Characterization of the human iris spectral reflectance with a multispectral imaging system

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We present a multispectral system developed and optimized for measurement of the spectral reflectance and the color of the human iris. We tested several sets of filters as acquisition channels, analyzed different reconstruction algorithms, and used different samples as training sets. The results obtained show that a conventional three-channel color camera (RGB) was enough to reconstruct the analyzed reflectances with high accuracy, obtaining averaged color differences of around 2–3 CIEDE2000 units and root mean square errors of around 0.01. The device developed was used to characterize 100 real irises corresponding to 50 subjects, 68 prostheses used in clinical practice, and 17 cosmetic colored contact lenses.

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1. Introduction

The study of the color of the human iris is not a deeply explored field so far. The coloration of this structure depends on hereditary factors, such as the amount of melanocyte cells and melanine granules inside the iris, as well as their distribution [1]. The first measurements performed in this area were limited to simple subjective observations of the eye [2,3]. Recently, some more studies focused on iris color measurement using standard color instrumentation, such as telespectroradiometers, have appeared [4]. However, due to the coloration and texture variability of the iris, measurement of its color becomes a difficult issue because of the limited spatial resolution commonly present in conventional devices. Often, large areas of the iris are integrated and, therefore, only an averaged spectral reflectance profile or, equivalently, a mean color, can be extracted from the collected data. Therefore, the use of systems with higher spatial resolution to characterize this structure is advisable and, in consequence, multispectral systems, which commonly consist of a digital camera with many pixels, are very appropriate to achieve this purpose.

In this work, based on preliminary studies [5–7], we analyze the feasibility of a conventional multispectral system based on a CCD monochrome camera to measure the spectral reflectance in the visible range associated to the human iris and, therefore, to characterize its coloration. In the study, the experimental setup of the multispectral system and the reconstruction routines used, as well as the training sets, are optimized to achieve high spectral efficiency and good color measurement. In this context, the system incorporated several sets of filters used as acquisition channels, which covered the whole visible range of the electromagnetic spectrum. According to research already carried out [8], in this study two

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different filter configurations were studied to achieve the best reconstruction results [9]: on one hand, an RGB tunable filter and an additional blue absorption filter were placed in front of the camera, allowing the acquisition of three or six images with only one or two exposures, respectively; on the other hand, a set of seven interference filters equispaced along the visible range allowed the consecutive measurement of seven spectral images. Furthermore, two different linear spectral reconstruction methods used to obtain the spectral reflectance of the iris from the corresponding digital levels were tested: the pseudoinverse technique [8,10,11] and the principal component analysis [8,10,12]. These methods allow the reconstruction of spectral reflectances from the camera responses by means of an estimation matrix, which can be computed using the known digital output levels corresponding to a training set of samples. These techniques also need *a priori* knowledge of the spectral reflectances associated to the training patches. In this study, several training sets with a different size are also tested to perform the reconstructions [8,13].

Once the developed multispectral system was optimized, it was finally used to characterize the visible spectral reflectance of 100 real irises corresponding to 50 subjects, 68 prostheses used in clinical practice, and 17 cosmetic colored contact lenses. The reconstructions of the spectral reflectance factors of the three groups of samples were obtained with different combinations of test and training sets. At first, the same group of samples was used as a test and training set to analyze the feasibility of the system for reconstructing the spectral data. Second, different groups of samples were used as test and training sets to study the capability of each group of samples for representing or describing the other two groups, in terms of spectral reflectance.

By setting up this system, it is possible to perform analysis of the color and texture of the human iris in detail, as well as the changes that take place in this ocular structure. With the measurements performed using the system developed, jointly with other color research groups, a representative spectral reflectance database associated to the human iris will be available, which can be useful in some applications, such as in medicine and the cosmetics industry. In these areas, the spectral characterization of the iris may be useful in some medical treatments that modify the iris coloration [14,15] and may also allow the analysis of the pigmentation of this structure [16], which is related to the retinal image quality. Because of the iris translucency, which highly depends on the pigmentation, some scattered light can reach the retina of the eye, originating retinal straylight. On the other hand, the knowledge of this database could make easier the choice of materials and colorants used to, for instance, manufacture colored contact lenses or the artificial eyeballs used as prosthetics. In this context, the use of some specific colorants can allow obtaining products with a more natural and realistic appearance.

This paper is structured as follows. In Section 2 the experimental setup of the multispectral system, the different filter configurations analyzed, and the spectral reconstruction algorithms are described, as well as the samples analyzed. In Section 3, the optimization of the multispectral system is presented and, finally, the reconstructions of the irises, prostheses, and colored contact lenses are shown. In Section 4, the most relevant conclusions regarding the reflectance reconstruction quality and the comparisons among groups of samples are described.

2. Methods and Materials

A. Experimental Setup

The multispectral system developed (Fig. 1) consists of a 12 bit depth cooled CCD monochrome camera (QImaging QICAM Fast1394) with 1.4 megapixels (1392 × 1040), an objective zoom lens (Nikon AF Nikkor 28–105 mm), and different sets of filters. The two different configurations of filters tested for the multispectral acquisitions were the following: configuration 1, a color RGB tunable filter attached to the CCD camera and an additional blue filter [Fig. 2(a)], which permitted obtaining three or six images by performing only one or two exposures, respectively, and configuration 2, a set of seven interference filters placed into a motorized wheel with a full width at half-maximum (FWHM) of approximately 40 nm [Fig. 2(b)], which allowed the consecutive measurement of seven images with different associated spectral information. The supplementary blue filter used in configuration 1 was chosen, based on previous study, in order to produce an additional three channels. As a result, we have six channels by combining the trichromatic camera signals with and without the absorption filter [17].

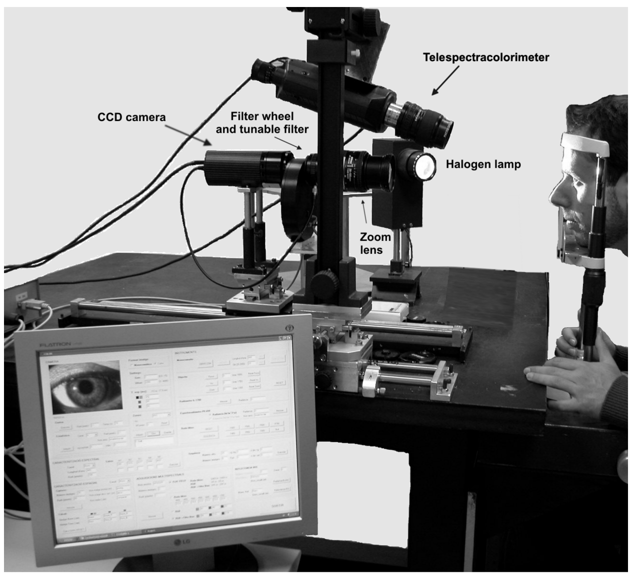

Fig. 1. Multispectral experimental setup.

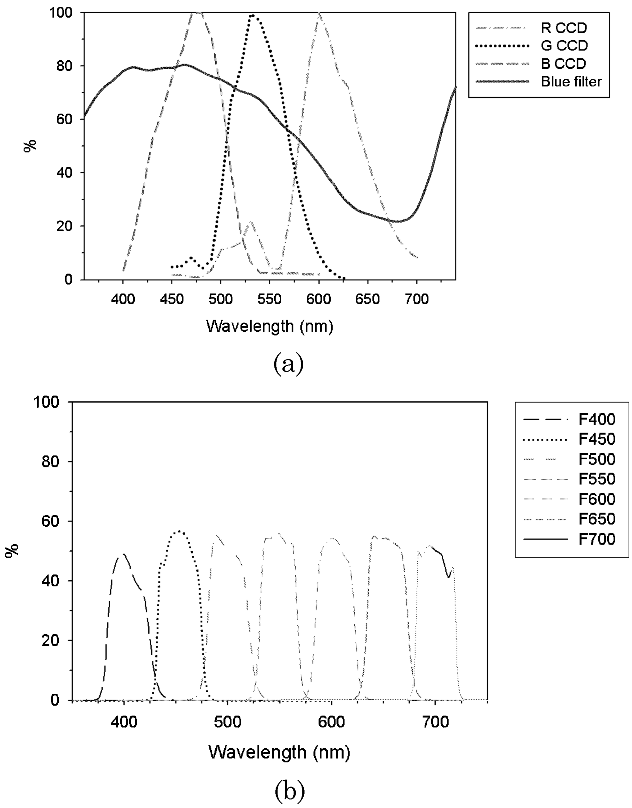

Fig. 2. (a) Configuration 1, relative spectral sensitivities of the RGB channels of the system (tunable filter and CCD camera) and percentage of transmittance of the additional blue filter and (b) configuration 2, percentage of transmittance of the seven interference filters.

Furthermore, an illumination system composed of an adjustable halogen lamp (Philips 15 V 150 W) attached to a stabilized dc power supply (Hewlett Packard 6642A) and a focusing lens, allowing illumination of the analyzed iris with a 45° angle of incidence and obtaining a rather uniform luminous field on the eye. A linear flat-field correction [18] was also applied on the images provided by the complete system in order to both correct the camera response and the nonuniformity of the illumination.

Finally, a telespectroradiometer (Photo Research PR-650) located beside the camera with a reasonably high spatial resolution that is sufficient to see clearly patterns on the iris was used to measure the spectral radiance associated with very small areas of the iris. To obtain the reflectance values of the samples, a previous measurement of the radiance corresponding to a reference white plate placed at the same position as the eye was also necessary. The knowledge of the true spectral reflectances of the irises is necessary to train the multispectral system and also to compare the reconstructed spectra with real data. The telespectroradiometer was slightly tilted (18°) with respect to the optical axis of the multispectral system. This becomes necessary if simultaneous measurements of the iris are required by means of the camera and the telespectroradiometer due to existing eye movements, in order to avoid decentering problems of the measured zones. Although the measurements with the camera and the telespectroradiometer were not performed with identical geometric features, we checked that this mismatch did not introduce significant errors into the experimental values.

With the described multispectral setup, magnified images with high resolution of the iris of each subject, who leaned on a chinrest with potential horizontal displacement, could be obtained through the various channels of the CCD and, therefore, it was possible to obtain the digital signals associated to different parts of it. Specifically, we measured the mean digital output levels corresponding to two square areas of approximately 1 mm × 1 mm (bottom and right) on the iris (Fig. 3), trying to select those with a rather uniform coloration. The bottom and right positions were selected in order to avoid the region of the iris usually covered by the upper eyelid and the specular reflection of the illumination system, respectively. The corresponding averaged spectral reflectances in the visible range (380–780 nm) of those zones were also measured with the telespectroradiometer. During the acquisitions, the movements of the eye can cause the measurement of slightly different regions on the iris.

As it was mentioned before, two different reconstruction algorithms were tested to estimate the spectral reflectance reconstructions of the iris from the digital output levels: the Moore–Penrose pseudoinverse estimation (PSE) and the principal component analysis (PCA). In each of the filter configurations described, we used a different number of channels to perform the reconstructions: in configuration 1 we took into account reconstructions performed using only three channels (RGB) and six channels (adding the blue filter in front of the RGB channels); in configuration 2 we carried out reconstructions using a subset of three interference filters (F450, F550, F650) apart from the complete set, that is, seven. These reconstruction techniques also need *a priori* knowledge of the spectral reflectances associated to the training patches. In this study, we used different training sets to perform the

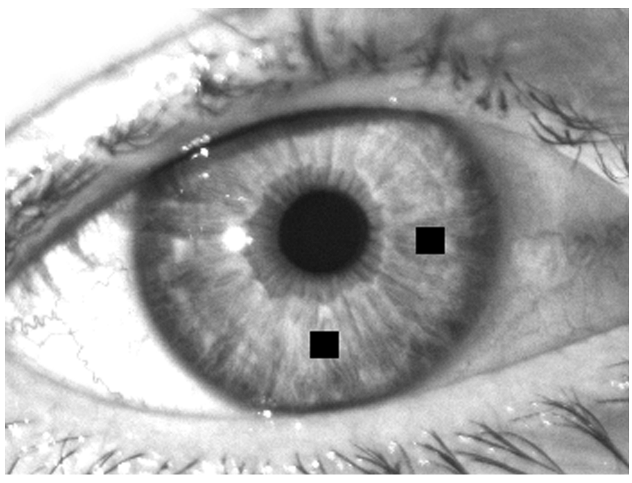

Fig. 3. Image of an iris and corresponding analyzed areas.

reconstructions, such as the GretagMacbeth ColorChecker color rendition chart (CCCR) and different subsets of the measured human irises.

To evaluate the accuracy of the spectral estimations of the iris, several parameters [19], such as the root mean square error (RMSE) and the CIEDE2000 color difference [20,21] were used. RMSE values smaller than 0.01–0.02 [10] correspond to acceptable spectral estimations. By using the CIEDE2000 formula, multispectral systems typically provided color differences in the range of approximately 2–3 units [22,23].

B. Analyzed Samples

A group of 52 real human irises corresponding to the right and left eyes of 26 different subjects were used to optimize the multispectral system. This subset of 104 samples (52×2 analyzed areas) covered a wide range of iris colorations, such as blue, green, and brown. Figure 4 shows the spectral reflectances of these samples measured with the telespectroradiometer PR-650. This delimited number of samples was selected for its reduced size, which allowed an easy manipulation of the data along the optimization process. Specifically, it consisted of 34 brown irises and 18 blue and green light irises.

Once the configuration of the system was optimized in terms of filters and reconstruction algorithms using the former group of samples, the device was finally checked by using it to estimate the spectral reflectance of 100 extra irises (54 brown and 46 blue and green) corresponding to 50 subjects (200 samples), a set composed of 68 prostheses provided by Ovidio S. L., (Barcelona, Spain) and used in daily clinical practice (136 samples), and 17 colored contact lenses (CIBA VISION Fresh Look) with very different colorations (34 samples). The subject used to measure the contact lenses was always the same and had a brown iris. The spectral reflectance profiles corresponding to these samples measured with the telespectroradiometer PR-650 can be seen in Fig. 5.

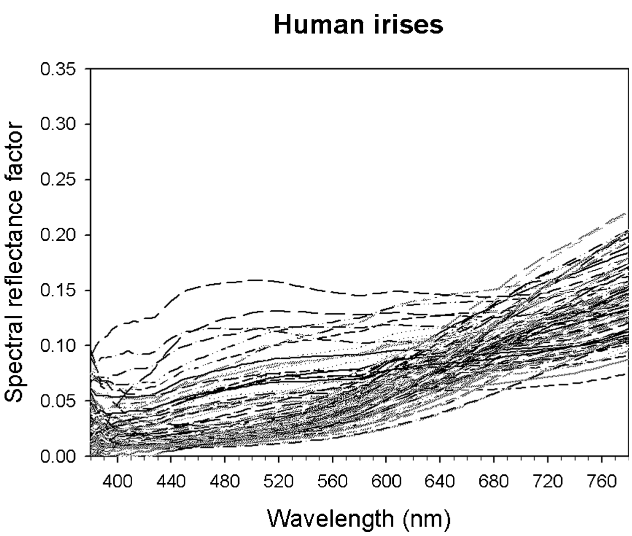

Fig. 4. Spectral reflectance factors of 52 human irises measured with the telespectroradiometer PR-650.

3. Results

A. Optimization of the System

As it was mentioned before, 52 irises were used for the optimization of the system. These samples were measured using the two different filter configurations described in Subsection 2.A. Subsequently, the mean digital output levels of the selected zones were calculated and the corresponding mean spectral reflectances were also determined by means of the telespectroradiometer. After these experimental measurements, we applied the PSE and PCA algorithms to estimate the spectral reflectances from the digital output levels.

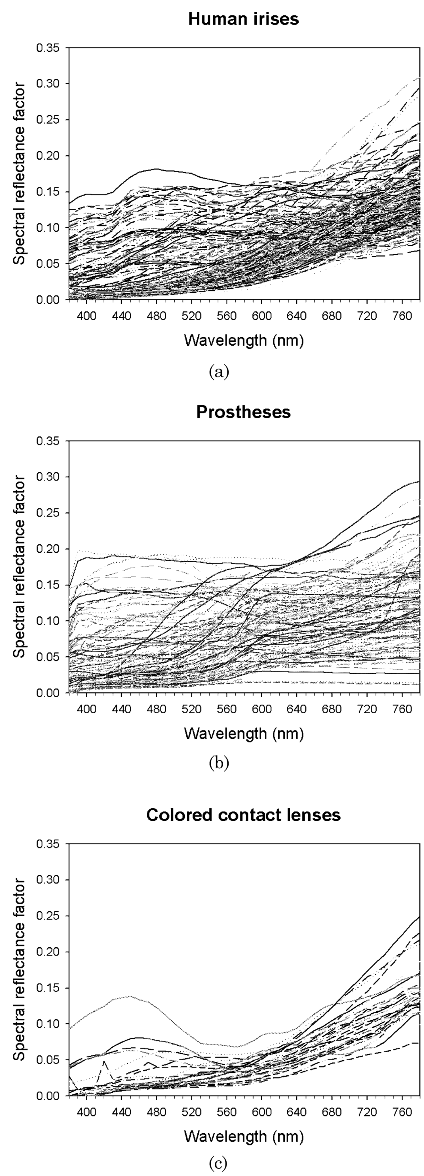

Fig. 5. Spectral reflectance factors of the (a) 100 human irises, (b) 68 prostheses, and (c) 17 colored contact lenses measured with the telespectroradiometer PR-650.

The reconstructions were performed by using different *a priori* known training sets: first, the 24 color patches of the CCCR were used as a training set and the 52 irises (104 samples) were considered as the test set. Reconstruction results obtained when the PSE algorithm and configuration 1 were used can be seen in Table 1. In this table, the mean and standard deviation of the CIEDE2000 color difference and the RMSE are shown. As it can be seen, the colorimetric and spectral accuracy achieved is not good, meaning that the CCCR is not an appropriate representation of the colors associated to the human iris tested and that, therefore, it is not useful for training the system. It can also be seen that the increase of channels still produces bad results due to the mismatch between the training and test colors. Similar results are obtained with the PCA method and configuration 2.

To improve these results, we also considered the 52 irises as training and test sets, simultaneously. The results obtained in this case are shown in Table 2. Now, the color differences obtained and the corresponding spectral accuracies are, in general, very satisfactory. With three channels, the results obtained by means of the PSE algorithm are slightly better than when the PCA is used, although the difference is negligible. However, the results are almost exactly the same when six or seven channels are used. Because of the easier implementation of PSE, this algorithm is preferred. Regarding the set of filters used in the acquisitions, it can be seen that configuration 1 provides slightly better colorimetric parameters than configuration 2, even though the spectral accuracy achieved is similar. Because of the similarity of the results, configuration 1 is preferred due to its easier implementation. This configuration only involves one or two acquisitions, depending on the number of channels desired, while configuration 2 consists of seven exposures, which can increase significantly the acquisition time and, therefore, can become more uncomfortable for the subject. Furthermore, because of the smaller spectral bandwidth (FWHM) of the interference filters and the use of only one focal position for the central channel (F550), the images corresponding to the extreme channels can appear slightly fuzzy. These facts may introduce some additional errors in the calculations and may explain the results found. Finally, the use of six channels in configuration 1, that is, the RGB channels and the extra blue absorption filter, does not report a significant improvement of the reconstruction results and the accuracy obtained with three spectral bands is already acceptable. This can be also understood from Fig. 6, where the cumulative proportion index associated to the components of the PCA performed over the 52 irises is shown. It is possible to see that three or four eigenvectors can theoretically reconstruct very well all the reflectance curves, which means that the use of three or four channels can be enough to obtain good colorimetric and spectral accuracy of the irises. Therefore, it can be stated that the use of a common RGB image and the PSE estimation provide good spectral reconstruction for the human irises analyzed, obtaining, in this case, CIEDE2000 color differences close to 2 units, and RMSE values smaller than 0.01.

Table 1. Color Difference and Root Mean Square Error (Mean ± St. Dev.) for the 52 Human Irises[a]

Configuration 1	CIEDE2000	RMSE
3 channels	22.37 ± 3.84	0.1736 ± 0.0579
6 channels	19.77 ± 6.28	0.0755 ± 0.0422

[a]Training, 24 CCCR; test, 52 human irises; method, PSE; configuration, 1.

To take advantage of any multispectral system, it must be trained with a limited set of samples, that is, using a training set smaller than the test one. Therefore, the 104 samples corresponding to the 52 irises were reconstructed again but. in this case. using smaller training sets, specifically with subsets of the measurements already performed. Because of the results previously shown, to perform the reconstructions we only took into account the PSE algorithm and configuration 1 with three channels. In this context, we used as training sets a subset of 56 samples corresponding to 28 irises and another one composed of 32 samples of 16 irises. In both cases, the subsets considered included varied reflectance curves, which constituted a wide representation of the whole set of irises measured. The results obtained are shown in Table 3. As it can be seen, the reconstructions are almost as good as before, with mean CIEDE2000 values close to 2 and RMSE values smaller than 0.01; the good reconstructions still obtained in terms of color and spectral accuracy using these subsets could be explained by the relatively small variability of the colors associated to the human iris. Therefore, the use of only a delimited amount of spectral basis curves could be enough to estimate a great number of different iris samples and this ensures the robustness of the system developed.

Figure 7 shows the CIEDE2000 histogram corresponding to the 52 irises, that is, the 104 measured and estimated reflectance values using the training sets described. As it can be seen, in reducing the training set size, the distribution of values in the shown intervals changes. The smaller the training set is, the greater differences appear, specifically, above 3 units, although the mean results can still be considered very acceptable.

Finally, the reflectance reconstructions have also been performed taking into account the color gamut of the measured eyes, that is, separating the dark irises (brown irises) from the light ones (blue and green irises). This has been done to try to improve the former obtained results in terms of color and spectral accuracy. The reconstructions have been first developed using the spectral reflectances corresponding to the 34 brown irises as training and test sets and, second, with the spectral profiles of the 18

Table 2. Color Difference and Root Mean Square Error (Mean ± St. Dev.) for the 52 Human Irises[a]

	PSE		PCA	
Configuration 1	CIEDE2000	RMSE	CIEDE2000	RMSE (×100)
3 channels	2.09 ± 1.05	0.0072 ± 0.0045	2.69 ± 1.06	0.0077 ± 0.0044
6 channels	2.06 ± 0.95	0.0069 ± 0.0042	2.06 ± 0.95	0.0069 ± 0.0042
Configuration 2				
3 channels	2.67 ± 1.44	0.0072 ± 0.0040	3.41 ± 1.47	0.0077 ± 0.0039
7 channels	2.31 ± 1.26	0.0065 ± 0.0038	2.31 ± 1.25	0.0065 ± 0.0038

[a]Training, 52 human irises; test, 52 human irises.

blue–green irises also included in the 52 irises database. As before, the reconstructions were carried out with the PSE algorithm and configuration 1 with three channels. The results obtained for the two analyzed groups are shown in Table 4. It can be seen that the reconstructions for the brown irises are slightly better in this case, that is, when only the dark samples are included in the training set. The mean CIEDE2000 value is now slightly smaller than 2 (1.97) and the RMSE parameter is 0.0065. However, this only represents a small improvement with respect to the results obtained when the complete set of 52 irises was used as a training and a test set (CIEDE2000 = 2.09, RMSE = 0.0072). Furthermore, in the case of the blue–green irises, the results are slightly worse, with a 2.12 CIEDE2000 and a 0.0084 RMSE mean values. Again, this only represents a very small change with respect to the reconstructions achieved with the complete set of human irises. Therefore, in the following reconstructions we will not separate the samples by taking into account the color gamut because, with the use of this methodology, a clear improvement of the spectral results is not reported.

B. Spectral Estimations

As it was previously mentioned, to test the developed system it has been finally tested over 100 real human irises (200 samples), 68 prostheses (136 samples), and 17 colored contact lenses (34 samples). First of all, the PCA was performed over them. The corresponding cumulative proportion indexes (%), that is, the percentages explained by different numbers of eigenvectors for the different groups are listed in Table 5. As it can be seen, for the three groups of samples, the three first principal components explain more than 99% of their variance. This is in agreement with the results obtained in the optimization of the system, where it was found that three channels (RGB) were enough to obtain good reconstructions of the spectral reflectances associated to the human iris.

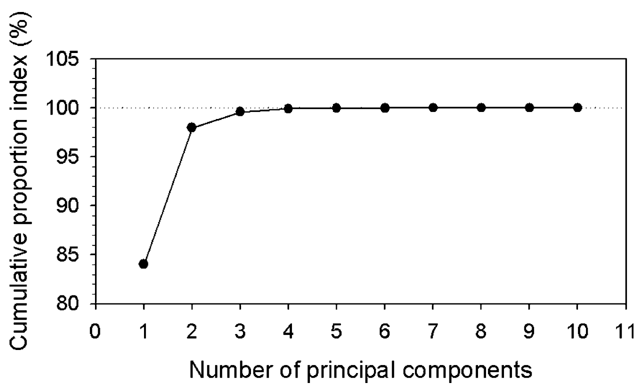

Fig. 6. Cumulative proportion index (%), that is, percentage explained by different numbers of principal components of the PCA analysis performed on the subset of 52 irises (104 samples).

The reconstructions of the spectral reflectances of the three groups of samples considered were first assessed using the same groups as training and test sets. The corresponding results are shown in Table 6. The three groups analyzed have mean color differences of around 2 CIEDE2000 units or even smaller, meaning that the reconstructions in terms of color differences are accurate in terms of multispectral imaging systems. The same conclusion is obtained from the RMSE parameter. In this case, averaged values similar to 0.01 are obtained, which mean good reconstructions of the visible reflectance. Furthermore, it can be seen that the best results are obtained for the prostheses. This can be explained by taking into account experimental errors associated with the measurements: the artificial eyeballs do not present any of the movement associated with the other two types of samples, whereas, when the human subject's eye is part of the scene, this is not true. This leads to a less precise measurement in the last cases. Figure 8 shows some representative examples of spectral reflectance reconstructions for the human irises, the prostheses, and the contact lenses. Specifically, the best and the worst reconstructions for each group can be seen. From the results presented above, it can be affirmed that the system has the capability of providing accurate reconstructions of the visible spectral reflectances of the samples.

Once the feasibility of the system has been tried for the last three groups of samples individually, the next step is answering whether the system can be trained with a different set of samples regarding

Table 3. Color Difference and Root Mean Square Error (Mean ± St. Dev.) for the 52 Human Irises[a]

Training	CIEDE2000	RMSE
28 irises	2.16 ± 1.15	0.0074 ± 0.0047
16 irises	2.20 ± 1.12	0.0079 ± 0.0049

[a]Test, 52 human irises; method, PSE; configuration, 1, with three channels.

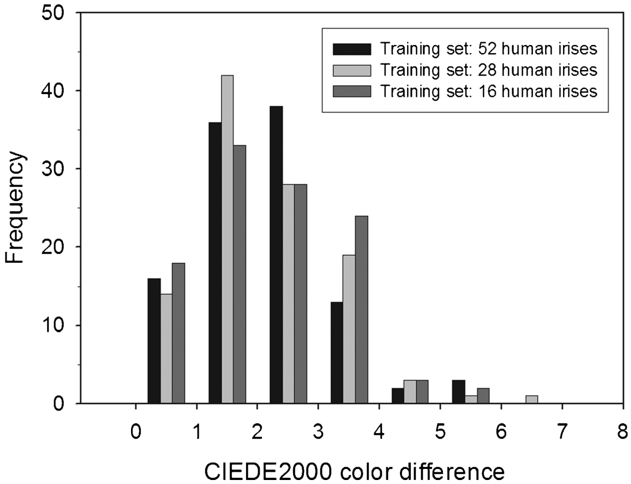

Fig. 7. CIEDE2000 histogram for the 52 human irises obtained using three channels (test, 52 human irises; method, PSE; configuration, 1).

the actual test set. This will inform us about the capability of each group of samples of describing the spectral reflectance profiles of the other two groups. The reconstruction results obtained when the training and test sets correspond to different groups of samples are shown in Table 7. It can be seen that, when the system is trained using the human irises, the reconstructions for the prostheses and the contact lenses are still rather accurate, meaning that the 100 irises are a quite good representation of all the colors associated to the different samples analyzed. In this case, the mean color differences are around 2–3 CIEDE2000 units and the RMSE is around 0.01, values for which the reconstructions can be still considered accurate. Better results are obtained for the contact lenses, probably because the measurements of these samples are performed on a real iris and, therefore, the actual reflectance measured is mainly affected by the contact lens, but also by the color of the subject's iris underneath. On the other hand, when the system is trained using the prostheses and the reflectances belonging to the other two groups of samples are reconstructed, the results are worse. The mean CIEDE2000 in these cases are close to 4 and the RMSEs are slightly higher. This implies that the reflectances associated to the 68 artificial eyeballs do not represent the other samples with as much precision as the real irises do. This could be because of the colorings and pigments present in this kind of samples, as well as the texture, features which can differ from the real

Table 4. Color Difference and Root Mean Square Error (Mean ± St. Dev.) for the 34 Brown Irises and the 18 Blue–Green Irises[a]

	CIEDE2000	RMSE
Brown eyes	1.97 ± 0.92	0.0065 ± 0.0030
Blue-green eyes	2.12 ± 1.01	0.0084 ± 0.0055

[a]Training, 34 brown irises/18 brown irises, respectively; test, 34 brown irises/18 brown irises, respectively; method, PSE; configuration, 1, with three channels.

Table 5. Cumulative Proportion Index (%) for the First Three Principal Components (PC) Corresponding to the 100 Human Irises, 68 Prostheses, and 17 Colored Contact Lenses

PC	Irises	Prostheses	Contact Lenses
1	64.71	68.85	51.71
2	95.82	97.35	94.67
3	99.21	99.08	99.01

colors of the iris. The same explanation could be applied to the contact lenses, because, as it has been stated before, the color measured on them is also affected by the real iris under them.

Finally, if the colored contact lenses are used as the training set, the results of reconstructing the human irises are similar to those obtained when the system is trained using the prostheses, while the results of reconstructing the prostheses are, in general, poor. In these cases, the mean CIEDE2000 is close to 4 and 6, respectively, and, in both cases, the standard deviation associated is very high, meaning that there is a high dispersion among the results. This can also be seen from the corresponding ranges, that is, the minimum and maximum color difference and RMSE values. Probably this can be due to the limited number of contact lenses analyzed, as well as their reflectance profiles, which cannot be representative of the real reflectances present in human eyes and the artificial eyeballs.

4. Conclusions

We showed the feasibility of a multispectral system to be used as a tool to estimate the spectral reflectance associated to the human iris. The system developed, which basically consists of a CCD camera, an objective zoom lens with great magnification, several sets of filters, and a halogen lamp used to light the analyzed iris, was optimized for this purpose. The system allowed performing a spectral reflectance

Table 6. Color Difference and Root Mean Square Error (Mean, Standard Deviation, Minimum, and Maximum Values) for the 100 Human Irises, 68 Prostheses, and 17 Colored Contact Lenses[a]

	CIEDE2000	RMSE
Training set = test set, human irises		
Mean	2.46	0.0108
St. Dev.	1.10	6.4739e-3
Min.	0.50	2.3433e-3
Max.	5.44	0.0345
Training set = test set, prostheses		
Mean	1.97	0.0111
St. Dev.	0.91	6.2001e-3
Min.	0.46	2.4249e-3
Max.	4.44	0.0342
Training set = test set, contact lenses		
Mean	2.57	0.0105
St. Dev.	0.95	6.1035e-3
Min.	0.77	2.5625e-3
Max.	4.01	0.0229

[a]Training set = test set; method, PSE; configuration, 1, with three channels.

Table 7. Color Difference and Root Mean Square Error (Mean, Standard Deviation, Minimum, and Maximum Values) for the 100 Human Irises, 68 Prostheses, and 17 Colored Contact Lenses

	CIEDE2000	RMSE
Training set, human irises; test set, prostheses		
Mean	2.90	0.0179
St. Dev.	1.22	0.0115
Min.	0.57	3.0910e-3
Max.	5.97	0.0569
Training set, human irises; test set, contact lenses		
Mean	2.42	0.0129
St. Dev.	1.09	6.8951e-3
Min.	0.79	2.3770e-3
Max.	5.48	0.0316
Training set, prostheses; test set, human irises		
Mean	3.78	0.0165
St. Dev.	1.23	8.4533e-3
Min.	0.55	4.6276e-3
Max.	7.58	0.0569
Training set, prostheses; test set, contact lenses		
Mean	4.04	0.0182
St. Dev.	1.05	7.0793e-3
Min.	1.82	9.6825e-3
Max.	6.78	0.0390
Training set, contact lenses; test set, human irises		
Mean	3.79	0.0167
St. Dev.	1.77	9.0554e-3
Min.	0.47	1.9612e-3
Max.	8.43	0.0458
Training set, contact lenses; test set, prostheses		
Mean	5.86	0.0250
St. Dev.	2.34	0.0118
Min.	1.30	5.3829e-3
Max.	11.38	0.0573

[a]Training set ≠ test set; method, PSE; configuration, 1, with three channels.

estimation of the iris by acquiring only some images of the eye and applying linear algorithms, such as the PSE and the PCA. We evaluated different configurations of the system in order to determine the one that provides the best spectral results and has the easiest implementation. This was accomplished by using a configuration composed of a RGB tunable filter, which allowed obtaining three monochrome images in sequence. The application of the PSE and the PCA algorithms led to similar results, although the PSE was preferred because of its simplicity. We also tested different training sets for the system and found that a reduced subset of real iris samples can be enough to obtain acceptable results of reflectance reconstruction.

With the optimized system, the spectral reflectance curves in the visible spectrum of three groups of samples were analyzed. The groups consisted of real human irises, clinical prostheses, and colored contact lenses. The reconstructed spectral profiles showed a high level of spectral and color accuracy and color, mainly when the system was trained by means of the human iris database. In general, the mean CIEDE2000 color differences obtained were close to 2–3 units and the RMSE parameter was similar to 0.01.

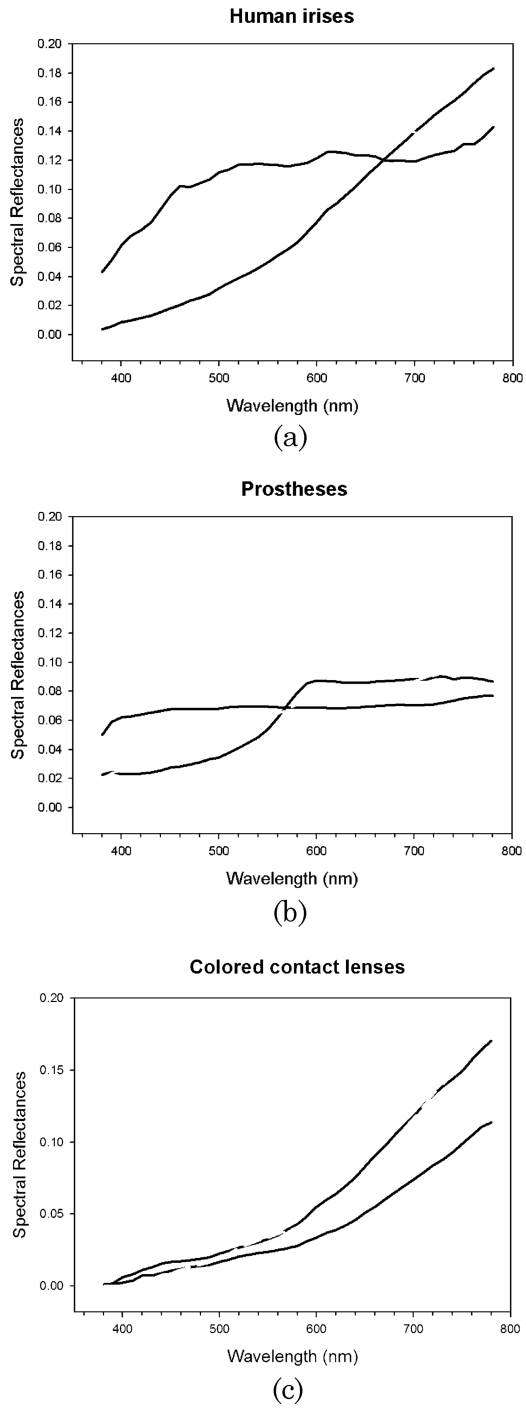

Fig. 8. Best and worst spectral reflectance reconstruction for the three groups of samples analyzed: (a) human irises, (b) prostheses, and (c) colored contact lenses. Solid curves indicate the reconstructed spectral reflectances and dashed curves indicate the measured (PR-650 telespectroradiometer) ones.

We showed the possibility of estimating the spectral reflectances of irises from simple RGB images. The use of this system will allow characterizing the color of human irises with high resolution and creating a wide database of spectral reflectances. This can be useful in some medical applications, for instance, in the determination of the pigmentation of the iris, which can affect the retinal image quality, as well as in the observation of color changes over time caused by some treatments. In the cosmetics industry, the spectral characterization of the iris can be useful in prostheses manufacturing, as well as in the contact lenses industry. This knowledge can lead to more a natural and realistic appearance of the manufactured products.

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