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ORIGINAL PAPER

Bi-histogram equalization using two plateau limits

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Abstract Histogram equalization is an effective method for contrast enhancement on images, but it suffers from some problems such as the tendency to change the mean brightness, loss of information and the introduction of saturation levels which causes an unnatural appearance in the resulting image. Due to the aforementioned problems, a variety of histogram equalization methods have been developed in order to preserve the image brightness, thus avoiding saturation levels that cause loss of information. In this paper, the bi-histogram equalization using two plateau limits (BHE2PL) for histogram equalization is proposed. BHE2PL divides the global histogram into two sub-histograms; then, each sub-histogram is modified by two plateau limits in order to avoid over-enhancement of the image. Experimental results indicate that the BHE2PL method exhibits a better mean brightness preservation compared to methods found in the state of the art; in addition to also presenting a reasonable computation time.

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Keywords Contrast enhancement · Brightness preservation · Histogram equalization · Plateau limit

1 Introduction

The histogram equalization (HE) is one of the most popular methods for digital image enhancement, but its implementation is not suitable for consumer electronic products such as televisions, digital cameras and video cameras, owing to the introduction of level saturation effects in small visually significant areas [1]. These saturation effects not only degrade the appearance of the image, but also lead to a loss of information [2]. Excessive changes in the brightness level introduced by the HE leads to an unnatural image enhancement, i.e., by increasing the image brightness level excessively, its quality tends to degrade significantly [3]. Therefore, the preservation of the image brightness is important to preserve its quality.

The idea of keeping the mean brightness of an image for consumer electronics was first introduced by Kim [4]. By preserving the mean image brightness, saturation effects are reduced and the unnatural image enhancement is avoided as well [5]. This paper proposes a modified version of the method presented by Lim et al. [6] called bi-histogram equalization using two plateau limits (BHE2PL), which like its predecessor improves the input image while preserving its mean brightness.

The rest of the paper is organized as follows, in Sect. 2 a formal formulation for HE and a small explanation of the clipped histogram equalization (CHE) are presented, both techniques are the foundation for the given proposal. In Sect. 3 works related to the proposed method in this paper are shown. In Sect. 4 the BHE2PL is presented and discussed. Experimental results are shown in Sect. 5, and finally Sect. 6 presents the conclusion of the work.

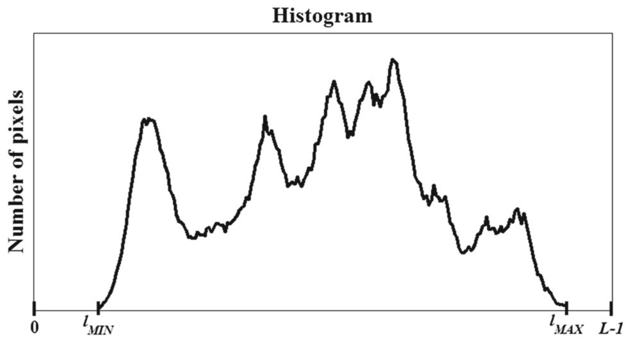

Fig. 1 Global histogram of an arbitrary image

2 Histogram equalization

In this section the formal formulation of the histogram equalization used throughout this paper is presented, as well as an explanation of the CHE, a method that helps improve in seeing the small objects in the image that could be visually important for the observer.

2.1 Transformation function for histogram equalization

For a given image X of dimension $M \times N$ pixels, where $X(i, j)$ represents the intensity of a pixel within the image and being (i, j) the spatial coordinates of the pixel within the image, the histogram H (see Fig. 1) associated with the image which describes the frequency of the intensity values appearing in it, where $k = 0, 1, ..., L - 1$, is defined as:

$$H(k) = n_k \tag{1}$$

where L is the number of gray levels in an image and n_k represents the number of occurrences of the intensity k in the image and $X(i, j) = k$. The probability density function $p(k)$ associated with H is given by:

$$p(k) = \frac{H(k)}{M \times N} \tag{2}$$

where $p(k)$ indicates the probability of occurrence of the k'th intensity. While its cumulative density function $c(k)$ is given by:

$$c(k) = \sum_{i=X_0}^{k} p(i) \tag{3}$$

where X_0 is the lowest intensity within the range where the cumulative density function is to be calculated. The transformation function $f(k)$ associated with the standard histogram equalization maps the input image to the dynamic range $[X_0, X_{L-1}]$, using $c(k)$. The function is given by the following equation:

$$f(k) = X_0 + (X_{L-1} - X_0) \times c(k) \tag{4}$$

for the particular case of HE the range is given by $X_0 = 0$, and $X_{L-1} = L - 1$. Thus, the resulting image produced by the histogram equalization, $Y = \{Y(i, j)\}$, can be expressed as:

$$Y = \{Y(i, j)\} = \{f(X(i, j))|\forall X(i, j) \in X\} \tag{5}$$

However, for our implementation equalization, the function $f'(x)$ modified by Ibrahim et al. [7] will be used rather than the one presented in (4). This is because it presents better results in the improvement in the image according to [7]. The function is given by:

$$f'(k) = X_0 + (X_{L-1} - X_0) \times [c(k) - 0.5 \times p(k)] \tag{6}$$

The histogram equalization stretches the contrast of the upper regions of the histogram and compresses the contrast in the lower regions of it [8]. Consequently, when the object of interest in an image occupies only a small portion of the image, the object will not be properly enhanced by histogram equalization. This method also pushes intensities extremely to the right or to the left of the histogram, causing saturation level effects.

2.2 Clipped histogram equalization

Methods based on clipped histogram equalization (CHE) try to solve the problems associated with HE mentioned in the previous subsection by restricting the improvement rate. For the histogram equalization methods, the improvement is obtained from the transformation function as the ones presented in (4) or (6). In them it can be seen that the histogram equalization depends strongly on $c(k)$; therefore, the improvement rate is proportional to the rate of $c(k)$ change given by the following equation:

$$\frac{\mathrm{d}}{\mathrm{d}k} c(k) = p(k) \tag{7}$$

Hence, to limit the improvement rate, the value of $p(k)$ or $H(k)$ should be limited [9]. CHE modifies the shape of the histogram by reducing or increasing the values in the histogram containers based on a plateau limit, which involves choosing a threshold value to limit the rate of improvement, before the equalization is carried out. The bounded portions can be redistributed back to the histogram as mentioned in [10].

CHE has two major problems: (a) Most of the methods require the user to enter the plateau limit manually, (b) Some methods place a modified histogram weight, and that weight factor is also dependent on the user. Despite the limitations, CHE is a fundamental method for this work. Therefore, as in [5,11] and [6], the plateau limits for this work will be calculated automatically, considering the information of the input image.

3 Related works

This section provides a brief description of the equalization methods that were developed to solve the problems presented by HE mentioned in the previous section. Among them, we can mention the methods based on mean brightness preservation, mean brightness preserving histogram equalization (MBPHE) and so-called hybrid methods that combine the best features of the MBPHE and CHE-based methods.

The mean brightness preserving histogram equalization (MBPHE) methods basically can be divided into two main groups: (a) bisections MBPHE [4,12,13] and (b) multi-sections MBPHE [14–16] and [17]. The bisections MBPHE group is the simplest group of MBPHE. Fundamentally, these methods separate the input histogram into two sections. These two histogram sections are then equalized independently. The greatest difference between the methods in this family is the criteria used to divide the input histogram.

The bisections MBPHE can only preserve the original mean brightness if and only if the input histogram has a quasi-symmetrical distribution around its separating point, but most of the input histograms do not have this property. This condition leads to the failure of bisections MBPHE in preserving the mean brightness intensity in real-life applications [5].

The brightness preserving bi-histogram equalization (BBHE) proposed by Kim [4] was the first method based on the preservation of the mean brightness and consists in dividing the input histogram using the average intensity value as the separating point, and once the histogram is divided each sub-histogram is equalized independently. Similarly, Wang et al. present a method called dual sub-image histogram equalization (DSIHE) [12] that uses the median intensity value as the separating point instead of the average intensity value used in BBHE. In 2003 Chen and Ramli [13] present minimum mean brightness error bi-histogram equalization (MMBEBHE). The purpose of this method is to provide the maximum brightness preservation in image enhancement. MMBEBHE separates the global histogram using a point of separation as the one that produces the smallest difference in brightness between the input image and the resulting image. For example, given an image of k-bits, MMBEBHE requires 2^k iterations to find the point of division that produces the smallest difference in brightness between the input image and the resulting image.

Later a method named bi-histogram equalization with a plateau limit (BHEPL) is presented [5] that combines the best features of brightness preservation techniques with clipped histogram equalization (CHE) in order to successfully improve the objects that occupy small portions of the image and perhaps may be of interest. BHEPL separates the global histogram using the average intensity of the input histogram as a separation point. Then, a histogram bounding process is carried out for each sub-histogram using the average number of the appearances of the respective intensities within each sub-histogram as plateau limit. Finally equalization is applied independently to each sub-histogram. Similar to BHEPL, bi-histogram equalization with median plateau limit (BHEPL-D) [11] is proposed, where the plateau limit for each sub-histogram uses the median of the respective intensities within each sub-histogram instead of the average intensity as in the case of BHEPL. In 2013, Lim et al. [6] presented an equalization method that also divides the global histogram into two sub-histograms, but in this case three plateau limits to each sub-histogram are applied. These limits are given by the values of the mean intensities of the global histogram and the mean intensities of the sub-histograms. The global histogram is divided using the average intensity as the separation point; then, the sub-histograms are modified using the three calculated boundaries and finally each sub-histogram is equalized independently. It is worth noting that the proposed method in [6] will be referred to in the following sections as BHE3PL.

In the next section a modification of the method proposed by Lim et al. [6] is presented. This is the main contribution of this work.

4 Proposed method

The idea of the new method of equalization is to use a total of four plateau limits, two plateau limits for each sub-histogram instead of the six plateau limits used in [6], three plateau limits for each sub-histogram. With the removal of these two limits what we want to achieve is to reduce the brightness difference between the input image and the resulting image, while still achieving an improvement in the image contrast. The proposed method is named bi-histogram equalization using two plateau limits (BHE2PL).

The first step we would take would be proceeding to calculate the expected average intensity SP of the global histogram of the image (see Fig. 1) given by the equation:

$$\mathrm{SP} = \sum_{k=0}^{L-1} p(k) \times k \tag{8}$$

Once the SP value has been calculated using Eq. (8), the histogram is split into two sub-histograms, the lower sub-histogram H_L and the upper sub-histogram H_U. H_L contains the values of intensities found from the minimum gray level in the image l_MIN up to the average intensity SP, while H_U

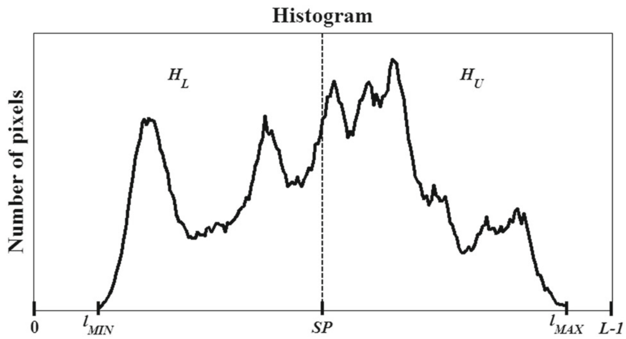

Fig. 2 Global histogram after the split

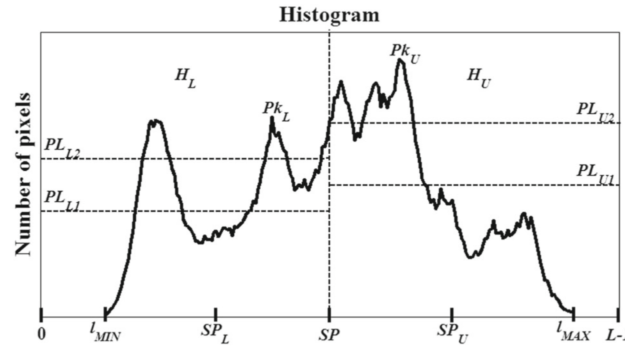

Fig. 3 Histogram with plateau limits calculated

contains the values of intensities found from SP + 1 up the maximum gray level in the image l_{MAX} (see Fig. 2). l_{MIN} is the lowest effective intensity within the image, i.e., the lowest intensity in the histogram that appears at least once in the image, likewise l_{MAX} represents the maximum effective intensity found in the image, i.e., the highest intensity within the histogram that appears at least once in the image. After the global histogram has been divided, the plateau limits PL's for each resulting sub-histogram are calculated. Basically, each plateau limit is calculated using the following formula:

$$\mathrm{PL} = R \times Pk \tag{9}$$

where R is a coefficient with a value between 0 and 1, and Pk represents the peak in the histogram given by:

$$Pk = \max\{H(k) | k = 0, ..., L-1\} \tag{10}$$

In this work, the values of the PL's will be selected using local information obtained from the input histogram. One way to extract information from the input histogram is to use the gray-level ratio GR for each obtained sub-histogram. Since GR is a value between 0 and 1, it replaces R in Eq. (9), GR being the value used to represent the level of improvement that needs to be applied. The low percentages of improvement are applied at low rates of gray, likewise, the high percentages of improvement are applied at high rates of gray. Given the GR's use as coefficients, the plateau limits can be calculated as:

$$\mathrm{PL}_{\mathrm{L1}} = \mathrm{GR}_{\mathrm{L1}} \times Pk_{\mathrm{L}} \tag{11}$$

$$\mathrm{PL}_{\mathrm{L2}} = \mathrm{GR}_{\mathrm{L2}} \times Pk_{\mathrm{L}} \tag{12}$$

$$\mathrm{PL}_{\mathrm{U1}} = \mathrm{GR}_{\mathrm{U1}} \times Pk_{\mathrm{U}} \tag{13}$$

$$\mathrm{PL}_{\mathrm{U2}} = \mathrm{GR}_{\mathrm{U2}} \times Pk_{\mathrm{U}} \tag{14}$$

where Pk_{L} is the maximum intensity peak for the lower sub-histogram, $\mathrm{PL}_{\mathrm{L1}}$ and $\mathrm{PL}_{\mathrm{L2}}$ are the lower and upper limits of the lower sub-histogram, likewise Pk_{U} is the maximum intensity peak for the upper sub-histogram, $\mathrm{PL}_{\mathrm{U1}}$ and $\mathrm{PL}_{\mathrm{U2}}$ are the lower and upper limits of the upper sub-histogram. The gray-level proportions of the lower sub-histogram $\mathrm{GR}_{\mathrm{L1}}$ and $\mathrm{GR}_{\mathrm{L2}}$, and the gray-level proportions of the upper sub-histogram $\mathrm{GR}_{\mathrm{U1}}$ and $\mathrm{GR}_{\mathrm{U2}}$ are defined as:

$$\mathrm{GR}_{\mathrm{L1}} = \frac{\mathrm{SP} - \mathrm{SP}_{\mathrm{L}}}{\mathrm{SP} - l_{\mathrm{MIN}}} \tag{15}$$

$$\mathrm{GR}_{\mathrm{L2}} = \mathrm{GR}_{\mathrm{L1}} + D_{\mathrm{L}} \tag{16}$$

$$\mathrm{GR}_{\mathrm{U1}} = \frac{l_{\mathrm{MAX}} - \mathrm{SP}_{\mathrm{U}}}{l_{\mathrm{MAX}} - \mathrm{SP}} \tag{17}$$

$$\mathrm{GR}_{\mathrm{U2}} = \mathrm{GR}_{\mathrm{U1}} + D_{\mathrm{U}} \tag{18}$$

where SP_{L} and SP_{U} are the average intensities of the lower and upper sub-histograms, respectively, D_{L} and D_{U} are differences in the gray-level proportions of the lower and upper sub-histograms, respectively. SP_{L} and SP_{U} are calculated as:

$$\mathrm{SP}_{\mathrm{L}} = \frac{\sum_{k=l_{\mathrm{MIN}}}^{\mathrm{SP}} k \times H(k)}{N_{\mathrm{L}}} \tag{19}$$

$$\mathrm{SP}_{\mathrm{U}} = \frac{\sum_{k=\mathrm{SP}+1}^{l_{\mathrm{MAX}}} k \times H(k)}{N_{\mathrm{U}}} \tag{20}$$

where N_{L} and N_{U} are the total number of pixels that are in the sub-histogram of the lower and upper part. D_{L} and D_{U} are calculated as follows:

$$D_{\mathrm{L}} = \begin{cases} \frac{1-\mathrm{GR}_{\mathrm{L1}}}{2} & \text{if } \mathrm{GR}_{\mathrm{L1}} > 0.5 \\ \frac{\mathrm{GR}_{\mathrm{L1}}}{2} & \text{if } \mathrm{GR}_{\mathrm{L1}} \leq 0.5 \end{cases} \tag{21}$$

$$D_{\mathrm{U}} = \begin{cases} \frac{1-\mathrm{GR}_{\mathrm{U1}}}{2} & \text{if } \mathrm{GR}_{\mathrm{U1}} > 0.5 \\ \frac{\mathrm{GR}_{\mathrm{U1}}}{2} & \text{if } \mathrm{GR}_{\mathrm{U1}} \leq 0.5 \end{cases} \tag{22}$$

Figure 3 shows the histogram with the respective plateau limits found. Thereupon, the shape of the histogram is modified, for the lower sub-histogram ($l_{\mathrm{MIN}} \leq k \leq \mathrm{SP}$), as follows:

$$H_{\mathrm{L}}(k) = \begin{cases} \mathrm{PL}_{\mathrm{L1}}, & \text{if } H_{\mathrm{L}}(k) \leq \mathrm{PL}_{\mathrm{L2}} \\ \mathrm{PL}_{\mathrm{L2}}, & \text{if } H_{\mathrm{L}}(k) > \mathrm{PL}_{\mathrm{L2}} \end{cases} \tag{23}$$

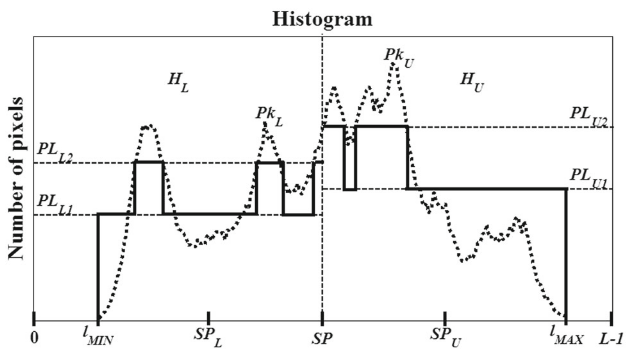

Fig. 4 Histogram after modifications by calculated limits

This means that for values in the lower sub-histogram that are less than or equal to PL_{L2}, the sub-histogram is modified with the PL_{L1} value, if this value is greater then the value of PL_{L2} is used.

Likewise for the upper sub-histogram ($SP + 1 \leq k \leq l_{MAX}$), the sub-histogram is modified as follows:

$$H_U(k) = \begin{cases} PL_{U1}, & \text{if } H_U(k) \leq PL_{U2} \\ PL_{U2}, & \text{if } H_U(k) > PL_{U2} \end{cases} \tag{24}$$

The modified histogram is shown in Fig. 4. Once the histogram modification process is finished each sub-histogram is equalized independently according to Eq. (6).

5 Experimental results

A comparative analysis of the proposed BHE2PL method with the algorithms: HE, BBHE [4], DSIHE [12], MMBEBHE [13], BHEPL [5], BHEPL-D [11] and BHE3PL [6] was carried out. In order to show the validity of the algorithm in terms of improving the contrast and brightness and the mean brightness preservation, the comparative analysis is performed using 5 metrics. During the experiment, 339 8-bit images were used. 100 images belonging to [18] have been taken from an internet repository, and the remaining 239 are images taken by the authors[1]. Images from the repository have 481×321 and 321×481 pixel sizes. The second set of images has sizes of 2248×4000 and 4000×2248 pixels. Both image databases were converted to grayscale, obtaining their intensities. The metrics used were:

1. The execution time of each method in milliseconds.
2. The absolute mean brightness error (AMBE) [19], which is defined as the absolute difference between the mean brightness of the input image and the resulting image, measuring the performance in preserving the original brightness and is given by:

$$\text{AMBE} = |E(X) - E(Y)| \tag{25}$$

where X and Y represent the input image and the resulting image, respectively, $E(X)$ and $E(Y)$ represent the mean brightness of the input image and the resulting image. The smaller the value of AMBE, the better the brightness preservation will be.
3. The peak signal-to-noise ratio (PSNR) [20] is used to determine the amount of noise introduced into the image after processing, i.e., given an input image $X(i, j)$ containing $M \times N$ pixels and a reconstructed image $Y(i, j)$, it indicates the image signal–noise ratio of Y compared with X. PSNR is given by:

$$\text{PSNR} = 10 \log_{10} \left[\frac{(L-1)^2}{\text{MSE}} \right] \tag{26}$$

where the mean squared error (MSE) is given by:

$$\text{MSE} = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} [X(i, j) - Y(i, j)]^2}{M \times N} \tag{27}$$

The PSNR is measured in decibels, and the higher the value, the lower the noise introduced into the image transformation will be; thus, the resulting image yielding better qualities.
4. The entropy [6] is a useful metric that determines the wealth of detail in the resulting image and is calculated as:

$$\text{Entropy} = -\sum_{k=0}^{L-1} p(k) \log_2(p(k)) \tag{28}$$

The higher the entropy the higher the richness of detail in the image.
5. The contrast [6] is defined as:

$$C = \sqrt{\sum_{k=0}^{L-1} (k - E(X))^2 \times p(k)} \tag{29}$$

where $E(X)$ represents the average brightness of the image. The value of the contrast of the resulting image must be greater than the input image to assume an improvement.

For this experiment, the algorithms were implemented in ImageJ version 1.48 and were executed on a personal computer with a Linux-Mint-17-Cinnamon-64bit OS, an Intel Core i5-2430M 2.4GHz processor, 6GB of RAM, and without threads.

[1] Images can be requested from the authors.

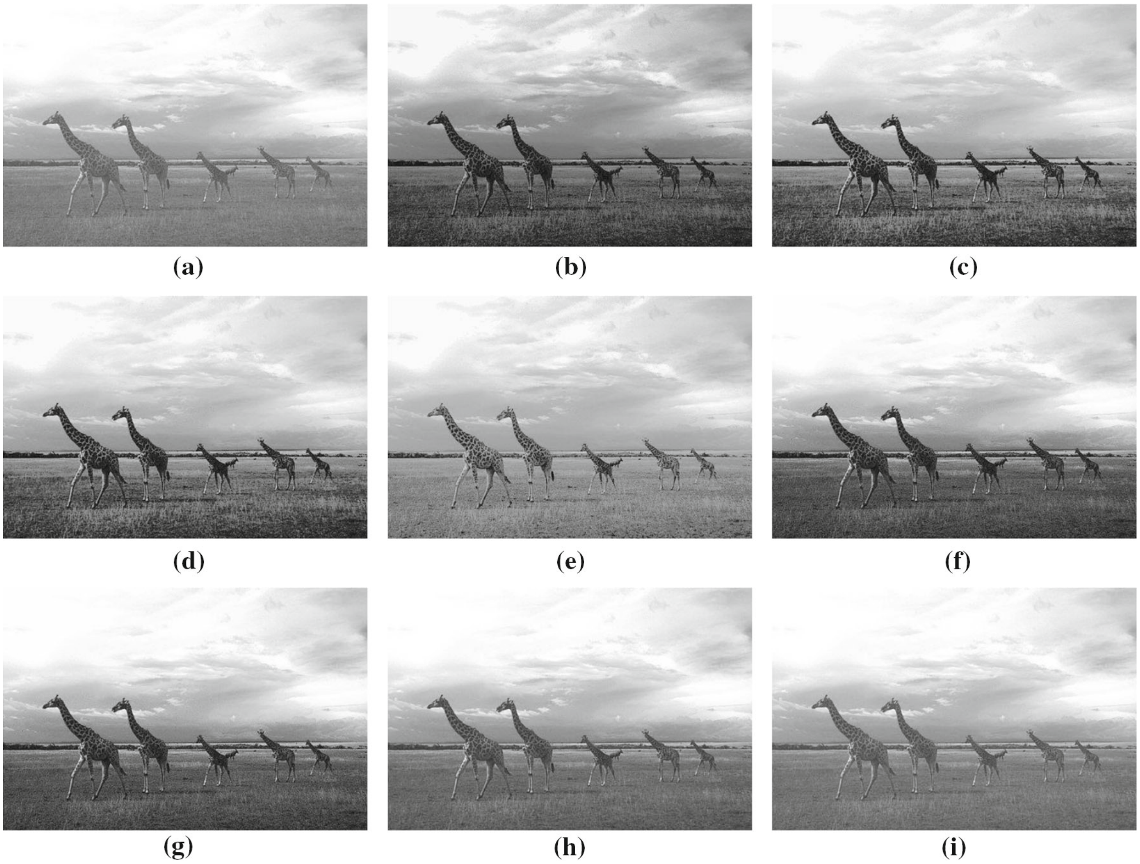

Fig. 5 Image taken from the Berkeley database with its respective equalizations. **a** Original **b** HE **c** BBHE **d** DSIHE **e** MMBEBHE **f** BHEPL **g** BHEPL-D **h** BHE3PL **i** BHE2PL

Figure 5 shows the chosen image of the Berkeley database [18] with its respective equalizations so as to visually appreciate the results obtained for each of the algorithms implemented. Given the original image and the one equalized by HE, it can be seen how each method improves the image the best it can without making it look too different from the original (noise is not introduced) and solving the unnatural improvement problems introduced by HE. It can also be seen that the image of Fig. 5i, which corresponds to the BHE2PL method, is the most similar to the original, observing in it an improvement in image detail.

In Fig. 6 the image selected from the database of images collected by the authors with its respective equalizers is shown. In Fig. 6b–e the clouds in the background can be seen with more detail, but as a trade-off the images have an unnatural appearance compared to the original image. In Fig. 6g the background details are completely lost with respect to the original image. Finally Fig. 6f, h and i are those that have a greater similarity to the original being (i) the one that presents a visually better mean brightness preservation. Figure 7 statistically shows the results considering all 339 images. In Fig. 7a the original image contrast improving performance of BHE3PL is displayed, improving contrast 73% of the time, keeping the original contrast 26% of the time and producing a lower contrast 1% of the time. Likewise, the performance of BHE2PL is displayed in Fig. 7b, improving contrast 71% of the time, maintaining the original contrast 28% of the time and producing a lower contrast 1% of the time. Both for (a) and (b) the contrast of the original image was compared directly to that of its respective equalized image for each method. Finally, a comparison of the brightness preservation between BHE2PL and BHE3PL is shown in Fig. 7c, which shows that BHE2PL is better 67% of the time. 28% of the time they are equal and 5% of the time BHE2PL is worse. These percentages were obtained by comparing the images equalized by each method with its corresponding pair. Tables with numerical results for each databases are presented below. The best results for each metric are highlighted in bold. Table 1 shows the average results of the 100 images of the Berkeley database. In it, the good results obtained by the proposed method can be seen, demonstrating a good brightness preservation (AMBE) while improving the image contrast at the same time. It is also note-

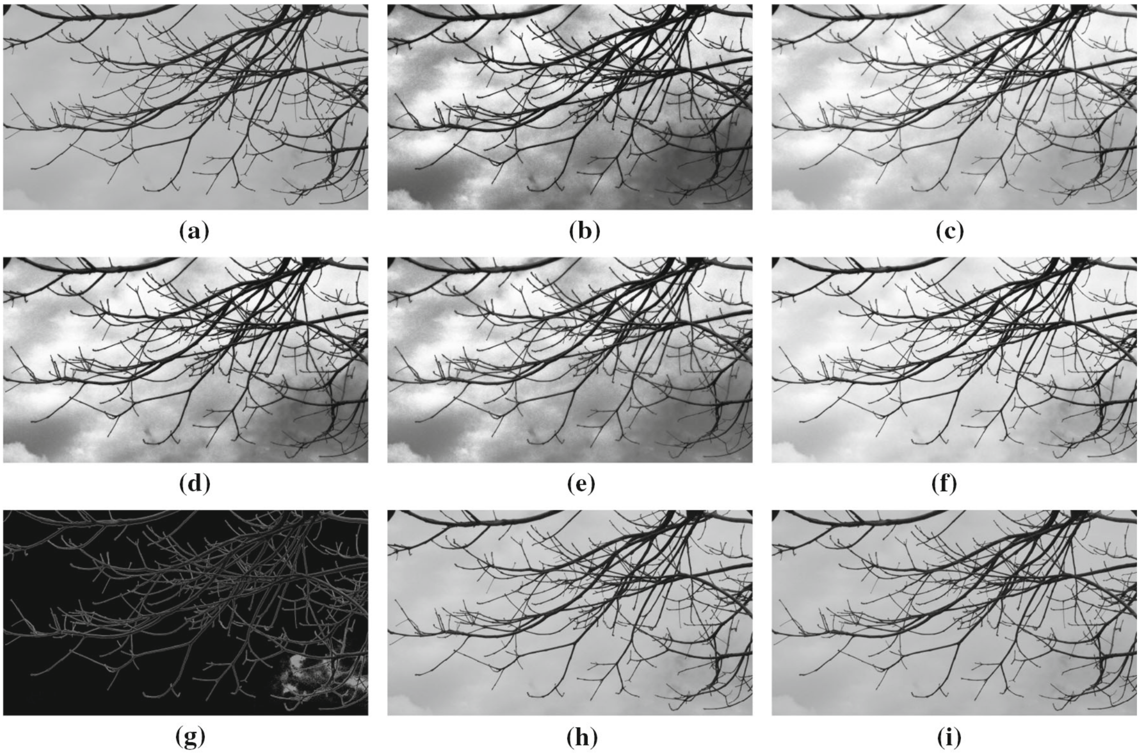

Fig. 6 Image taken from the database of collected images with its respective equalizations. **a** Original **b** HE **c** BBHE **d** DSIHE **e** MMBEBHE **f** BHEPL **g** BHEPL-D **h** BHE3PL **i** BHE2PL

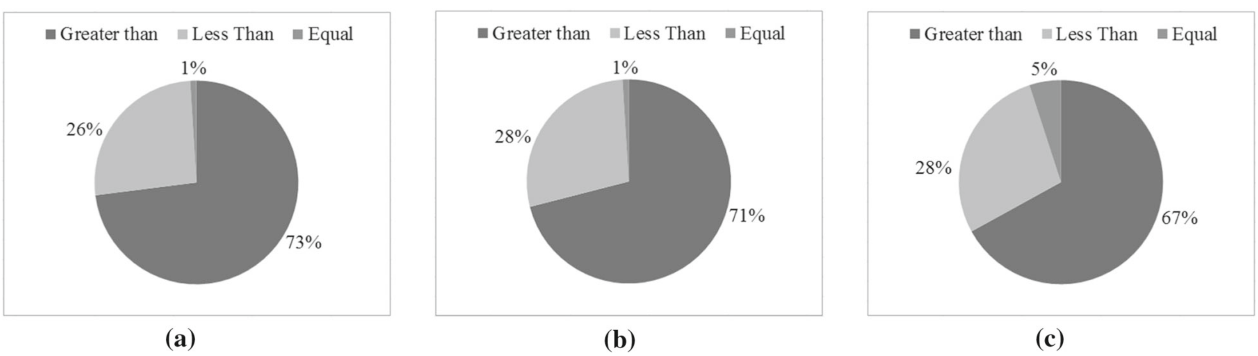

Fig. 7 Shows the performance of BHE2PL and BHE3PL graphically in terms of contrast enhancement and mean brightness preservation. **a** Performance of BHE3PL in contrast enhancement. **b** Performance of BHE2PL in contrast enhancement. **c** Performance of BHE2PL versus BHE3PL in mean brightness preservation

worthy that it has the highest PSNR and the highest entropy ensuring good image quality and detail. Table 2 shows the average results of the 239 images collected by the authors. It can be seen that the trend continued, and the method still has a good brightness preservation (AMBE) contrasting the original image with good values for the PSNR and entropy compared to the other 7 existing methods in the state of art. Finally, it is important to mention that the entropy of all methods is smaller than that entropy of the original images because the methods are not based on entropy increasing but are based on preserving the mean brightness (see [6] and [11]).

6 Conclusion

In this paper, a new method of equalization based on the mean brightness preservation named bi-histogram equalization using two plateau limits (BHE2PL) was presented. The method is a modification of the proposed method at

Table 1 Averaged results for the 100 images of the Berkeley database

Methods	T (ms)	AMBE	PSNR	Entr.	Cont.
Original				7.134	50.160
HE	**1.029**	30.249	15.616	6.943	73.587
BBHE	1.136	11.725	18.950	6.967	73.036
DSIHE	1.204	13.572	18.218	6.962	**74.946**
MMBEBHE	1.090	1.917	22.408	6.953	64.411
BHEPL	1.182	6.798	22.405	7.063	67.587
BHEPL-D	1.204	5.523	24.733	7.055	63.822
BHE3PL	1.180	1.981	35.990	7.130	53.983
BHE2PL	1.182	**0.974**	**41.331**	**7.132**	52.065

The best results for each metric are highlighted in bold

Table 2 Averaged results for the 239 images collected by the authors

Methods	T (ms)	AMBE	PSNR	Entr.	Cont.
Original				6.887	53.591
HE	**55.630**	37.245	14.659	6.688	73.552
BBHE	56.173	13.763	19.158	6.718	72.424
DSIHE	59.681	15.952	18.145	6.718	**75.573**
MMBEBHE	56.741	2.852	22.449	6.703	64.209
BHEPL	57.650	9.026	22.761	6.813	69.135
BHEPL-D	58.922	7.654	26.276	6.716	63.094
BHE3PL	60.116	1.265	40.321	**6.828**	55.145
BHE2PL	57.325	**0.763**	**44.272**	**6.828**	54.439

The best results for each metric are highlighted in bold

[6], where instead of modifying the sub-histograms using three plateau limits only two plateau limits are used. This is done with the idea to contrast the image meanwhile obtaining a better mean brightness preservation by removing the lower limits of each sub-histogram that introduce a wide variation in the mean brightness. Experimental results indicate that the proposed method has a good preservation of the mean brightness in comparison with the bisection-based methods used for comparison, while successfully enhancing the contrast of the input image. As future works an analysis of the so-called anomalous cases in which the proposed method BHE2PL loses in preserving the mean brightness in comparison with its predecessor BHE3PL and a generalization of the method using multiple plateau limits are proposed.

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