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Gaze-Contingent Visual Presentation Based on Remote Saccade Detection

Abstract

Pursuing new display techniques based on insights into human visual perception can reveal new possibilities for visual information devices. Here, we propose a novel information presentation technique that exploits the perceptional features during rapid eye movements called saccades by using a fast remote eye-measuring method. When light sources are fixed on a vertical line, and the flashing pattern is changed quickly during a horizontal saccade, 2D images can be perceived due to spatio-temporal integration in the human vision system. We use this phenomenon to present 2D images with only one-dimensional light sources, and to show these images even in midair. The flashing cycle and flash timing of light sources are important elements in developing the design theory for this display technique. The flashing cycle determines the maximum resolution of a perceived 2D image. The flash timing is a crucial issue for our purpose because 2D images are perceived only when the timing of the saccade coincides with the flash timing. Therefore, in this paper, we describe the relationship between a flashing cycle and the maximum resolution of a perceived 2D image, and then propose a concise saccade detection method. By using this method, saccades can be detected and the light sources can be flashed within the saccade interval as it occurs in real time, and 2D images can be successfully presented.

1 Introduction

The display of 2D images is fundamental to nearly all forms of visual presentation, and pursuing display techniques based on insights into human visual perception may reveal many new possibilities. In this paper, we propose a visual information display that can effectively present 2D images with only a 1D light source by remotely detecting a viewer's saccadic eye movements.

When a vertical line of light sources flashes quickly in a temporal pattern during a horizontal saccadic eye movement, 2D images can be perceived because of the spatio-temporal integration of the human visual system. The flashing pattern is expanded into a spatial pattern by the eye movement as represented in Figure 1(a). During eye movement, the vertical light array travels on the retina while changing the flashing pattern. Then, the different vertical images at different retinal locations are integrated into a 2D image. This phenomenon has been used for artistic expressions and entertainment tools. For

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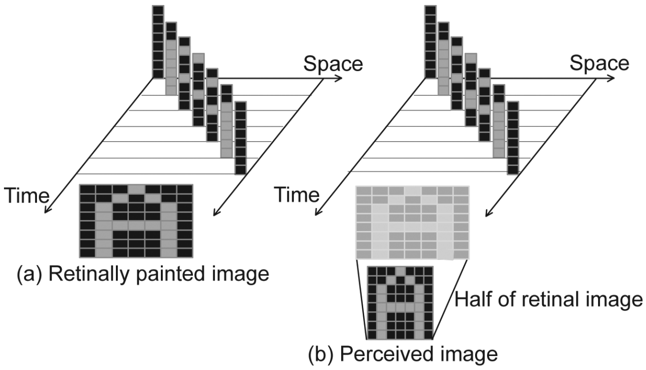

Figure 1. *Representation of the moving light array in space-time coordinates. The horizontal axis is space, and the vertical axis is time. During a saccadic eye movement, the vertical light array travels on the retina while the flashing pattern changes. The different vertical images at different retinal positions are integrated into a 2D image (projection to the space axis in space-time coordinates). (a) Retinally painted image, (b) Perceived image.*

Figure 2. *Example of displaying 2D images using 1D light sources and viewers' eye movements (conceptual image).*

example, Exploratorium displays an artwork "Light Stick" based on this phenomenon by the artist Bill Bell (Exploratorium, 1993). Rave parties such as "Burning Man" (Burning Man Project, 1989) and the Media performance group "cell/66b" (Watanabe et al., 2004) employ this phenomenon as a visual effect.

In addition, when we consider this phenomenon as a visual information display principle, it thus enables presenting 2D images with only 1D light sources, and showing images even in midair in a dim environment (see Figure 2). These features can be applied to an augmented reality visual display that can superimpose various types of information onto real environments, to the field of entertainment, and to light devices for commercial advertising. However, a feature of this phenomenon is that if the timing of the saccade does not coincide with the flash timing of the light source, only 1D light will be perceived, instead of a 2D image. This point is crucial when we use this phenomenon as a visual information display principle. Here, we propose a novel information presentation technique achieved by combining the saccade-contingent phenomenon with a remote and fast eye-measuring method. Saccades can be detected and the light sources can be flickered within the saccade interval as it occurs in real time, and then 2D images can be successfully presented. Moreover, if we can detect where the saccade is made, we can selectively present different 2D images to different viewers using only one light array.

We discuss the design theory of saccade-contingent visual display in Section 2 and our remote saccade detection method in Section 3. The novel aspect brought up in our study is the concept of timing the display to saccades as our eye tracking method remotely detects them. Although the saccade-contingent phenomenon and remote eye measuring methods may be previously known and partly established, pursuing the possibility of the visual display technique studied in this paper should be fruitful for investigating new possibilities for designing visual information display devices.

2 Design Theory of Saccade-Contingent Display

2.1 Features of the Perisaccadically Presented Image

When the described phenomenon is employed as a basis for a visual display principle, investigating the perceptual features of perisaccadically presented images is important. Previous studies have reported that while the eye is moving, the visual system becomes blind. Various aspects of sensitivity loss occur around the time of the saccade (Latour, 1962; Volkmann, Schick, & Riggs, 1968; Zuber & Stark, 1966). Thus, the images presented during saccades can be suppressed. Some studies, however, showed that sensitivity to images with high contrast and high spatial frequency is not suppressed (Burr, Morrone, & Ross, 1994; Uchikawa & Sato, 1995). Actually, 2D images generated with a high luminance LED (light emitting diode) can be observed, as long as environmental light is dim (that is to say in high contrast to the light source). For example, when flashing patterns are presented with vertically arranged LEDs in dim light (around 50 lx) and the usual saccades occur (10–20° in amplitude), images 50 pixels in width can be perceived. People, even naïve viewers, can recognize 3–5 characters in one saccade eye movement.

One interesting feature of the perceived image that has been reported is that when a light stimulus is presented through a saccade, the width of the perceived image is only half of the retinal image, the width of which is saccade amplitude, as in Figure 1(b) (Hershberger, 1987; Hershberger & Jordan, 1992; Jordan & Hershberger, 1994; Hershberger, Jordan, & Lucas, 1998; Sogo & Osaka, 2001; Noritake, Kanzai, Terao, & Yagi, 2005; Watanabe, Maeda, & Tachi, 2005a; Watanabe, Noritake, Maeda, Tachi, & Nishida, 2005b). When 20° saccades occur, images 10° in width can be perceived. This indicates that the perceived 2D images are not just the result from a retinally bleached afterimage, but are instead the result of spatio-temporal information processing in the visual stream. (See the details of the perceptional features of spatio-temporal integration in the paper by Watanabe et al., 2005b).

2.2 Maximum Resolution of the Image

When a vertical light array flashes and a horizontal saccade occurs, the vertical resolution of the perceived image coincides with the number of vertically arranged light sources. On the other hand, the horizontal resolution of the perceived image can be determined by the flashing cycle of the light source. Here, we discuss the relationship between the flashing cycle of the light array and the maximum resolution of the perceived 2D.

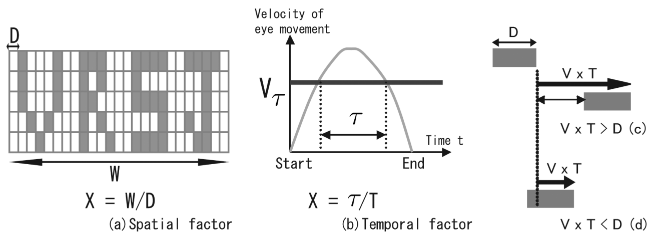

Figure 3. *Definition of the maximum resolution by (a) spatial factors and (b) temporal factors. (c, d) D is the width of light source, and V is the velocity of the eye movement. Light source travels V × T on the retina during one flashing cycle. If V × T is larger than D (c), we can present 2D images properly. If V × T is smaller than D (d), the image presented at time t overlaps the images at time t + T.*

The maximum resolution of the perceived image can be described by spatial or temporal factors as in Figure 3(a) or 3(b). The maximum resolution described as X in the figure, can be defined as $X = W/D$ (W is the expanded width of image on the retina; D is the width of the light source) or $X = \tau/T$ (τ is the time of information presentation during a saccade; T is the flashing cycle). When we define X based on the spatial factors as in Figure 3(a), the flashing cycle of a light source has to be changed during the saccade according to the position of the light source on the retina, because the velocity of the eye movements change over time during a saccade. Therefore, to achieve the maximum resolution as $X = W/D$ is difficult. Consequently, we consider the maximum resolution based on temporal factors ($X = \tau/T$) as in Figure 3(b). We can present 2D images properly only when the velocity of eye movement exceeds a threshold $V\tau$, and $V\tau$ can be calculated by the width of light source D and the flashing cycle T. We assume that, if the flashing cycle is T, the light source is turned on for very a short moment and is turned off for T. The light source moves $V \times T$ on the retina during one flashing cycle (V is the velocity of eye movement). If $V \times T$ is larger than D as in Figure 3(c), we can present 2D images properly. If $V \times T$ is, however, smaller than D as in Figure 3(d), the image presented at time t overlaps the image at time $t + T$. Therefore, to present each pixel of an image without

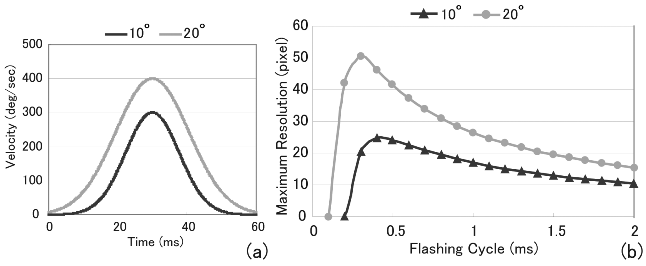

Figure 4. *(a) Assumed velocity of eye movement (normal distribution). (b) Simulation of maximum resolution according to flashing cycle.*

overlapping, $V \times T$ must be larger than D, and the threshold $V\tau$ can be calculated by $D = V\tau \times T$. In summary, the maximum resolution X is calculated by $X = \tau/T$, τ is determined by $V\tau$, and $V\tau = D/T$. If the width of light source D and time course of the velocity of eye movement are known, X can be a function of T.

For example, assuming that the width of light source D is 0.1° in visual angle (corresponding to the width when one sees a light source 5 mm in width from the distance of 3 m), 10 and 20° saccades, and the time courses of velocity are as shown in Figure 4(a), we can simulate the maximum resolution X corresponding to the flashing cycle T. The results of such a simulation are shown in Figure 4(b). The horizontal axis represents flashing cycle T (ms) and the vertical axis represents X (pixels). When 10° saccades occur, 24.7 pixels can be presented with at most a 0.4 ms flashing cycle. When 20° saccades occur, 50.4 pixels can be presented with a 0.3 ms flashing cycle. Therefore, one pixel for these maximum resolutions can be perceived at about 0.2° in visual angle in both conditions, and this pixel width is sufficient for viewers with normal visual acuity to perceive. Actually, we confirmed in our observation that images with these resolutions could be perceived in the described conditions.

3 Design Theory of Real-Time Remote Saccade Detection

The flash timing of the light source is essential for successfully presenting visual information based on the saccade-contingent phenomenon, because 2D images can be perceived only when the timing of the saccade coincides with the flash timing of the light source. As described above, we detect a viewer's saccade as it occurs in real time, and then, a single light array is flickered immediately after detecting the viewer's saccades for effective information presentation. In vision science experiments, presenting stimuli triggered by saccadic eye movements has been achieved, and a saccade-contingent presentation was accomplished in a virtual reality study (Triesch, Sullivan, Hayhoe, & Ballard, 2002). However, they used a limbus eye tracking technique. Although eye tracking performed remotely and without viewer constraints is preferable for our presentation principle, the viewers were forced to attach sensors to their heads and their heads were fixed on a chinrest.

Most previous techniques for remotely measuring eye movement used a video camera and infrared LEDs. The camera captured high-resolution images around the iris to measure eye movements with high accuracy. However, the frame rate in previous studies (such as Ohno, Mukawa, & Yoshikawa, 2002) with normal high resolution cameras was about 60 Hz, or roughly 16 ms per frame. This is not fast enough to accurately detect a saccade because its maximum velocity is more than 700°/s and its duration is less than 50 ms.

Recently, a few fast remote eye tracking systems, such as R-HS-S6 by Applied Science Laboratory, have been developed (Applied Science Laboratories, 2006). However, they are very expensive and require large scale equipment. Considering our purpose, the simpler method of fast and single horizontal line scanning, instead of 2D scanning, is sufficient because detection of saccades, not measuring eye position, is required. Moreover, only horizontal saccades with large amplitudes and high frequencies are useful for our visual presentation technique. Therefore, to achieve visual presentation using our method based on a saccade-contingent phenomenon, we propose a concise and economical saccade detection method based on a fast pupil detection technique.

3.1 Principle of Proposed Method

Recently, a number of fast and robust pupil detection techniques have been proposed (Ebisawa, 1995; Ebisawa, 1998; Morimoto, Koons, Amir, & Flickner, 2000; Ji & Yang, 2001; Nguyen, Wagner, Koons, & Flickner, 2002). The basic principle is as follows. As in Figure 5(a), two light sources (one is on the optical axis of a camera, the other is off the axis) generate an image with a bright pupil and an image with a dark pupil (Young & Sheena, 1975; Hutchinson, White, Reichert, & Frey, 1989). By subtracting the level of brightness in each position of the two images, we can localize the positions of the pupils due to the brightness difference in the pupils. In addition to that, even when the eye gaze is not directed toward the camera, the bright pupil can be observed, as is described in the following experiment. Therefore, the eye movements can be detected by measuring the displacement of pupil position as in Figure 5(b). However, as mentioned above, this subtraction technique was performed by using an ordinary camera that provides good accuracy but provides poor temporal resolution. Therefore, detecting saccades with high temporal resolution is not possible.

Consequently, we propose a concise way of detecting saccades remotely based on the subtraction technique. We capture a horizontal line image around a viewer's pupil with high temporal resolution, and then measure the pupil position and its velocity. When the velocity exceeds a certain threshold, the onset of a saccade can be detected. Immediately after detecting the saccade onset, a light source starts to flicker to present 2D images.

Figure 5(c) shows the arrangement of the proposed method. The arrangement is composed of infrared LEDs, a half mirror, and a camera. LEDs for obtaining an image of a bright pupil are placed on the optical axis. LEDs for the dark pupil are placed relatively far from the optical axis. The flash is synchronized with the camera's frame rate. Pupil positions are acquired by subtracting the level of brightness in each position of the captured images. We used a partial scan camera that can change the spatial resolution and frame rate, but with a spatio-temporal tradeoff. When we detect a viewer's

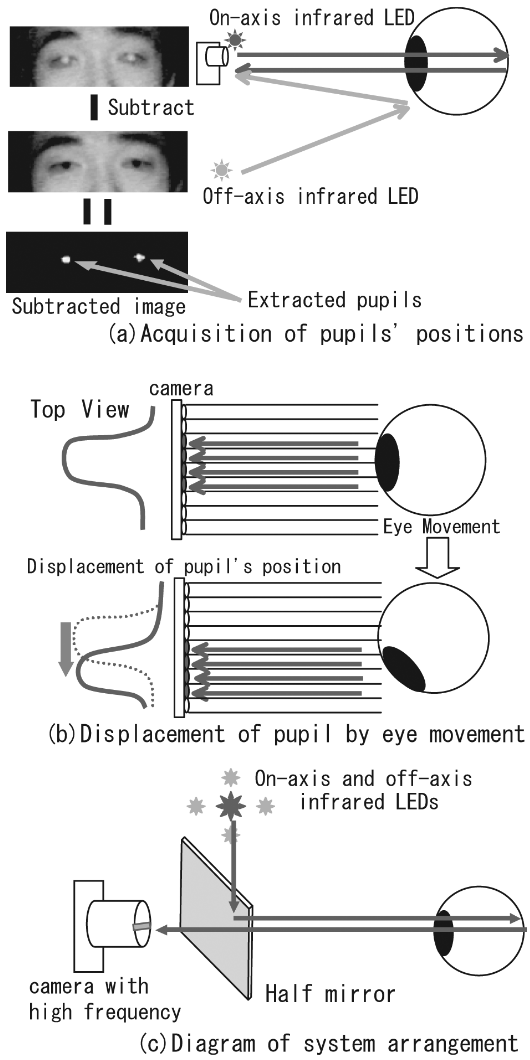

Figure 5. *Diagrams of (a) acquisition of pupil's position, (b) observation of displacement by eye movement, (c) diagrams of system arrangement.*

saccades, first of all, the pupil position must be localized. Therefore, we first use the camera to capture 2D images with normal temporal resolution to specify the pupil positions before scanning a line image around the eye. This first procedure follows the same strategy as in the subtraction technique presented in previous work by Morimoto et al. (2000). Then, the camera performs 1D fast scanning around the eye and the image is processed for detecting saccades.

In summary, remote pupil detection techniques have

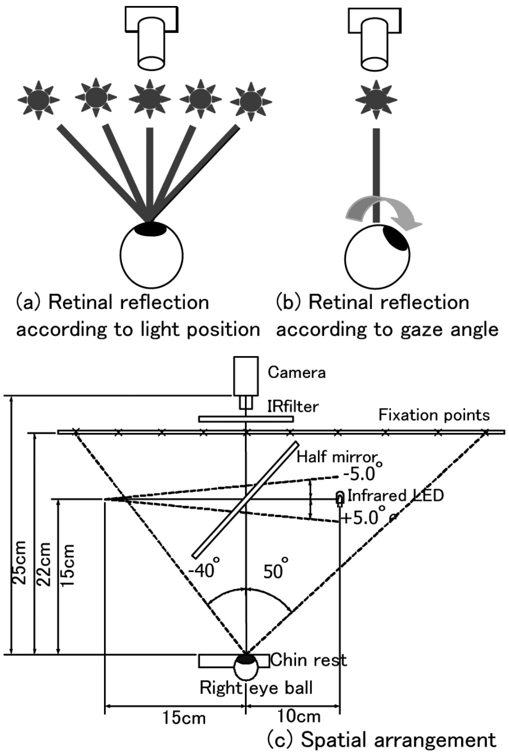

Figure 6. *(a) Diagram of retinal reflection according to light source position. (b) Diagram of retinal reflection according to gaze angle. (c) Spatial arrangement of experiment.*

been developed. However, the frame rates of the cameras they were using were not fast enough to detect saccades in real time. Therefore, we used horizontal line images with a high temporal frequency. The fast pupil detection technique and 1D measurement specific to our purpose accomplishes this real-time saccade detection.

3.2 Retinal Retroreflective Feature

To develop our technique, we had to investigate the retroreflective feature of the retina, specifically the relationship between the gap between the light source and the optical axis, the amount of retinal reflection [Figure 6(a)], the relationship of gaze angle to the axis, and the amount of retinal reflection [Figure 6(b)]. Although previous researchers have partly identified the required parameters of the retina (Miller, Hall, Greivenkamp, & Guyton, 1995; Nguyen et al., 2002), we conducted an experiment to clarify this in a comprehensive manner. Figure 6(c) represents the experimental arrangement.

The subject gazed at one of 10 fixation points arranged from −40 to +50° in 10° intervals. We placed an infrared LED at one of the 11 positions, arranged from −5 to +5° at 1° intervals. We used 110 combinations for LED positions and fixation points. The amount of retinal reflection was measured with a camera placed 25 cm from the subject's eye. The camera's resolution was 320 × 240 pixels, and subject's pupil occupied about 50 pixels horizontally.

While the subject kept his/her gaze fixed on one point, the position of the LED was changed over 11 steps, and the eye image was captured at each step. Additionally, in the case of fixation at 0°, a measurement was done in two lighting conditions, in a dark room (0.1 lx) and with indoor lighting (100 lx). For all other angles, measurements were performed only inside the dark room. Two subjects participated in this experiment. Typical data is shown in Figure 7.

Figure 7(a) shows the amount of retinal reflection when the subject fixed his/her eye at 0°. The horizontal axis represents the gap angle (°) between the LEDs position and the optical axis of the camera. The vertical axis represents the sum of brightness in the pupil area. The square and triangle symbols represent the respective results from the dark room and the indoor lighting. In both conditions, when the gap was 0°, the sum of brightness reached the maximum, and decreased as the gap angle increased until around 3°. This means that the retroreflected light from the retina was unobservable when the LED position was separated by more than 3° from the camera axis. This value is consistent with the measurements of Miller et al. (1995).

Figure 7(b) shows the results with regard to the fixation positions from −20 to +30°. The horizontal and vertical axes are the same as in Figure 7(a). In all data, retinal reflection could no longer be observed when the gap reached 3°. This means that our technique can detect eye positions even when large eye movements occur. As the fixation point drifted from 0°, the maximum value decreased. In Figure 7(c), the square and triangle symbols represent the area of the pupil, and the brightness per pixel, respectively. As the eyeball rotated, the brightness per pixel was not changed regardless of any decrease in the pupil area. Therefore, it is likely that the amount of retinal reflection decreased due to a decrease in the captured pupil area.

In summary, the LEDs for the bright and dark pupil should be separated by more than 3° to extract the pupil position efficiently, and the pupil position is detectable even after large eye movements like saccades. The variation of the retinal reflection is caused by the change in the captured pupil area since the retroreflective feature is a stable phenomenon regardless of the fixation position.

3.3 Required Spatial Resolution for Saccade Detection

Our next investigation explored how much spatial resolution is required to accurately detect saccades. The experimental setup was generally the same as for the previous experiment, and we captured 10 and 15° rightward saccades by using a high frequency camera at 200 Hz (Point Grey Research Inc. SCORPION). Ten trials were conducted for each amplitude. The infrared LED at 0° was always lighted during the measurements.

In this experiment, the subtraction of the two images with bright and dark pupil was not performed because pupil position was given. We performed image processing to detect the saccade onset from the captured images as in Figure 8(a). First we extracted one horizontal line image that passed through the pupil center. From the brightness distribution of the line image, the pupil edges were found by using a threshold. We defined the center of two edges as the pupil position. This procedure was conducted on all captured frames. Then, the velocity of pupil displacement was calculated as the positional difference between two sequential frames. When the velocity exceeded a certain threshold, this technique detected the onset of a saccade.

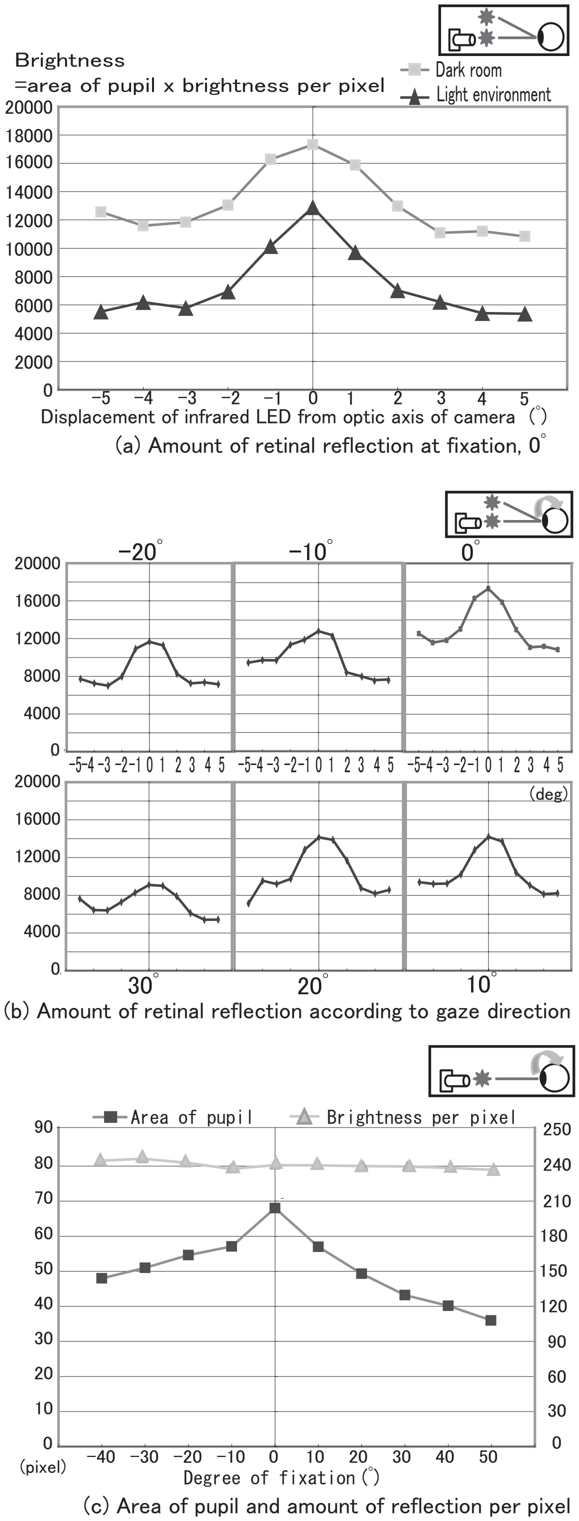

Figure 7. *(a) Amount of reflection at fixation 0° (dark room and indoor condition) according to LED's position. (b) Amount of reflection according to gaze direction. (c) Area of pupil and amount of reflection per pixel.*

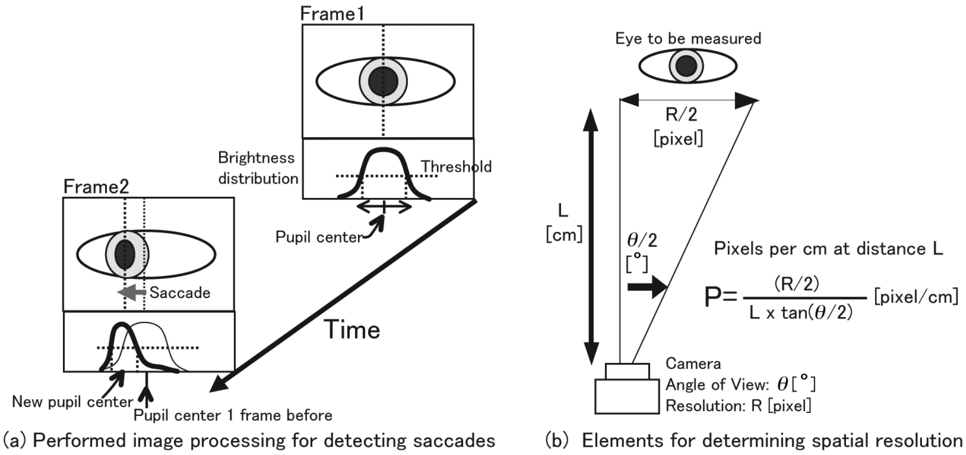

Figure 8. *(a) Performed image processing for detecting saccades. (b) Elements for determining spatial resolution.*

To evaluate the required spatial resolution, we considered the value P as described in Figure 8(b), which is the number of pixels per centimeter according to the distance from the measured person. The value of P is calculated with the formula on the right in Figure 8(b), assuming that the camera's angle of view is θ, the camera's horizontal resolution is R, and the distance of the measured subject from the camera is L. In this experimental condition, P is 60.6 pixel/cm, R is 1280 pixels, θ is 55.8°, and L is 25 cm. We made low spatial resolution images by down-sampling the original images by 1/2, 1/5, and 1/10. The down-sampled images are shown in Figure 9. The corresponding values of P are 30.3, 12.1, and 6.0 pixel/cm. The same image processing was conducted in each scaling condition.

Figure 10 shows the averages (thin line) and standard deviations (error bars) of the obtained velocities of all scaling conditions of 10 and 15° saccades. The horizontal axis represents time from saccade onset (ms) (physical onset of the saccade was defined as the time when the velocity exceeds 10 cm/s) and the vertical axis represents obtained velocity (cm/s). The bold line is the threshold for detecting saccades. The bold line is extended to the time when saccades can certainly be detected (i.e., until the threshold falls below the error bar). As the value of P decreased, the standard deviation increased.

When 40 mm/s is used as the threshold for detecting saccades, in the conditions of $P = 60.6$, 30.3, and 12.1, we could detect a saccade near its onset. However, when $P = 6.0$, the standard deviation was too large to detect the saccade at its early stage. This means that a value of P greater than 12.1 is required to accurately detect saccades. This value corresponds to about 1 pixel per millimeter. In a previous study, it was reported that eye movements were measurable with 0.5° accuracy when the pupil image is captured in 160 pixels horizontally, and this corresponds to about 6 pixels per millimeter (Matsuda & Nagami, 1997). Therefore, when we detect a saccade using the proposed technique, the required spatial resolution is 1/6 that of previous techniques.

Additionally, the proposed technique can allow head movements, although not without restrictions. For example, assuming that R is 1200 pixels, θ is 60 or 90°, head movements are allowed within 60 cm ($R/2$ divided by P) at the distance $L = 104$, or 60 cm ($P = 10$ pixel/cm), respectively.

3.4 Discussion

The proposed method can detect the initiation and direction of a viewer's saccade by measuring the velocity change of the pupil movement. Basically this method functions properly in dim light conditions because the pupil size increases. Considering that perisac-

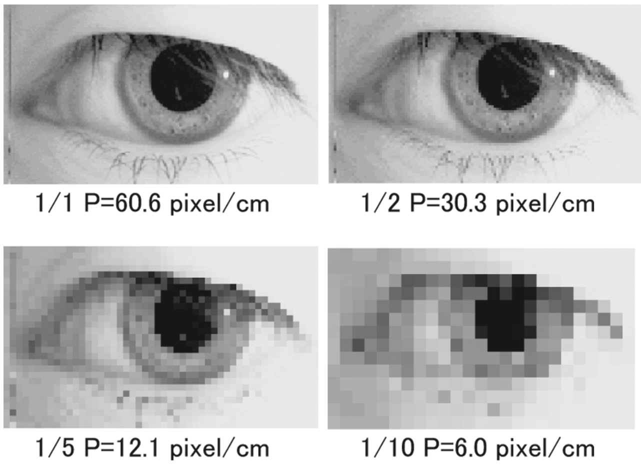

Figure 9. *Down-sampled images.*

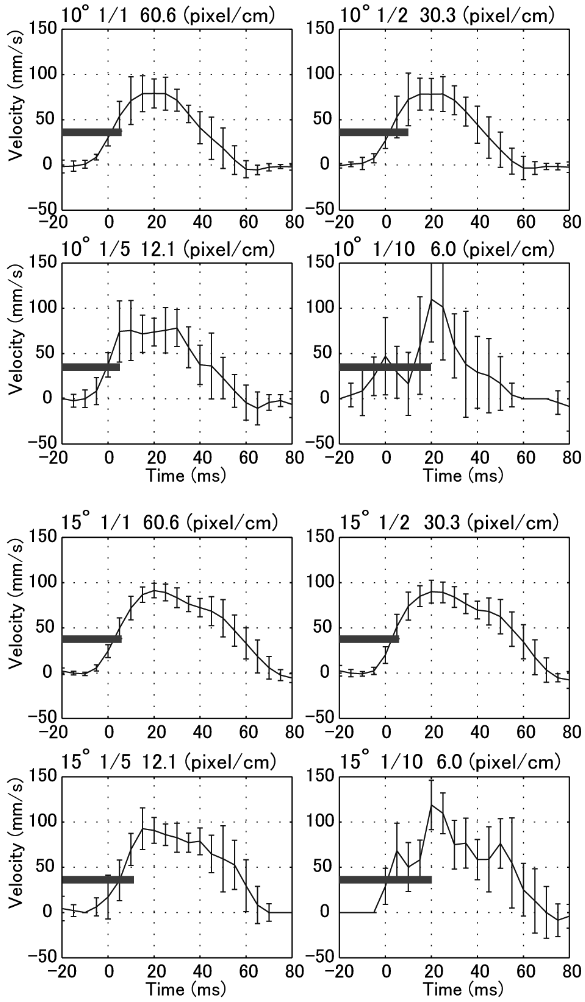

Figure 10. *Difference of accuracy according to spatial resolution. Top four graphs, 10° saccades; bottom four graphs, 15° saccades. The bold bar is the threshold for detecting saccades and extends to the time when the saccade is surely detected, that is, when the error bar exceeds 40 mm/s. The resolution of each set is 60.0, 30.3, 12.1, or 6.0 pixel/cm.*

cadically presented images can also be perceived in dim conditions, this display technique can be used effectively in dimly lighted environments.

In order to use the described method, the distance between the camera and the observer must be known. In the experiments discussed above, 40 mm/s is used as the threshold for detecting saccades. This threshold for the captured image differs according to the distance. Therefore, the distance must be measured in some way before detecting saccades. In this method, the positions of the two pupils are measurable, so we can calculate the approximate distance by comparing the general distance between the two pupils with the measured distance.

One of the characteristics of our method is that it allows head movements. However, head movements cause displacement of pupil position. When translational movements to front and back occur, the pupils of both eyes move in the opposite direction, although saccades made eye movements in the same direction. Therefore, we can segregate the saccade and the movement to front and back by observing the directions of the pupils' movements.

As to the segregation of the movements right and left, we think that by focusing on their velocity we can segregate these movements. The maximum velocity of a saccade reaches somewhat more than 700°/s, and this is equivalent to 16 cm/s horizontal movement of the pupil. Assuming that the hip of a subject is in a fixed position on a chair while the measurement is being performed, the subject would find it difficult to move his or her head faster than 10 cm/s. As to the segregation of the head, since the features of the vestibulo-ocular reflex accompanying head rotation is similar to the feature of the saccade, the segregation with one camera is difficult. However, obviously, if two cameras or a marker on the head are used for measuring head position, we can easily discriminate velocities by eye and head movement.

3.5 Summary of Measurement Method

We proposed a concise and remote saccade detection method, and clarified the feasibility of this method by investigating the retinal retroreflective features and the required spatial resolution for accurately detecting saccades. Our results indicates that this method can detect saccades in their initial stages, and this can be useful for presenting 2D images by exploiting the saccade-contingent phenomenon.

4 Conclusion

In our current paper, we proposed a novel 2D information presentation technique that uses perceptional features during saccades and a concise remote saccade detection method. We discussed the relationship between a flashing cycle and the maximum resolution of perceived 2D images, and confirmed the feasibility of this real-time saccade detection technique. Through these discussions, we have described how to specify a suitable flashing cycle that maximizes the resolution of perceived images. We also explained how a saccade-contingent display can be achieved by detecting a viewer's saccade and displaying images within the saccade's duration.

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