Statistical Evaluation of Color Components for Pupil Detection and Diameter Measurement Under Visible-light Conditions

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Abstract A variety of systems have been developed that use information on pupil diameter variation. These systems typically require a general-purpose PC or a portable terminal. In addition, a near-infrared camera and an illumination system are required to obtain pupil diameter information. However, a near-infrared camera and an appropriate illumination source are usually not installed in conventional PCs or mobile devices. If the pupil diameter can be measured using a visible-light camera equipped with a general-purpose PC or portable terminal, the aforementioned systems could become more widely used. However, it is difficult to discriminate between the iris and pupil regions in an image captured using a visible-light camera because the colors of the iris and the pupil are similar in individuals of Asian ancestry. In this study, we determine effective color components for the detection and diameter measurement of the pupil under visible light conditions based on eye images obtained using a visible-light camera. The experimental results revealed that the effective color components for the detection and diameter measurement of the pupil are the R, Y, and K color components for brown eyes and the R and C color components for hazel eyes. The suitable color components differ depending on the color of the iris.

Key words: Image processing, Visible light camera, Color specification system, Multiple comparison test

1. Introduction

The pupil diameter is controlled not only by the amount of incident light but also by the autonomic nervous system\(^1\) and varies depending on several factors, e.g., emotion, fatigue, interest, and attention\(^2\)\(^3\). A wide variety of systems using information related to pupil diameter have been developed. For example, a recommendation system in which the variation of the diameter of the pupil is used to determine human interest has been developed\(^4\)\(^5\)\(^6\).

The pupillary reaction is a time series variation of the pupil diameter. The diameter is generally measured via image processing based on an eye image acquired using a near-infrared camera. Near-infrared illumination is also required to capture the pupil. However, a general-purpose PC or portable terminal usually does not have a near-infrared camera or illumination source. If the pupil diameter can be measured by using a visible-light camera, measurement systems can be operated on a general-purpose PC or portable terminal. Other systems that use the information of pupil diameter, e.g., gaze tracking, emotional estimation, evaluation of autonomic nerves, etc., can also be operated via a PC or portable terminal without the need for near-infrared image acquisition or illumination.

In the case of blue or green iris, it is relatively easy to detect the pupil region in an eye image that is acquired using a visible-light camera because the pupil color is distinctly different from that of the iris. Pupil detection methods using edge detection with the Canny operator and the circular Hough transform have been proposed\(^7\)\(^8\). In these methods, a color eye image is first converted to a grayscale image. Subsequently, the pupil diameter in the grayscale image is measured using edge detection with the Canny operator and the Hough transform. However, it is difficult to discriminate between the iris and pupil regions in the eye images of individuals of Asian ancestry that are acquired using visible-light cameras. This is because the iris of these individuals is dark brown and the pupil has a similar color. Thus, the grayscale conversion requires suitable color components that can facilitate discrimination of the pupil portion from the iris region. For the generalization of a system using information related to pupil diameter variation, we investigated the effective color
component for detection and diameter measurement of the pupil under visible-light conditions. In the evaluation experiment, we used images of brown eyes for individuals of Japanese descent. Hazel eye images with light brown and dark green irises were also used to determine whether the suitable color components required for grayscale conversion were the same as those required for brown irises. The hazel eye images used in the experiments were selected from the UBIRIS database that is generally used to evaluate iris recognition algorithms\(^9\). The major contribution of this paper is the evaluation of the effective color components used in image processing for pupil detection and pupil diameter measurement for images of dark brown irises.

This paper is organized into several sections. In section 2, the method for pupil detection and pupil diameter measurement is presented. Section 3 describes the experimental method to investigate the effective color component for pupil detection and pupil diameter measurement under a visible light environment. Section 4 presents the experimental results. The experimental results are discussed in Section 5. Finally, the main conclusions are presented in Section 6.

### 2. Pupil Detection Method

In this section, we describe the method for pupil detection and pupil diameter measurement based on eye images acquired using a visible-light camera. The presented approach is almost the same as that used in a previous study described in Section 1\(^7\)\(^8\). In this study, we used a conventional pupil detection method because the main purpose of this investigation is to evaluate the effective color components for pupil detection of the dark brown eyes. The flowchart for pupil detection and pupil diameter measurement is shown in Fig.1. A captured color image of the eye is first converted to a grayscale image using only the blue component for iris detection. Edge detection is then performed using the Canny operator. The edge intensity of the boundary between the iris and pupil is increased when the blue component of the eye image is used. The blue component is used for grayscale conversion because the brightness of the iris region in the grayscale image generated using the red component is the highest. This is because red is the most prominent color component of the iris region for individuals of Japanese descent. The sclera region includes red, green, and blue components in equal proportions, and the brightness value in the sclera region is very high. Thus, the edge intensity of the boundary between the iris and sclera that is obtained for grayscale conversion using the red component is relatively small. However, grayscale conversion using the blue component results in a large edge intensity in the boundary between the iris and sclera because the blue component in the iris region is the lowest.

Next, the iris region is detected using the circular Hough transform based on the detected edge points as candidature points of the iris contour. A square image that includes the iris and pupil is then extracted based on the center position of the detected iris. The size of the square image is equal to 80% of the iris diameter. The eye and extracted iris images are shown in Fig.2. White-tinged corneal reflections are observed in the region of the pupil and iris in this image. Corneal

![Fig. 1](flowchart.png)  
**Flowchart for pupil detection.**

![Fig. 2](image.png)  
(a) Eye image used in the experiment and (b) the extracted iris image.
reflections cover the portion of pupil region.

In the pupil detection process, the grayscale conversion is performed using any one of R, G, B, H, S, V, C, M, Y, and K color components. The H, S, and V color components represent the hue, saturation, and value in HSV color space, respectively. The C, M, Y, and K color components are cyan, magenta, yellow, and black components in CMYK, respectively\(^{10}\)–\(^{12}\). These color components are obtained from Eqs. (1) to (7). In the experiment, the weighted grayscale conversion with R, G, and B color components represented in Eq. (8) is used for comparison with the common grayscale conversion. After grayscale conversion, edge detection was performed using the Canny operator. Finally, the pupil contour is detected using the circular Hough transform based on the edge pixels obtained as candidature of the pupil contour. After the pupil is detected, the diameter of the circle that outlines the contour of the pupil is defined as the pupil diameter. In addition, the center position of the circle is defined as the center position of the pupil.

The shape of the iris and pupil is elliptical in the image because the gaze direction deviates from the optical axis of the camera. If the experiment is conducted under the condition that the gaze direction is oblique towards the camera, it is difficult to determine whether the accuracy of pupil detection and pupil diameter measurement is influenced by the selected color component for grayscale conversion or the distortion of the pupil’s shape. Thus, the experiment results presented in this report was obtained under the condition that the subject was facing the front of the camera, and the circular Hough transform was utilized for pupil contour estimation.

\[
l_{\text{max}} = \max\{R, G, B\} \\
l_{\text{min}} = \min\{R, G, B\} \\
V = l_{\text{max}} \\
S = \begin{cases} 
l_{\text{max}} - l_{\text{min}} & \text{if } V \neq 0 \\ 0 & \text{otherwise} \end{cases} \\
H = \begin{cases} 
\frac{G - B}{l_{\text{max}} - l_{\text{min}}} \times 60 & \text{if } V = R \\
\frac{B - R}{l_{\text{max}} - l_{\text{min}}} \times 60 + 120 & \text{if } V = G \\
\frac{R - G}{l_{\text{max}} - l_{\text{min}}} \times 60 + 240 & \text{if } V = B \\
\end{cases} \\
K = \min\{255 - R, 255 - G, 255 - B\} \tag{4} \\
\]

\[
C = \frac{255 - R - K}{255 - K} \tag{5} \\
M = \frac{255 - G - K}{255 - K} \tag{6} \\
Y = \frac{255 - B - K}{255 - K} \tag{7} \\
\]

\[
Y_G = 0.299R + 0.587G + 0.114B \tag{8} \\
\]

3. Experimental Method

To investigate the effective color component for pupil detection, two kinds of eye image databases were used in the experiment. One is the dataset of brown eye images for individuals of Japanese descent. The other consists of hazel eye images selected from the UBIRIS database. In this section, the eye image databases and the evaluation method are described.

3.1 Image Acquisition of Brown Eyes

The eye images were acquired using a visible-light digital camera (Lw115-10, Argo). Partitions were used to surround the experimental setup and the illumination sources were white fluorescent lamps installed on the ceiling. The brightness around the eye of the subject was 240 ± 7.0 [lx]. Twelve students (8 males, 4 females), ages of 21 to 24, participated in the experiment. The camera was set in front of the subject at a separation distance of 34 [cm]. The subject’s head was fixed using a chin support device during the acquisition of an eye image. Prior to commencing the experiment, the subjects were instructed to gaze at the camera lens. No instruction to keep their eyes wide open or not blink was given. These experiments were approved by the Ethics Committee of Toyama Prefectural University. In addition, written informed consent was obtained from each participant.

In this experiment, 47 eye images were obtained from 12 subjects. The size of the eye images was 1240 × 1024 [pixels]. The pupil detection method represents in this paper involved the use of a general-purpose PC with a web camera. The size of images used in this investigation was determined based on the maximum resolution of the most recent web cameras, e.g. Logitech C925e\(^{13}\) and LifeCam Studio\(^{14}\). Examples of images are shown in Fig.3. From Fig.3, the iris color is very similar to that of the pupil. Corneal reflection is observed around the iris and pupil regions in these eye images.

3.2 Image Database of Hazel Eyes

To investigate the effective color components for
3.3 Evaluation Method

The center position and diameter of the pupil obtained using the method explained in Section 2 were evaluated by a comparison with their true values. The true values were obtained by manually fitting a circle to the pupil region of the eye image. The fitting process was conducted three times for each eye image and the average of the pupil position and its diameter were provided as their true values.

In the evaluation of the measured pupil center position, the Euclidean distance \(E_c\) [pixels] shown in Eq.(9) was employed. In Eq.(9), \(x_{cc}\) and \(y_{cc}\) represent the \(x\) and \(y\) coordinate values of the measured pupil center position, respectively. The \(x_{ac}\) and \(y_{ac}\) represent the true values of the \(x\) and \(y\) coordinates of pupil center position, respectively.

\[
E_c = \sqrt{(x_{cc} - x_{ac})^2 + (y_{cc} - y_{ac})^2} \quad (9)
\]

The difference \(E_{pd}\) [pixels] shown in Eq.(10) is used in the evaluation of the measured pupil diameter. In Eq.(10), \(D_{mv}\) and \(D_{ac}\) represent the measured and true values of the pupil diameter, respectively.

\[
E_{pd} = D_{mv} - D_{ac} \quad (10)
\]

Finally, the units of \(E_c\) and \(E_{pd}\) in [pixels] are changed into the unit of [mm] in the following process. Firstly, a ruler image is acquired using the visible-light camera. The distance between the camera and the ruler is maintained at 34 [cm], which is the same as the distance between the camera and the subject. The number of pixels per unit scale length of 1 [mm] of the ruler image was then counted manually. In the result, the unit length of 1 [mm] in the image corresponds to 34 [pixels]. As such, one pixel in the image acquired using the camera is equal to 1/34 [mm]. Using this relationship, the units of \(E_c\) and \(E_{pd}\) were changed to [mm]. In the evaluation experiments for detection and measurement of the pupil, the \(E_c\) and \(E_{pd}\) were obtained with an accuracy of 1/34 [mm]. The pupil diameter measurement in the millimeter unit is required when the information regarding the pupil diameter variation is used for the estimation of emotion and interest.

4. Experimental Results

The \(E_c\) and the absolute value of \(E_{pd}\) are used in the evaluation of the detection and measurement of the diameter of the pupil. The pupil center position and diameter for all the images used in the experiments were obtained using the circular Hough transform. The effective color component of the grayscale conversion was obtained by conducting the Tukey’s multiple comparison test for \(E_c\) and \(|E_{pd}|\). The results of the evaluation experiments with brown and hazel eye images are shown in this section.

4.1 Results with Brown Eye Images

The experimental results for the brown eyes are shown in Figs.4 and 5. The average values and the standard deviations for the difference of the pupil center position are shown in Fig.4. The average values and the standard deviations for the absolute difference of the pupil diameter are shown in Fig.5. In Figs.4 and 5, the vertical axes represent the \(E_c\) [mm] and \(|E_{pd}|\) [mm] and the horizontal axes represent the color components. “YG” represents the results of the weighted grayscale conversion using Eq.(8). In addition, the results for the Tukey’s multiple comparison test are shown in Tables 1 and 2.

From Fig.4 and Table 1, the differences of pupil center position obtained using the R, Y, or K component are significantly smaller than those of other color components. The average difference of the pupil center position with the R, Y, or K component was less than 0.3 [mm]. In addition, the standard deviation of \(E_c\) with the R, Y, or K component was smaller than that of the other color components.

The experimental results for Fig.5 and Table 2 indicate that the averages of \(|E_{pd}|\) with the R, Y, and K components are 0.22, 0.20, and 0.22 [mm], respectively. The standard deviation of \(|E_{pd}|\) for the R, Y, and K components is smaller than that of the other color com-
components. The average of $E_c$ and $|E_{pd}|$ with the R, Y, and K components is also smaller than that of the $Y_G$ component used for the common grayscale conversion. These results indicate that the R, Y and K components are effective for separation of the pupil region from the brown iris region under the visible-light conditions.

4.2 Results with Hazel Eye Images

The experimental results for hazel eyes are shown in Figs. 6 and 7. The average and standard deviation of the difference of the pupil center position are shown in Fig. 6. The average and standard deviation of the absolute difference of the pupil diameter are shown in Fig. 7. In Figs. 6 and 7, the vertical axes represent the $E_c$ [mm] and $|E_{pd}|$ [mm] and the horizontal axes represent the color components. In addition, the results of the Tukey’s multiple comparison test are shown in Tables 3 and 4. From Fig. 6 and Table 3, the difference of pupil center position obtained with R or C component is significantly smaller than that obtained using the other color components. The average difference of the pupil center position using the R or C component is less than 0.11 [mm]. In addition, the standard deviation of $E_c$ obtained using the R or C component is significantly smaller than that of the other color components.

The experimental results for Fig. 7 and Table 4 show that the averages of $|E_{pd}|$ with the C or Y component are 0.15 and 0.19 [mm], respectively. The average of $|E_{pd}|$ with the R component is relatively small and 0.25
Table 3 Result of Tukey’s multiple comparison test for $E_p$ (hazel eye).

|   | R | G | B | H | S | V | C | M | Y | K | $Y_G$ |
|---|---|---|---|---|---|---|---|---|---|---|-------|
| R | – | *** | *** | *** | *** |   |   |   |   |   |       |
| G | – | ** | *** |   | ** |   |   |   |   |   |       |
| B | – | – | * | * | *** |   | ** |   |   |   |       |
| H | – | – | – | ** | *** | *** | *** | *** | *** |   |       |
| S | – | – | – | – | – | – | – | – | – | – |       |
| V | – | – | – | – | – | – | – | – | – | – |       |
| Y | – | – | – | – | – | – | – | – | – | – |       |
| K | – | – | – | – | – | – | – | – | – | – |       |

*: $p < 0.05$,  **: $p < 0.01$,  ***: $p < 0.001$

Table 4 Result of Tukey’s multiple comparison test for $|E_{pd}|$ (hazel eye).

|   | R | G | B | H | S | V | C | M | Y | K | $Y_G$ |
|---|---|---|---|---|---|---|---|---|---|---|-------|
| R | – | ** | *** | *** |   |   |   |   |   |   |       |
| G | – | *** |   | * |   |   |   |   |   |   |       |
| B | – | – | ** | * | *** | *** | *** | ** | ** |   |       |
| H | – | – | – | ** | *** | *** | *** | *** | *** | *** |       |
| S | – | – | – | – | – | – | ** | * | * | * |       |
| V | – | – | – | – | – | – | – | – | – | – |       |
| Y | – | – | – | – | – | – | – | – | – | – |       |
| K | – | – | – | – | – | – | – | – | – | – |       |

*: $p < 0.05$,  **: $p < 0.01$,  ***: $p < 0.001$

Result of Tukey’s multiple comparison test for $E_p$ (hazel eye).

Result of Tukey’s multiple comparison test for $|E_{pd}|$ (hazel eye).

Fig. 8 Example of a brown eye image and grayscale images generated by R, Y, and K components.

By adopting the grayscale conversion with any one of the R, Y, or K color component, the accuracy of the pupil diameter measurement for brown eyes drastically increased compared with that of the weighted grayscale conversion with R, G, and B color components. The grayscale images with R, Y, or K color component are shown in Fig. 8. The boundary between the iris and pupil region can be observed in these eye images. It is considered that the spectral distribution of room illumination is related to the increase of the accuracy for pupil diameter measurement using the grayscale conversion with the R or Y color component. Three-wavelength white fluorescent lamps were available in the laboratory. These fluorescent lamps used for room illumination have spectral peaks at approximately 570 [nm] and 620 [nm]. These wavelengths represent the colors yellow-green and red, respectively. This experimental condition is equivalent to image acquisition under yellow-green and red illumination. Thus, the brightness difference between the pupil and iris regions increases after grayscale conversion using the R or Y color component. The increase of this brightness difference provides an improvement of performance for pupil detection and pupil diameter measurement. However, the effective color component changes depending on the ambient lighting condition. To adjust the variation of the lighting condition, the grayscale conversion in combination with multiple color components is required. The pupil detection process using the grayscale image converted using the Y component is shown in Fig.9. Figure 9 (a), (b), (c), and (d) show the extracted iris image, the grayscale image obtained using the Y component, the image obtained using the Canny operator, and the pupil detection result, respectively. In Fig.9 (a), corneal reflection is observed around the pupil’s contour. Figure 9 (c) shows that the edge of the pupil’s contour partially disappears due to corneal reflection. However, the pupil contour is accurately detected despite the contamination caused by the corneal reflections.

For hazel eyes, the R and C color components are suitable for grayscale conversion of the pupil diameter measurement. The performance of the pupil diameter measurement for brown eyes using the C color component is relatively low although the grayscale conver-
The experiments described in this report were conducted under constrained conditions that are different from the actual environment. The eye images used in the experiment were obtained from images captured in front of the subjects. The corneal reflection and undesirable effects due to the eyelids and eyelashes were not significant in the eye images. Furthermore, the resolution of the images used in the experiment was higher than that obtained in an actual environment. Thus, the accuracy for pupil detection and pupil diameter measurement was obtained under these constrained conditions. To apply the pupil detection method to an actual environment, these issues are considered as follows.

Firstly, the subjects rarely glance at the camera in the real-world. Under this condition, the shape of the iris and pupil of the eye images are almost elliptical instead of circular. Thus, pupil contour detection via elliptical fitting is required in the actual environment. Next, the performance of pupil detection decreases due to corneal reflection and occlusion by the eyelids and eyelashes. Some of the eye images used in the experiment exhibited corneal reflection or eyelash contamination. Unfortunately, the experimental results shown in this report are insufficient to evaluate the performance of pupil detection and pupil diameter measurement relative to the degree of contamination by corneal reflection, the eyelids, or the eyelashes. In the future, the accuracy of the pupil detection and the pupil diameter measurement with respect to the degree of contamination should be investigated by controlling the capturing conditions. In addition, high-resolution eye images are not always obtained in the actual environment. The resolution of the eye images required for pupil detection and pupil diameter measurement also needs to be established. Moreover, the processing time for pupil detection needs to be considered. The total processing time for the pupil detection and the pupil diameter measurement in this study was approximately 253 [ms]. A conventional eye tracker measures the pupil diameter at 30 or 60 [fps], i.e. 1/30 or 1/60 [s] per frame. Recently, a fast pupil detection method using a near-infrared camera was proposed\textsuperscript{15,16}. Considering the practical application of pupil detection, the fast pupil detection method should be adopted.

6. Conclusions

In this study, we investigated the effective color components for pupil detection under visible-light conditions. Each color component of the RGB, HSV, and CMYK color spaces was used in the experiment. The experimental results for brown eyes show that the average values for the difference of the pupil center position using any of the R, Y, or K component is sufficiently small. For hazel eyes, grayscale conversion with either R or C color component provides high accuracy for pupil diameter measurement. For pupil diameter measurement under visible-light conditions, the effective color component for grayscale conversion should be adaptively changed depending on the iris color. Grayscale conversion using a suitable color component depending on the iris color facilitates high accuracy of pupil detection and pupil diameter measurement. In future works, we plan to develop a grayscale conversion method that is adaptive to the iris color. We will also investigate the performance of the detection and measurement of the pupil by developing a grayscale conversion that incorporates multiple color components. In addition, the performance of pupil de-
tection and pupil diameter measurement will be evaluated in actual environments.

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