Statistical Characterization of Face Spectral Reflectances and Its Application to Human Portraiture Spectral Estimation

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Abstract

Spectral reflectances of various parts of human faces from various ethnic races were measured as part of experiments on spectral imaging for human portraits. Principal components analysis (PCA) was applied to the spectral reflectances from the various races, and a variety of face parts. The first three principal components explain about 99.8% of cumulative contribution of variance of spectral reflectances for each race and each face part, and for all races as well. Color differences of spectral reconstruction either for individual races and all races or for individual face parts based on different sets of principal components were estimated. The results indicate that, when using 3 basis functions and under D_{50} illumination, the basis functions based only on spectra of Pacific-Asian subjects will provide the best overall color reproduction. However, from a spectral matching point of view, three basis functions based on all spectra will provide the best spectral reproduction with minimum overall mean value of metameric indices. More analyses were applied to spectral reflectances of human facial skin from different sources and their corresponding spectral reconstruction based on different sets of principal components. Those results provide practical suggestions for imaging, or spectral imaging, system design, especially imaging systems for human portraiture.

Keywords

Human Face, Human Skin, Human Portraiture, Facial Spectral Reflectance, Principal Components Analysis, Basis Functions, Spectral Imaging, Spectral Image

Introduction

Facial color reproduction is an important aspect of color-imaging system design and analysis. Because of the problems involved in the image capture and reproduction of metameric objects, spectral matches between the original objects and their reproductions are becoming more popular in recent years.[1,2,3] The color, or spectral reflectance of human skin depends chiefly on the presence of pigment and blood.[4, 5] Different complexions of human beings have different spectral characteristics though the pigments involved are the same. When designing a spectral imaging system for human portraiture, for better color and spectral reproduction, it is very important to determine the number of channels used and the basis functions selected for spectral reconstruction of the final spectral images. Therefore, from the imaging point of view, it seems very important to understand the statistical characteristics of spectral reflectances of different racial complexion. In this research, we will concentrate on the face which is the main target of spectral imaging for human portraits.

Extensive research has been done on the coloration of human beings, especially human skin. Biological and anatomical research indicates that the skin is made up of three layers, epidermis, dermis and hypodermis. Dealing with the color, we simply divide the skin into an outer thin layer, epidermis, and an inner, relatively thick layer, dermis. For normal human skin, the absorption of the epidermis is dominated by a black pigment called melanin though there are five different pigments in the skin.[6] The spectral characteristics of different races or different individuals are due only to variation in the amount of melanin present.[7,8] Buckley and Grum,[9] and Kollias and Baqer[8] indicated that the spectral reflectance of melanin in the visible range is monotonically increasing. The inner layer, dermis, is rich with blood vessels that contain hemoglobin. Hemoglobin has marked absorption bands around 575nm, 540nm and 410nm.[10,11] Brumsting and Sheard[4,5] indicated that the marked absorption bands of hemoglobin occur only when it bonds with oxygen within vivo skin. Heavily pigmented skin will present less pronounced effect of the hemoglobin absorption bands because of the masking effect of the greater amount of melanin pigmentation. Human lips, on the other hand, are in rich of blood vessels and will present hemoglobin absorption bands. Optically, the epidermis is a strongly forward scattering layer and, for all wavelengths considered, scattering is much more important than absorption.[12] Details of skin biology are beyond the scope of this research.

The skin is not the only part of the human body that differs in color from one individual to another. The eyes have the same elements affecting their coloring. In dealing with an individual's eye color one is referring to the pigmentation of the iris. The iris, from the standpoint of color, consists of the anterior layer together with its underlying stroma and the posterior pigmented epithelium.[13] In the eye, as in the skin, melanin is the dominant pigment material. However, in this case, the location of the melanin is as important as the amount.[6] Eye color also depends partly on optical phenomena. Blue eyes are not the effect of blue pigment, but due to Tyndall scattering.

As in the skin and eyes, melanin, eumelanin (brown-black) and phaemelanin (yellow-red), is also the most important pigment in hair.[6] Hair contains center section (central medulla), middle area (cortex) and scaly outer cuticle.[14] When there are only a few melanin particles in the middle area, the colorless outer skin softens the brownish-black color of the melanin so much that the hair appears blond. When both the middle area and the center section of each hair are rich with melanin, the hair appears brown. When the center section is packed with melanin the hair is black. Hair becomes white or gray when there is little or no melanin in the center or middle sections.

In summary, the colors, or spectral reflectances, of human faces depend chiefly on the presence and variation of pigment and blood. Recent research on spectral imaging for human faces[1,2,3] has been very successful. However, these experiments concentrate mainly on a single race and only on skin. The spectral measurement geometry is generally fixed to 45/0 or d/0. The statistical analysis of spectral reflectances for different human races and different parts of the face is not available. Considering the capability of spectral imaging systems for different races of human portraits it seems worth measuring spectral reflectances of different races and those spectral data should include skin, and hair, eyes and lips as well. Since the human head is not planar but a 3-dimensional object, the spectral reflectances observed by the camera should consider geometry. To perform an accurate calibration of the spectral imaging system, the spectral database should cover a large range of spectral reflectances with various geometric configurations. Accordingly, a new spectral imaging system was designed for human portraiture that has the capability to capture spectral images for human subjects from different races and describe spectral reflectances of skin, hair, eyes and lips very well.[15] The spectral data for this research contains measurements from individuals of five different races, Pacific-Asian, Caucasian, Black, Subcontinental-Asian, and Hispanic.[16] The data can also be divided into four face locations/parts, skin, hair, eyes and lips. Due to the large variation in complexion used in this study, the accuracy of three basis functions used by other researchers need to be re-evaluated. It is important to verify the accuracy of the number of basis functions used for all races and the accuracy of these basis functions applied to individual races and individual parts of human faces. The PCA method used in this research attempts to construct a small set of basis functions that summarize the original spectral data, thereby reducing the dimensionality of the original spectral data. The color accuracy of spectral reconstruction for all races, as well as individual races and individual parts, described by the extracted basis functions is provided and discussed. Moreover, some statistical characteristic comparison for the spectral reflectances of the human face skin, collected from different sources is included.

Experiment

The details of the experiment can be found in reference 15. The lighting system included two lighting heads (Scanlite Digital 1000, Elinchrom) with Halogen Photo Optic lamps (FEL/1000W, 120V). A Photo Research Spectroradiometer, SpectraScan 704, was used in the spectral measurements. The measurement system was calibrated by a high quality white reference, a barium sulfate coated paper which was spectrally flat and uniform. The distance from PR-704 to the subject was about 1.6m. The subjects sat on a chair with their heads against a brace. During the experiment the subjects were asked to adjust their chair up and down, left and right, until the position of interest fell into the center of the camera image frame. The center of image frame was marked by a small grid box, which is a function of the camera system and could be displayed on the monitor. Based on this system setting, the spectral measurement would match the different geometries as detected by the camera. A total of 34 subjects with ages ranging from 18 to 40, 11 female and 23 male, participated. The experiment was performed over a period of 7 months. The subjects can be divided into five races, 11 Pacific-Asian subjects, 8

Caucasian, 7 Black, 6 Subcontinental-Asian and 2 Hispanic. Each subject provided 16 spectral reflectances which, in general, included 10 for facial skin, 3 for hair, 2 for eyes and 1 for lips. The locations of spectral measurement were randomly selected considering uniformity of sampling.

Results and Discussion

Based on the PCA results, the cumulative contribution percentages of the first one to six principal components for spectral reflectances of all races (the combined data set) as well as individual races are shown in Table 1. The abbreviations PA for Pacific-Asian, C for Caucasian, SB for Subcontinental-Asian, B for Black, H for Hispanic and AR for all races will be used in the following sections.

The results in Table 1 indicate that the first three principal components will cover over 99.8% of the variance for all spectral data of all races and spectral data of individual races as well. This suggests that a spectral imaging system with the proper selection of three basis functions will provide sufficiently accurate spectral reconstruction for all races as well as any individual race. Further observation indicates that, with three basis functions, the spectral reconstruction of Pacific-Asian, Caucasian and Hispanic races will have slightly more accurate results than that for Black and Subcontinental-Asian. The corresponding first three principal components are shown in Fig. 1.

Fig. 1 shows that the first three principal components of each race and all races have very similar shapes. This suggests the possibility that the first three principal components of any race may be used to describe the spectra of other races.

The cumulative contribution percentages of the first one to six principal components for spectral reflectance of each facial part are given in Table 2. Not surprisingly, the first three principal components for most parts will provide over 99.8% of the variance of spectral reflectances with one exception of spectra of lips which is about 99.7%. The PCA results in Table 1 and 2 here also verify that the spectra, or color, of the human body depends chiefly on the presence of pigment and blood, melanin and hemoglobin.

Next the mean color differences between spectral reflectances measured and reconstructed based on the first three basis functions are considered for the application of certain sets of basis functions to their own group and to spectra of other groups as well. The CIELAB color difference equation was applied with the CIE 2° observer and D_{50} illuminant. The results shown in Table 3 are for different races. The horizontal items are the spectral groups that yielded the principal components while the vertical items are the predicted spectral groups. Similar item arrangements are used in Tables 4, 5 and 9.

The basis functions based on spectra of all races will give smaller color difference for races of Pacific-Asian, Caucasian and Hispanic than that for races of Black and Subcontinental-Asian. This may be due to the facts that in heavily pigmented races, such as Black and Subcontinental-Asian, the spectral characteristics of hemoglobin are masked and show some slight specific property in spectra that need more basis functions to reproduce at the same level of accuracy as that for light pigmented races. It could also be due to the fact that more noise was involved in those data with lower signal level. Considering individual race, not surprisingly, most races will have smallest color difference when the basis functions used for spectral reconstruction are based on their own spectra data (the diagonal color difference values in the tables). The basis functions based on lightly pigmented races will give smaller color difference when they are applied to lightly pigmented races. The same is true for the basis functions based on heavily pigmented races applied to heavy pigment races. Mathematically, for basis functions based on all races, the variance of the data of five races are comparatively large because of including both low- and high-order statistics; for one race using its own set of basis functions the variance of spectral data is comparatively small because of the inclusion only low-order statistics. Therefore, generally, the best color reproduction or spectral matching will occur when spectra of each race employ its own set of basis functions.

Most interesting is that the first three basis functions based on any individual race can provide a smaller mean color difference for overall spectral reconstruction of all races than that derived from the three basis functions based on overall spectra (the last row). The first three basis functions from Pacific-Asian subjects will provide the smallest color difference for overall spectra of all races by about 40%. Moreover, using this set of three basis functions, the color difference of spectral reconstruction for other races will be decreased about 20 ~ 55% compared to that using the first three basis functions yielded from overall spectra. This suggests that to obtain better color reproduction of spectral imaging system, when using three basis functions under illumination D_{50}, the basis functions based on spectra of Pacific-Asian race will be the best choice, not the basis functions based on spectra of overall races. This may be partly due to the fact that the Pacific-Asian is medium pigmented race and its spectra have both characteristics shown in lightly and heavily pigmented races.

It should be emphasized that, for calibration purposes, the spectral data of all races is still required to get the maximum spectral range. Further research indicates that when using six basis functions, the set of basis functions based on the spectra of overall races will be a much better choice for color reproduction of the overall spectra . The same is true in the case of using six basis functions that the best color reproduction will occur when spectra of each race employs its own set of basis functions.

One should always keep in mind, however, that the best colorimetric matching does not always guarantee the best spectral matching, and vice versa. Considering spectral reproduction itself, it may be better to estimate the root mean square (RMS) error between original spectra and reconstructed spectra. To more precisely demonstrate the color reproduction of spectral matching, the indices of metamerism employing Fairman's metameric correction using parameric decomposition[17] are an alternative choice. Table 4.1 and 4.2 show the results of RMS error and mean metameric indices using the same sets of basis functions as in table 3, respectively. The indices of metamerism were calculated using illuminants D50 and A.

Table 4 indicates that for best spectral matching of overall spectra the set of basis functions based on spectra of overall races will be the best choice. Because of the reason mentioned above, the best spectral reproduction or spectral matching for spectra of each race will occur when it employs its own set of basis functions (the diagonal values). Table 4 also shows that overall reconstructed spectra based on the basis functions yielded from lightly pigmented races will provide better color as well as spectral reproduction. As similar to the situation in the results of Table 3, Table 4.2 shows that the basis functions based on spectra of Pacific-Asian subjects will still give much better color reproduction when applied to overall spectra of all races although basis functions based on spectra of all races will be the best choice, precisely.

Further research indicates that when using more than three basis functions, basis functions based on spectra of all races will provide smaller errors in spectral and colorimetric matching compared to using other sets of basis function based on other individual races. However, the differences may not be visually detectable. In practice, one should consider the advantage provided by spectra of all races.

It should be emphasized that caution should be used when using RMS error to analyze the spectral reproduction since RMS error only provides information on the absolute spectral difference between measured and estimated results. For example, in Table 4.1, RMS values for Caucasian and Black subjects are the same when using basis functions based on all spectra. However, considering the much smaller absolute values of spectral reflectances of Black subjects compared to that of Caucasian subjects, one concludes that basis functions based on all spectra will provide better spectral reproduction for Caucasian than for Black subjects, which can be proved from the results in Table 4.2 that the mean index of metamerism for Black subjects is double the value for Caucasian subjects.

The results shown in Table 5 are indices of metamerism and RMS spectral error for spectral reconstruction using various sets of three basis functions for spectra of different facial parts. Table 5.1 indicates that the set of first three basis functions based on all spectra will give at least double the mean color difference for hair spectral reconstruction compared that for other parts (the last column). This may be due to the fact that spectral reflectances of hair are so dark that spectral reconstruction using three basis functions based on all data will yield negative values at some wavelengths, hence the larger color difference. The results also indicate that the basis functions from skin can not be used to describe the spectra of hair. On the other hand, somewhat surprisingly, basis functions based on spectra of hair can be used to describe other parts very well. However, since most area within human portraits will contain skin, it is worth using the set of basis functions yielded from overall spectra with the cost of relatively large color difference of spectral reproduction for hair. Our further research indicates that this problem can be solved using more basis functions based on overall spectra. Considering three basis functions based on spectra of lips, due to their specific spectral characteristics they cannot be used to describe spectra of other parts.

The corresponding indices of metamerism are shown in Table 5.2. Table 5.2 illustrates that the set of first three basis functions based on all spectra will provide very good color and spectral reproduction for skin, eyes and lips with the cost of relatively high color and spectral error for hair. On the other hand, an interesting result is that the basis functions based on spectra of eyes will provide the smallest mean metameric index of overall spectra. However, it is not a best choice for spectral reproduction of skin. As mentioned, it is worth using the set of basis functions yielded from overall spectra, which will improve by about 30% the color and spectral reproduction of spectra of skin compared to that using basis functions based on eyes.

Since facial skin is the most important part in color and spectral reproduction of human portraits its spectral characterization is considered in more detail. As an overview to the skin spectra of individual races, their mean spectra are plotted in Fig. 2.

Fig. 2 shows that each race has roughly similar shape of mean skin spectral reflectance. However, the heavy pigmented races, Black and Subcontinental-Asian, mask most of the spectral characterization of hemoglobin and appear more nearly monotonically increasing, revealing the spectral characteristic of melanin in the visible range. Light pigmented races, Caucasian, Pacific-Asian and Hispanic, on the other hand, show apparent absorption bands of hemoglobin around 575nm, 540nm and 410nm. Those spectral characteristics are consistent with the results discussed in the introduction section. The cumulative contribution percentages of the first one to six basis functions of skin spectra for individual races are shown in Table 6. It shows that three basis functions will cover over 99.7% of variance of skin spectra for each race.

The first three basis functions are shown in Fig. 3. Fig. 3 shows that for skin spectra, three lightly-pigmented races have very similar first three basis functions while the same is true for two heavily-pigmented races. However, it is obvious that the third basis functions of lightly and heavily pigmented races are different. This may be due to the fact that skin of heavily-pigmented races has a masking effect on spectral characterization of hemoglobin. Comparing basis functions based on spectra of all skin in Fig. 3(f) and basis functions based on all spectra of all races in Fig. 1(f), it shows that the two sets of first three basis functions are very similar. This may be the reason why basis functions based on all spectra of all races can provide quite accurate color and spectral reproduction for spectra of skin, and vice versa.

The results of color and spectral reproduction of skin for individual races when using 3 and 6 basis functions based on all spectra of all races are given in Table 7. Table 7 shows that three basis functions based on all spectra of all races will provide good color and spectral reproduction for lightly-pigmented skin (Pacific-Asian, Caucasian and Hispanic) while there are relatively large color difference and metameric indices, but still small enough for practical application, for heavily-pigmented skin (Black and Subcontinental-Asian). It also suggests that color and spectra reproduction will be improved when using more basis functions, especially for heavily pigmented skin.

The spectral reflectances shown above were measured using remote-type method. It is worth doing some comparison with spectra measured by contact-type method from other researchers. Based on current available spectral data only face skin spectra will be evaluated. The skin spectra measured by contact-type method here are provided by Dr. Pietikäinen from Oulu University, Finland[18] and referred to as the Oulu data. The Oulu data contains 357 spectra measured from facial skin of 119 subjects with a Minolta CM-2002 spectrophotometer. Each subject provided 3 spectral measurements from the left and right cheek and the forehead. Details of the Oulu data are given in reference 18. The Oulu data are characterized into three races, Pacific-Asian, Caucasian and Black. There were 10 Pacific-Asian, 101 Caucasian and 8 Black subjects. The mean skin spectra of individual races in the Oulu data are shown in Fig. 4.

Comparing Fig. 2 and Fig. 4, it shows that mean skin spectra of Oulu data are higher than mean skin spectra in our data for the same races. This is due to two major reasons. One is the different locations selected for spectral measurements. Our measurement selected more locations than the Oulu data measurement. The other reason is the different measurement geometries involved in the two data sets. Our spectral data contained various geometries while Oulu data contained only d/8 geometry[19]. It could also be partly due to the population measured. Fig. 4, like Fig. 2, shows apparent absorption bands of hemoglobin around 575nm, 540nm and 410nm for light pigmented races.

The first three basis functions of Oulu data are given in Fig. 5. Comparing Fig. 3 and Fig. 5, it shows that basis functions of light-pigmented skin have very similar shapes while basis functions of heavy-pigmented skin, Black skin, have very similar shapes of their own. The cumulative contribution percentages of the first one to six principal components of skin spectra for individual races in the Oulu data are shown in Table 8.

Table 8 shows that the cumulative percentage using three basis functions for light pigmented races, Pacific-Asian and Caucasian, in Oulu data are relatively small compared to that of the spectral data in Table 6. Japanese skin spectra reported by Imai[1] has comparable cumulative percentage using three basis functions with that of Pacific-Asian skin in our spectral data. The reason for this difference is unknown, but we presume that geometric difference may play a role. For comparison purpose, we also calculated the color differences applying various three basis functions shown in Fig. 5 to skin spectra in Oulu data. The results are shown in Table 9. Not surprisingly, basis functions based on all races will provide best color reproduction for overall skin spectra. Also, like the results in Table 3, basis functions based on light pigmented skin cannot provide good color reproduction for heavily pigmented skin, and vice versa.

So far the color and spectral reproductions of skin spectral reflectances using different sets of basis functions based on statistical analysis have been discussed. The deviation or degree of deviations of color within the skin spectral reflectances of individual races and individual subjects might also be at interest. These are provided in tables 10 and 11. Table 10 shows the mean color differences between the skin spectral reflectances and their mean (shown in Fig 2 and Fig 4) of individual races. It also provides the standard deviation, maximum and minimum values of those color differences. Table 11 also provides the results of mean color difference, but with different approach. First the color differences of each different pair of skin spectral reflectances of each subject are calculated. Then the mean of those color differences within individual races is determined. It also provides the maximum and minimum values of those color differences. The results of table 10 show that the deviations of color perception between the skin spectral reflectances and their mean spectra within individual races are very large, over 5 units in our data and over 3 units in Oulu data. The relatively small mean values of Oulu data sets are probably due to their fewer sampling points. It can also indicate that the variation of skin color perception of Pacific-Asian subjects is the smallest. Table 11 shows that the deviation of facial skin color perception is very large even within a single subject, which may be one of the reasons that people can be distinguished easily one another from their facial skin features. Oulu data sets show relatively small values with the same reason as discussed for table 10. Considering the large variation of facial skin color in tables 9 and 10, color reproductions of skin (see results in table 5) using three basis functions derived from all spectral reflectances measured are accurate enough in practical application.

The above results provide a practical suggestion for imaging or spectral imaging system design, especially imaging systems for human portraiture. It may also have potential application to designing digital camera systems, i.e., optimizing the selection of spectral sensitivities of digital camera to provide best color reproduction of human face images. These results might help in choosing optimized sets of inks to print images of human faces with better color and spectral reproduction. It might also provide some practical data for the cosmetic industry.

Conclusion

This research analyzes the statistical characteristics of spectral reflectances of human portraiture using PCA method. The results showed that the first three basis functions will provide quite accurate color and spectral reproduction for spectra of all races and individual races and individual facial parts as well. Considering color reproduction of spectral reconstruction using three basis functions in each race, the set of basis functions based on spectra of Pacific-Asian subjects will provide the best overall results. However, from spectral matching point of view, three basis functions based on all spectra will provide the best spectral reproduction with minimum overall mean value of indices of metamerism. Further observation indicates that more basis functions may be necessary to improve the color and spectral reproduction of facial spectral reflectances of heavily-pigmented races and hair in facial part.

Spectral reflectances of skin measured from remote-type of this research and contact-type instruments of the Oulu data show very similar statistical characterizations though there are some differences in absolute values due to different measurement geometries and selection of measurement location involved. Considering the colors of facial skin, the deviations are very large either in the same race or the same subject with different facial parts.

The results of color and spectral reproduction using different sets of basis functions discussed above may suggest that universal set of basis functions of human facial spectral reflectances of various ethnic races is possible, especially for the spectra of human facial skin.

The spectral data and basis functions are posted on Lippmann2000, a spectral imaging database of Munsell Color Science Laboratory, at http://www.cis.rit.edu/mcsl/online/lippmann2000.shtml.

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Table 1. Cumulative contribution percentage of principal components calculated from spectra of all races and individual races. See text for abbreviations.

	Number of principal components					
Race	1	2	3	4	5	6
PA	98.56	99.76	99.95	99.98	99.99	99.99
C	97.75	99.65	99.91	99.96	99.98	99.99
SB	97.39	99.47	99.84	99.99	99.99	100.00
B	94.12	99.46	99.82	99.98	99.99	100.00
H	98.57	99.73	99.95	99.99	100.00	100.00
AR	97.89	99.57	99.89	99.97	99.99	99.99

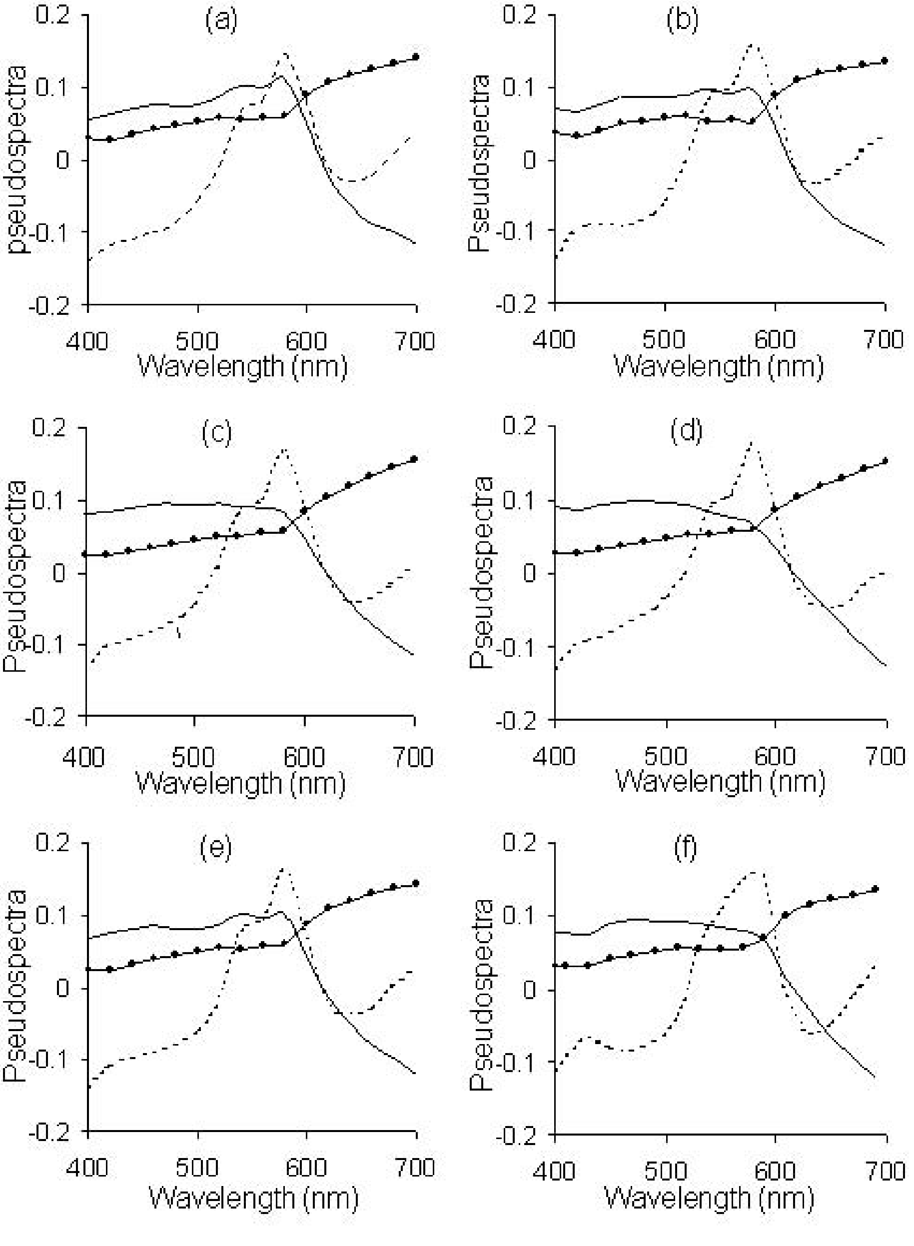

Figure 1. Graphs of the first three principal components of spectral reflectances for individual races and all races. Solid-dot line is for the 1st component, solid line for the 2nd component and dot line for the 3rd component. (a) Pacific-Asian. (b) Caucasian. (c) Subcontinental-Asian. (d) Black. (e) Hispanic. (f) All Races.

Table 2. Cumulative contribution percentage of principal components calculated from face spectra of individual parts.

	Number of principal components					
Parts	1	2	3	4	5	6
Skin	97.90	99.40	99.83	99.95	99.98	99.99
Hair	98.76	99.88	99.95	99.99	100.00	100.00
Eye	91.97	99.53	99.81	99.95	99.98	99.99
Lip	95.86	99.17	99.67	99.88	99.95	99.97

Table 3. Mean color difference in reproduction of individual races and all races using different sets of 3 principal components. The horizontal races are the spectral groups that yielded the principal components while the vertical races are the spectral groups the basis functions were applied to. See text for abbreviations.

	PA	C	SA	B	H	AR
PA	**0.45**	0.95	0.73	1.05	0.60	0.98
C	0.66	**0.65**	1.06	1.20	0.65	0.83
SA	0.77	1.30	**0.54**	0.81	0.92	1.28
B	1.00	1.52	0.68	**0.84**	1.16	1.51
H	0.47	0.76	0.73	1.07	**0.46**	0.90
AR	0.67	1.05	0.76	1.00	0.78	**1.10**

Table 4. RMS values and mean metameric indices of spectral resproduction for individual races and all races using different sets of three principal components. The horizontal races are the spectral groups yielded the principal components while the vertical races are the spectral groups the basis functions were applied to. (1) RMS values, unit of 10^{-4}; (2) Metmeric indices. See text for abbreviations.

	PA	C	SA	B	H	AR
PA	**29**	41	69	75	32	34
C	56	**38**	108	107	50	43
SA	51	55	**30**	32	48	40
B	57	58	34	**32**	54	43
H	27	32	62	69	**24**	32
AR	47	47	70	72	44	**39**

(1)

	PA	C	SA	B	H	AR
PA	**0.15**	0.29	0.38	0.46	0.21	0.26
C	0.25	**0.18**	0.51	0.52	0.23	0.19
SA	0.37	0.49	**0.24**	0.32	0.37	0.34
B	0.46	0.56	0.30	**0.34**	0.46	0.39
H	0.14	0.28	0.30	0.39	**0.18**	0.23
AR	0.28	0.35	0.37	0.43	0.29	**0.28**

(2)

Table 5. Mean color difference and indices of metamerism in reproduction of individual face parts using different sets of 3 principal components. The horizontal races are the spectral groups yielded the principal components while the vertical races are the spectral groups the basis functions were applied to. (1) Mean color differences; (2) Indices of metamerism.

	Skin	Hair	Eyes	Lips	AR
Skin	**0.64**	0.97	1.04	4.57	0.75
Hair	6.16	**0.13**	0.98	16.38	2.57
Eyes	1.20	0.40	**0.37**	2.03	0.62
Lips	1.45	0.70	1.13	**0.69**	1.13
AR	1.81	0.72	0.95	6.28	**1.10**

(1)

	Skin	Hair	Eyes	Lips	AR
Skin	**0.17**	0.82	0.23	0.90	0.18
Hair	1.95	**0.05**	0.29	4.47	0.71
Eyes	0.31	0.67	**0.12**	0.62	0.16
Lips	0.19	0.88	0.41	**0.13**	0.22
AR	0.53	0.66	0.24	1.50	**0.28**

(2)

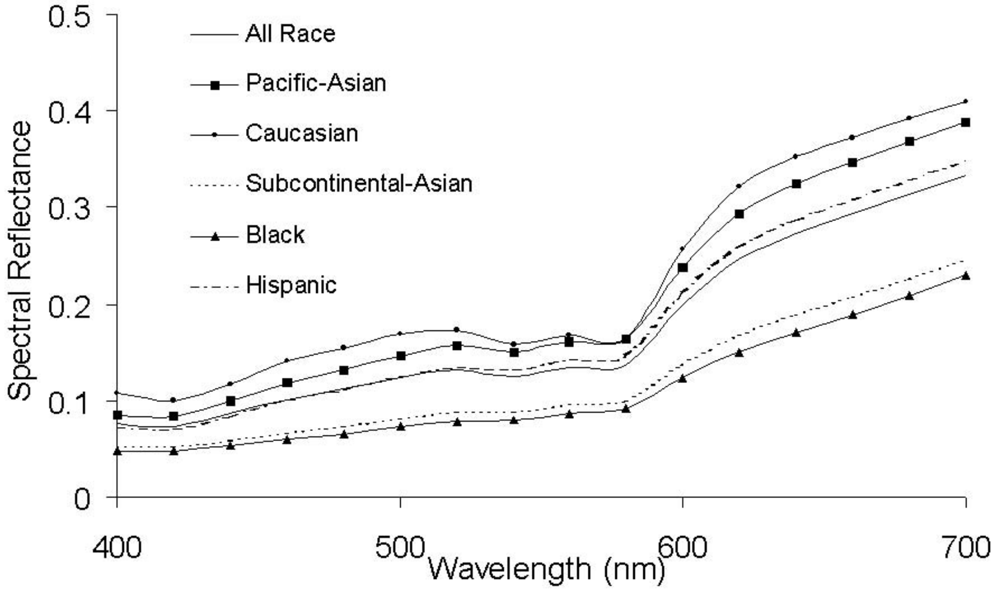

Figure 2. Mean spectral reflectances of individual races and all races.

Table 6. Cumulative contribution percentage of principal components calculated from spectra of skin spectra for individual races. See text for abbreviations.

	Number of Principal Components					
Race	1	2	3	4	5	6
PA	95.65	99.04	99.69	99.89	99.95	99.96
C	94.21	99.01	99.71	99.84	99.94	99.97
SA	97.36	99.34	99.78	99.98	99.99	99.99
B	97.77	99.60	99.92	99.98	99.99	99.99
H	96.40	99.45	99.82	99.97	99.98	99.99

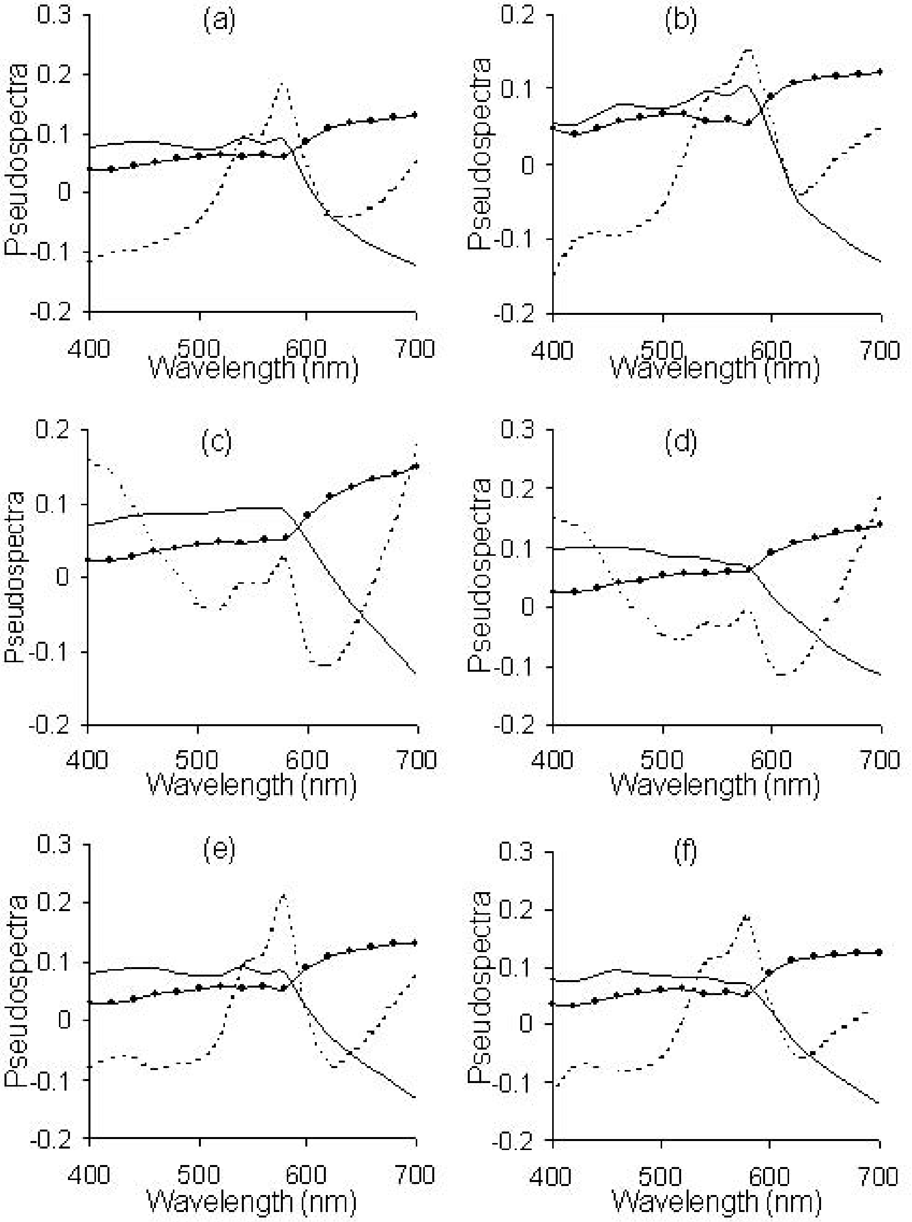

Figure 3. Graphs of the first three basis functions for spectral reflectances of facial skin of individual races and all races. Solid-dot line is for the 1st component, solid line for the 2nd component and dot line for the 3rd component. (a) Pacific-Asian. (b) Caucasian. (c) Subcontinental-Asian. (d) Black. (e) Hispanic. (f) All Races.

Table 7. Color differences and indices of metamerism in spectral reproduction of skin for individual races when using 3 and 6 basis functions based on all spectra of all races. (1) color difference; (2) indices of metamerism. See text for abbreviations. See text for abbreviations.

No.	PA	C	SA	B	H	AllSkin
3	0.53	0.67	0.83	1.17	0.53	0.75
6	0.16	0.20	0.11	0.08	0.17	0.15

(1)

No.	PA	C	SA	B	H	AllSkin
3	0.14	0.15	0.21	0.28	0.12	0.18
6	0.02	0.02	0.01	0.01	0.02	0.02

(2)

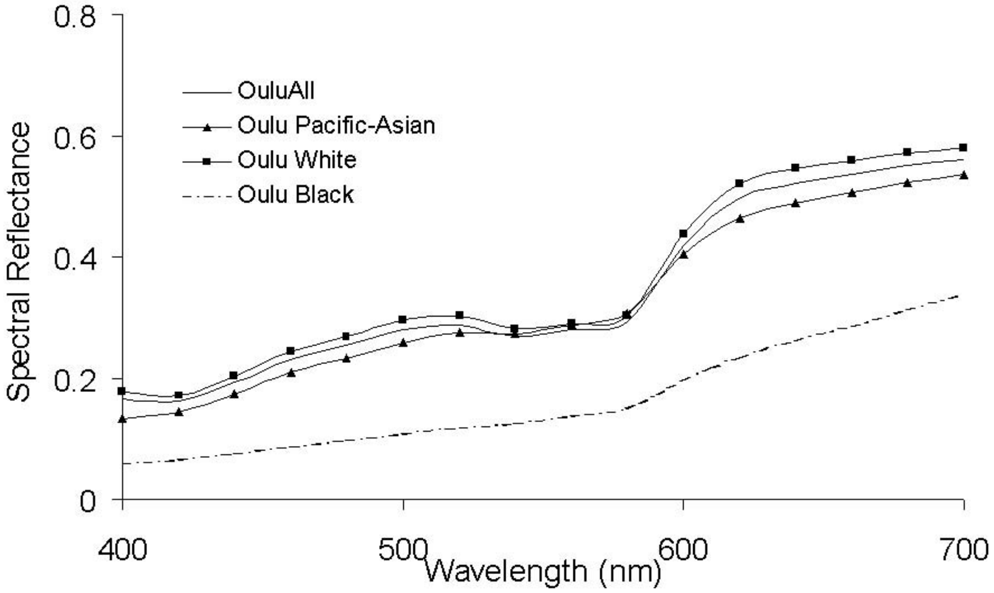

Figure 4. Mean spectra of skin for individual races in Oulu data.

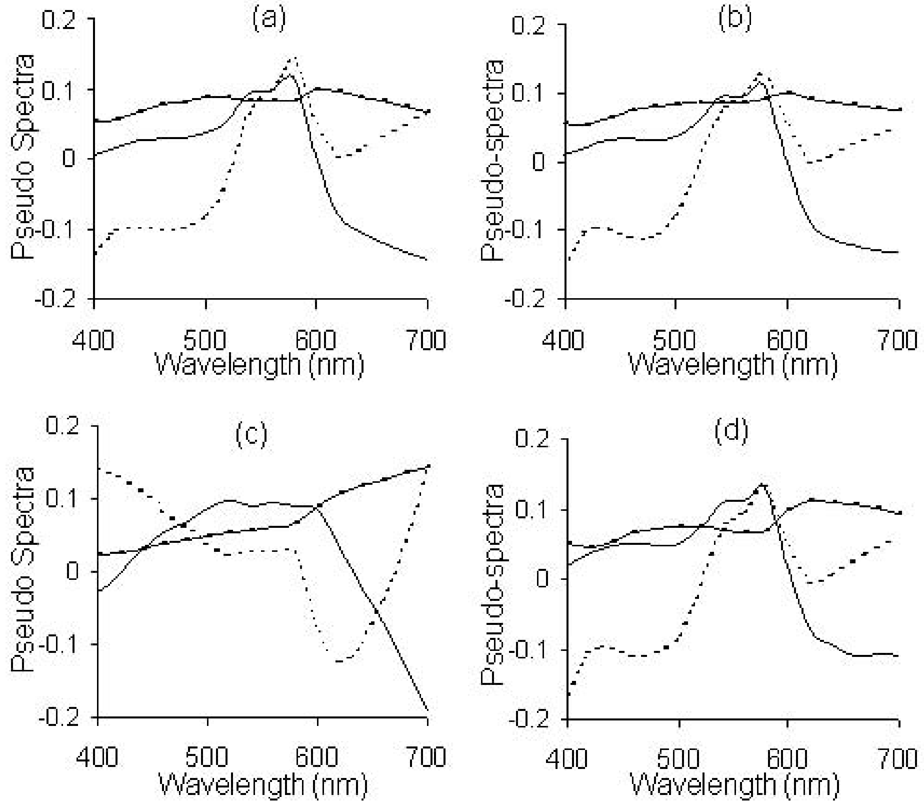

Figure 5. First three basis functions of skin spectra of individual races and all races in Oulu data. Solid-dot line is for 1st component, solid line for 2nd component and dot line for 3rd component. (a) Oulu Pacific-Asian; (b) Oulu Caucasian; (c) Oulu Black; (d) Oulu All.

Table 8. Cumulative contribution percentage of principal components calculated from spectra of skin spectra for individual races in Oulu data. PA is Pacific-Asian; C is Caucasian; B is Black; RA is all races.

	Number of Basis Functions					
Race	1	2	3	4	5	6
PA	93.42	97.52	99.27	99.71	99.91	99.97
C	82.41	95.24	98.53	99.37	99.74	99.87
B	98.30	99.71	99.87	99.97	100.00	100.00
AR	94.20	98.45	99.60	99.81	99.92	99.96

Table 9. Color differences of spectral reproduction for skin spectra of individual races and all races in Oulu data using different sets of three principal components. C is Caucasian; PA is Pacific-Asian; B is Black; All skin is all skin spectra in Oulu data.

	C	PA	B	All Skin
C	**0.42**	0.56	3.89	0.45
PA	0.48	**0.26**	1.53	0.33
B	1.51	1.08	**0.85**	0.54
All Skin	0.50	0.57	3.45	**0.44**

Table 10. Mean, maximum, minimum and standard deviation of color difference values calculated between spectral reflectances and their mean spectra in individual races. See text for abbreviations.

	mean E	Max	Min	Std
PA	5.07	12.33	1.03	2.55
C	6.48	17.48	1.15	3.31
B	6.99	18.81	1.03	4.03
SA	5.97	27.98	0.67	4.33
H	5.22	15.55	1.03	3.40
OuluPA	2.98	7.54	0.65	1.64
Oulu B	5.70	15.87	0.24	3.86
Oulu C	3.48	11.98	0.60	1.94

Table 11. Results of mean, maximum and minimum color difference values calculated from each pair of skin spectral reflectances of each subject within individual races. See text for abbreviations.

	Mean E	Max	Min
PA	6.25	17.66	0.32
C	7.05	19.59	1.56
B	8.09	27.04	0.83
SA	7.95	30.4	0.65
H	6.73	11.94	1.56
OuluPA	3.96	8.07	0.61
Oulu B	3.13	7.53	0.87
Oulu C	3.34	12.52	0.41