 45% of the images in subset 5 scored a quality value less than 0.3, while its highest GLQ score is only 0.59. This reflects the poor illumination quality of the images in subsets 4 and 5 due to the extreme changes in illumination direction (horizontally and/or vertically) with regard to the camera axis (see Fig. 1 for details).

The above evaluation demonstrates that the luminance quality index (LQ) is a suitable illumination quality estimator for face image samples. To determine if the choice of the reference

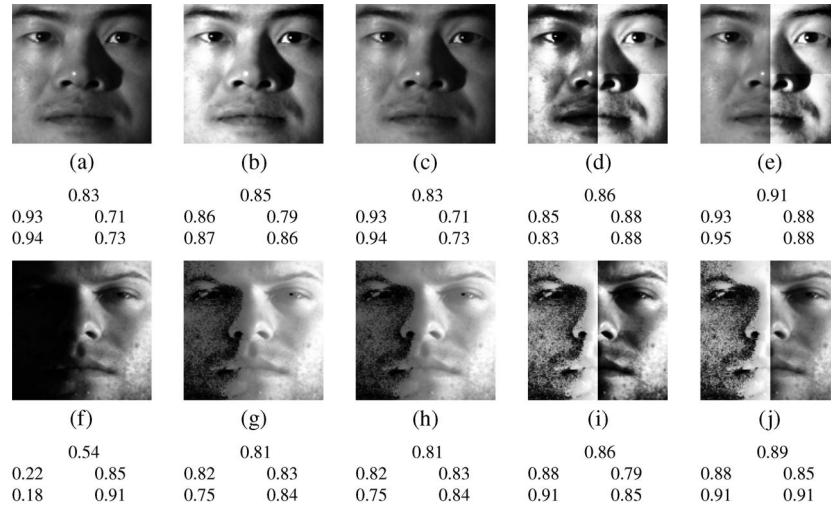|	(a)	(b)	(c)	(d)	(e)
	0.83	0.85	0.83	0.86	0.91
	0.93 0.71	0.86 0.79	0.93 0.71	0.85 0.88	0.93 0.88
	0.94 0.73	0.87 0.86	0.94 0.73	0.83 0.88	0.95 0.88
	(f)	(g)	(h)	(i)	(j)
	0.54	0.81	0.81	0.86	0.89
	0.22 0.85	0.82 0.83	0.82 0.83	0.88 0.79	0.88 0.85
	0.18 0.91	0.75 0.84	0.75 0.84	0.91 0.85	0.91 0.91

Fig. 6. GLQ and RLQ scores of original and normalized face images. (a) Original. (b) HE. (c) QbHE. (d) RHE. (e) RQbHE. (f) Original. (g) HE. (h) QbHE. (i) RHE. (j) RQbHE.

image, i.e., the average image of the 38 subjects in the database itself, influenced the above evaluation, the experiment was repeated using the reference image based on face images from the AT&T database. The reference image [see Fig. 3(c)] is the average image of the first image of each of the 40 subjects of the AT&T database [see Fig. 3(d) for example face images].

The distribution of GLQ scores of images in Extended YaleB, based on the AT&T reference image, is shown in Fig. 4(b), and it is similar to that of the reference image calculated from Extended YaleB. This shows that the reference image used to calculate illumination quality is independent of enrolled images and subjects.

The LQ index is further evaluated using images from the AT&T, which consists of well-lit face images. However, variations in pose and face size are a characteristic of the images in this database. The distribution of GLQ scores for 360 images of the AT&T database is presented in Fig. 4(c), and it confirms that all images of the AT&T database have a very high illumination quality and shows that the LQ measure is unaffected by the pose and size variations present in the database.

The GLQ of nearly all the images from subsets 1 and 2 is higher than 0.8, while it is less than 0.8 for all the images from subsets 4 and 5. Taking these factors into account, a sensible threshold that could distinguish between images with good illumination and images with poor illumination is an LQ score of approximately 0.8.

1) GLQ Versus RLQ: The previous section demonstrated the suitability of using the GLQ index as an objective measure of illumination quality of face images. However, in real-life scenarios, variations in illumination between enrolled and test images could be confined to a region of the face image due to the changes in the direction of the light source or pose. Therefore, it is sensible to measure the illumination quality on a region-by-region basis.

The distribution of GLQ and RLQ scores is shown in Fig. 5. The analysis demonstrates that the RLQ measure is a better representation of the illumination quality of a face image than the GLQ as it identifies individual regions that have either good

or poor illumination quality. This is particularly reflected in the differences of the distribution of GLQ and RLQ scores of subsets 3, 4, and 5.

C. Effect of Illumination Normalization on Image Quality

To determine the effect of illumination normalization by HE on image quality, the evaluation in Section IV-B is repeated for Extended YaleB after normalizing all the images by the conventional HE as well as the proposed global and regional adaptive approaches to normalization. Two example images, with their GLQ and RLQ scores, before and after normalization are shown in Fig. 6. The distribution of GLQ scores before and after normalizing all the evaluation images in Extended YaleB is shown in Fig. 7.

The distribution of quality scores for subsets 1 and 2 shows that HE has an adverse effect on well-lit face images. This could be a result of the noise that HE process adds to images. The quality scores demonstrate that HE is still a useful illumination normalization tool when there is a significant variation in lighting between the enrolled and test images (i.e., subsets 4 and 5 and, to some extent, subset 3) as it improves illumination quality of these images. However, the most improvement is achieved by the RQbHE.

V. EXPERIMENTS AND DISCUSSIONS

The accuracy of the proposed illumination-quality-based face recognition scheme is tested using Extended YaleB. First, the effect of adaptive normalization on recognition accuracy is investigated. This is followed by an evaluation of the proposed adaptive multistream fusion scheme for wavelet-based face recognition.

The identification experiment setting adopted here is the same as in [9]. Only the P00A+000E+00 image of each of the 38 subjects is used for the gallery, and the remaining 2376 images are used as probes to test the accuracy of the identification system. The Haar wavelet filter is used for the
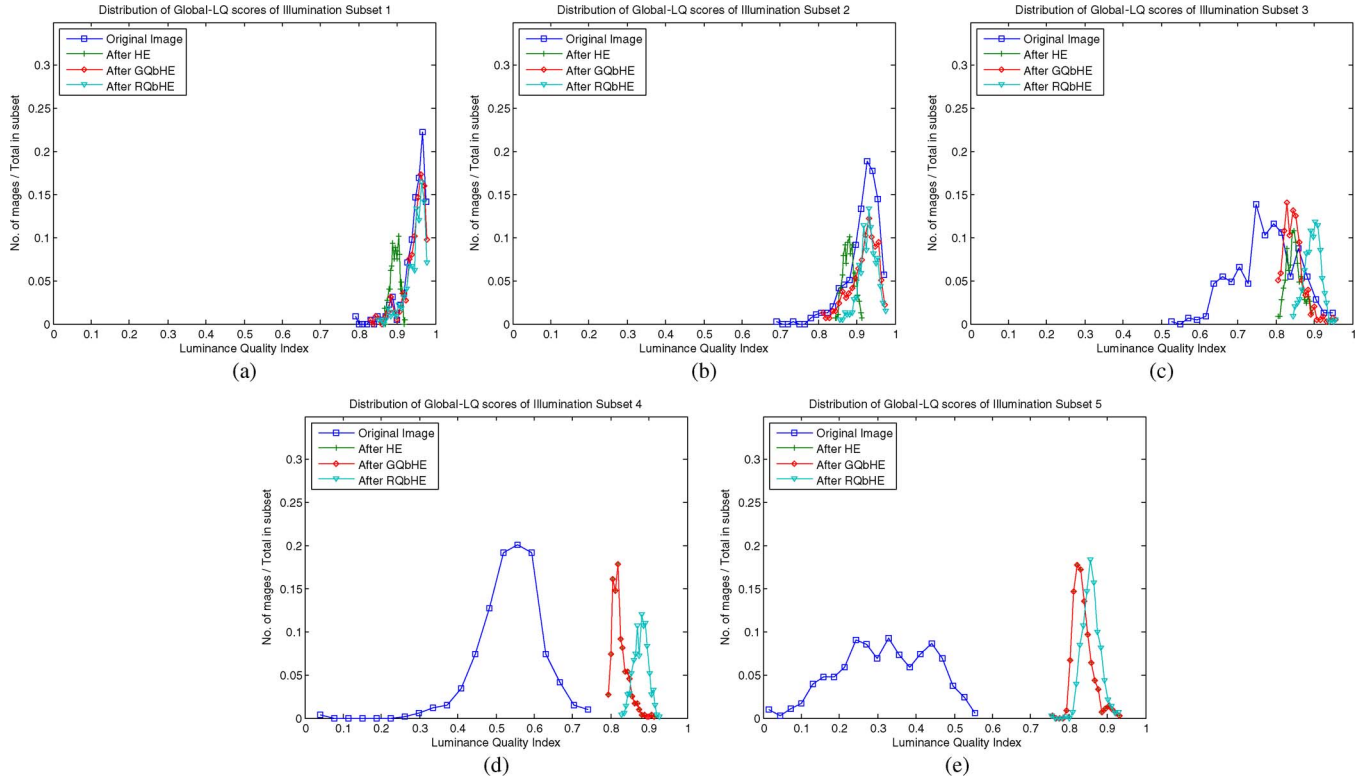
Fig. 7. Distribution of LQ index scores of the five illumination subsets of Extended YaleB before and after illumination normalization. (a) Subset 1. (b) Subset 2. (c) Subset 3. (d) Subset 4. (e) Subset 5.

DWT, and all subband coefficients are normalized by ZN. The CityBlock distance is used to calculate a distance score between a probe image and a gallery image.

A. Illumination-Quality-Based Adaptive Normalization

Based on the earlier analysis of the distributions of LQ scores for each illumination subset (see Section IV-B), an LQ score threshold of 0.8 is selected for the global and regional quality-based HE. Identification errors of different wavelet-based feature representations, with different approaches to illumination normalization, are shown for each illumination subset in Table I.

Compared to the traditional use of HE, the proposed GQbHE further decreased the overall identification error by a further 1–2% across different feature representations. More significantly, unlike HE, the use of GQbHE did not result in a noticeable increase in identification error that is achieved by original images. The proposed RQbHE further reduced the identification error, with LH_2 representation being the best overall feature descriptor, bringing the identification error down to almost 10%. As these results indicate, the lowest overall recognition error rate, as well as the lowest error rate of majority of the illumination subsets are achieved by using the proposed regional quality-based adaptive normalization.

The experiments confirms the findings in [9] that the LL subband is the most robust feature representation for face recognition under controlled lighting conditions, while the LH and HL subbands are the better option for face recognition in

TABLE I
IDENTIFICATION ERROR RATES FOR EXTENDED YALEB BASED ON
DIFFERENT ILLUMINATION NORMALIZATION TECHNIQUES

Extended Yale Database B							
Wavelet subband		Identification Error Rates (%)					
/Pre-process		Set 1	Set 2	Set 3	Set 4	Set 5	Total
LL_1	None	1.33	15.35	61.98	92.40	95.80	64.18
	HE	1.78	17.32	65.27	88.97	82.77	60.56
	QbHE	1.33	15.79	62.64	88.97	81.23	59.26
	RHE	0.00	0.00	22.64	73.00	79.55	44.40
	RQbHE	2.67	13.16	34.51	70.34	73.11	46.93
LL_2	None	1.33	20.18	64.40	92.59	96.22	65.74
	HE	2.67	22.37	67.47	89.92	84.73	62.84
	QbHE	1.33	20.39	64.62	89.92	83.47	61.41
	RHE	0.00	0.00	25.93	77.00	81.09	46.38
	RQbHE	3.56	17.54	38.24	73.57	75.91	50.13
LH_2	None	10.67	0.00	15.16	30.42	68.21	31.14
	HE	11.56	0.00	19.56	17.68	11.06	12.08
	QbHE	10.67	0.00	15.38	14.83	11.90	10.82
	RHE	12.44	0.00	17.80	14.64	10.36	10.94
	RQbHE	10.67	0.00	14.95	14.45	10.36	10.19
HL_2	None	9.33	0.88	15.82	61.41	93.70	45.83
	HE	12.00	0.88	16.70	33.27	54.34	28.20
	QbHE	9.33	0.88	14.51	34.41	56.02	28.28
	RHE	12.44	0.88	16.26	34.41	56.72	29.12
	RQbHE	9.33	0.88	15.16	39.35	61.62	31.19

the presence of varying illumination. Hence, the motivation for an image-quality-based adaptive approach to multistream face recognition, where during recognition, the selection of weighting parameters of subband scores is to be determined by the illumination quality of the given probe image. Section V-B

TABLE II
IDENTIFICATION ERROR RATES FOR EXTENDED YALEB FOR THE LL-
AND LH-BASED MULTISTREAM SUBBAND FUSION APPROACH

Extended Yale Database B							
$LL_2 + LH_2$		Identification Error Rates (%)					
W_{LL}	W_{LH}	Set 1	Set 2	Set 3	Set 4	Set 5	Total
1.0	0.0	3.56	17.54	38.24	73.57	75.91	50.13
0.9	0.1	2.22	7.68	30.11	65.78	70.73	43.27
0.8	0.2	2.22	3.29	22.64	57.03	63.31	36.83
0.7	0.3	1.33	0.44	18.46	46.2	51.26	29.38
0.6	0.4	2.22	0.00	15.16	36.12	38.94	22.81
0.5	0.5	3.56	0.00	14.73	27.95	27.17	17.51
0.4	0.6	4.89	0.00	13.41	19.96	18.91	13.13
0.3	0.7	5.78	0.00	12.97	17.87	14.57	11.36
0.2	0.8	8..00	0.00	14.07	15.59	11.62	10.4
0.1	0.9	8.89	0.00	13.85	13.5	10.36	9.6
0.0	1.0	10.67	0.00	14.95	14.45	10.36	10.19

TABLE III
IDENTIFICATION ERROR RATES FOR EXTENDED YALEB FOR THE LH-
AND HL-BASED MULTISTREAM SUBBAND FUSION APPROACH

Extended Yale Database B							
$LH_2 + HL_2$		Identification Error Rates (%)					
W_{LH}	W_{HL}	Set 1	Set 2	Set 3	Set 4	Set 5	Total
1.0	0.0	10.67	0.00	14.95	14.45	10.36	10.19
0.9	0.1	8.44	0.00	14.73	12.55	9.52	9.26
0.8	0.2	7.56	0.00	12.75	12.74	9.38	8.8
0.7	0.3	5.78	0.00	11.65	11.41	9.8	8.25
0.6	0.4	5.33	0.00	9.23	10.65	11.76	8.16
0.5	0.5	4.44	0.00	7.47	10.65	13.17	8.16
0.4	0.6	3.11	0.00	7.47	11.98	18.49	9.93
0.3	0.7	2.22	0.00	8.13	15.78	24.37	12.58
0.2	0.8	5.33	0.00	9.23	19.96	36.97	17.8
0.1	0.9	7.11	0.00	12.75	29.09	51.68	25.08
0.0	1.0	9.33	0.88	15.16	39.35	61.62	31.19

evaluates the proposed image-quality-based adaptive fusion approach for wavelet-based multistream face recognition.

B. Quality-Based Adaptive Fusion for Face Recognition

The multistream approach to face recognition [8] is tested on Extended YaleB with the same gallery and probe images as in the previous experiments. Illumination of the face images is normalized by the proposed region quality-based HE with an LQ threshold of 0.8. The identification error rates based on the fusion of LL_2 with the LH_2 subband and LH_2 with the HL_2 subband using fixed weights are given in Tables II and III, respectively, followed by the error rates for the proposed illumination-quality-based adaptive fusion approach in Table IV. For the adaptive fusion, if the LQ of a probe image is greater than 0.9, the weight given to its LL_2 subband score, i.e., W_{LL}, is 0.7. Otherwise, W_{LL} is set to 0. The last row of Table IV represents the fusion of distance scores from three subbands (i.e., LL, LH, and HL). In this case, LH_2 and HL_2 scores were fused by giving an equal weight to both scores. The resulting score is then fused with the LL subband score according to the proposed QbF.

The results in Tables II and III show that the overall identification accuracy of the multistream approach is higher than any of the individual subband representations. However, this depends on the selection of weights as well as the choice of sub-

TABLE IV
IDENTIFICATION ERROR RATES OF EXTENDED YALEB USING THE
PROPOSED IMAGE-QUALITY-BASED ADAPTIVE FUSION APPROACH

Extended Yale Database B							
Feature	Subband	Identification Error Rates (%)					
		Set 1	Set 2	Set 3	Set 4	Set 5	Total
Single stream	LL_2	3.56	17.54	38.24	73.57	75.91	50.13
	LH_2	10.67	0.00	14.95	14.45	10.36	10.19
	HL_2	9.33	0.88	15.16	39.35	61.62	31.19
Adaptive Fusion	LL_2+LH_2	2.22	0.00	14.73	14.45	10.36	9.34
	$LL_2+LH_2+HL_2$	1.78	0.22	7.47	10.65	13.17	7.95

bands. On the surface, it appears as if the LL_2 subband makes little or no contribution to improve the identification accuracy. However, a closer examination of the results in Table II shows that the LL_2 subband is the most suitable feature representation for probe images of subset 1.

The results for the proposed approach (in Table IV) shows an improvement in recognition accuracy when LL and LH subband scores are fused using adaptive weights selected by measuring the probe image quality. The highest identification accuracy is achieved by fusing the similarity scores of LH and HL subbands by giving an equal weight to both subbands and by combining LL subband score with the adaptive weights. With a single gallery image per enrolled subject, these results are comparable to, if not better than, most other face recognition schemes reported in the literature for Extended YaleB [13], [15], [22].

Overall, the experimental results demonstrate the viability of using the LQ index to objectively select the weighting parameters for the wavelet-based multistream face recognition scheme. The adaptive fusion strategy could be improved further by incorporating other aspects of face biometric sample quality (e.g., changes in expression and pose).

VI. CONCLUSION AND FUTURE WORK

This paper is the first part of a project to develop image-quality-based adaptive approaches to face recognition. We investigated the challenges of face recognition in the presence of extreme variation in lighting conditions. The luminance component of the already known universal quality index is used to associate a quantitative quality value to an image that measures its luminance distortion in comparison to a predefined reference image. This measure is called the LQ index and it was used to develop global and region quality-based adaptive illumination normalization procedures. Using the well-known Extended Yale Database B, we demonstrated the effectiveness of the proposed image-quality-based illumination normalization schemes in face recognition compared to the traditional approach to illumination normalization.

Finally, the observation that the wavelet-based multistream recognition scheme that was developed previously has no objective means of selecting fusion parameters and that it performed differently for face images captured with different lighting conditions has led to developing of a new adaptive approach to face recognition. The illumination-quality-based adaptive fusion approach works by adapting the weights given to each subband according to the LQ values of the probe

image, and again, this led to significantly improved identification accuracy rates.

Our future work will investigate other aspects of face image quality such as facial expression, pose, and occlusion. Such objective quality measures are to be used in a fully adaptive face recognition system, which will be able to select the most suitable gallery images, an appropriate face feature representation (or a combination of them), and a classification algorithm for a given probe image and then be able to predict the confidence of the system's decision.

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