INVITED PAPER *Special Section on Electronic Displays*

# A Study on the Increase of Perceivable Information in the Saccade with High Speed Line Display

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**SUMMARY** A line display that utilizes saccade has been proposed. When an observer moves his or her eyes on a one-dimensional fixed line display, two-dimensional information is perceived on the retina. In this paper, a high speed flashing line display was developed using a CPLD and PIC microcontroller. The flashing period was reduced to 20 $\mu$s, which was less than half that of our previous system. The relationship between the flashing frequency and the optimum distance that can be perceived with the least distortion was clarified. The results show that the higher the flashing frequency is, the more information can be perceived from a farther position. Calculated values, which were based on the relationship between the flashing period and the width of the light source, were almost identical with measured values at the flashing frequencies from 3.3 kHz to 10 kHz. Due to short flashing period, the developed line display not only was visible at distance of 15 m or more, which is suitable for outdoor use, but also realized 16 gray levels.

***key words:*** *saccade, line display, flashing frequency, perceivable pixels*

## 1. Introduction

We frequently move our eyes to the object of interest in our lives. The fast eye movement occurring at this time is called a saccade [1]. A line display using this saccade has been proposed [2], [3]. When an observer moves his or her eyes across a one fixed dimensional line display, a series of linear images produced by vertically dividing an image to be displayed are sequentially flashed at high speed, whereby the two-dimensional information is perceived on the retina by the eyeball movement and the flashing vertical pattern appears to be expanded horizontally. On the other hand, the technology called persistent of vision (POV) or versa-writer has been used for a long time as a method of presenting two-dimensional information by using the after-image from the fixed one-dimensional flashing point sequences. In this case, a large space and high power are required to move the device, but in the case of a line display, the human retina perceives the after-image on a single line. Therefore, this system can display information without moving the device, and is expected to be useful for nighttime advertisements and lighting for entertainment, such as illumination.

An earlier study reported on the temporal relationship between the size of the perceived image and eyeball movements in a similar device [4]. In Ref. [5], a method of creating content images based on perceptual characteristics by saccades was proposed, in which the flashing frequency of the device was set to 2 kHz. We have been studying and developing line displays, and our previous studies have clarified the relationship between the flashing period of one line and the angle of eyeball movements [6]. We also developed a line display driving 64 LEDs and conducted experiments to evaluate the size of the image for the flashing period using saccade [7]. With respect to grayscale of displayed images, a 5 gradations image was displayed by the fastest flashing period of 42 $\mu$s [8]. In the previous experiments, the distance between the device and the subject was fixed at 2 to 3 m for domestic use. However, it is required to be visible from a larger distance for outdoors use at night such as advertising.

In this paper, we have developed a fast flashing line display with 20 $\mu$s, and by varying the distance between the subject and the display, we have clarified the relationship between the distance and the flashing frequency that can be perceived with no visible distortion. We have also verified that the number of pixels and color gradation can be increased with the high speed flashing [9].

## 2. Principle of Line Display Using Saccades

The principle of the line display is shown in Fig. 1. When a string of light dots is moved at faster than a certain speed, the trajectory is perceived as a continuous line due to the afterimage. On the other hand, when the eye moves at faster than a certain speed, a similar phenomenon happens. A line display is used to present information by changing the emission pattern of a fixed string of light dots, using the mislocalization caused by the saccade of the eyeball that

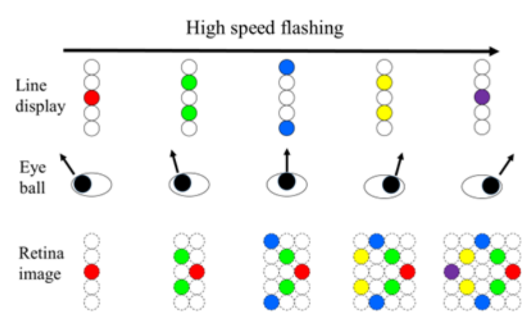


**Fig. 1** Perceptual of line display.

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catches it [5], [10]. In addition, the image is perceived as the reversed of the pattern of the issuing optical point sequence [11]–[14]. Typically, the rotational speed of a saccade is 300-500 deg/s with a duration of 30 - 50 ms [15]. The maximum speed of the saccade varies with amplitude, from 250 deg/s for 5 deg to 650 deg/s for 20 deg [16]. Similarly, the saccade duration also increases with amplitude, and the duration $T$ of the saccade increases with amplitude $A$. The relationship is approximated by the following Eq. (1).

$$T = T_0 + d \cdot A \quad (1)$$

$T_0$ is 20 - 30 ms, and $d$ is the amount of increase per deg of amplitude, which is about 2-3 ms [17]. However, the maximum speed and duration of the saccades were slightly different among research results [18]–[22], which may be caused by measurement methods and individual differences [15]. The saccades used here are high-speed eye movements that catch up with the object captured in the peripheral vision, and can move the gaze at extremely high speed, but during the movement, saccade suppression occurs and the visibility characteristics decrease [1]. In general, saccade suppression begins several tens of milliseconds before the onset of the saccade, reaches its maximum during the saccade, and continues after the saccade ends [23]–[25]. However, saccade suppression is less likely to occur in the case of stimuli that contain many high spatial frequency components [26]–[29]. In addition, the darker the background is the more suppression occurs [2], [30], [31]. Therefore, it is preferable to use the system in dark environments such as dark rooms or outdoors at night.

## 3. Development of High Speed Flashing Line Display

In this paper, a line display is created using a complex programmable logic device (CPLD) and a PIC microcontroller in order to shorten the data transfer time. It consists of a microcontroller board that transfers data and four sub-boards, where each sub-board drives 16 LEDs, as shown in Fig. 2. It was designed to enable the connection of five or more sub-boards using a comparator. Figure 3 shows the sub-board configuration and Fig. 4 shows the timing diagram. The data transferred in 8 pixels divided into 24 times is held in the latch circuit, and after all the data is completely transmitted, it is sent to the transistor arrays all at the same time. The latch circuit that holds the data, the comparator for selecting the sub-board and the decoder were designed using the CPLD. The PIC24EP512GP204 is used as the microcontroller. The pattern diagram of the sub board designed by CDA software Eagle and the developed sub-board are shown in Fig. 5. The board was 122 mm long (16 LEDs) and 100 mm wide. Connect the microcontroller board and the sub board as shown in Fig. 6. A developed line display with four sub-boards and a microcontroller board is shown in Fig. 7. Figure 8 shows the result of measuring the fastest flashing period with an oscilloscope. The fastest flashing period is 20 $\mu$s, which is more than twice as fast as the device developed in our previous work (42 $\mu$s) [8].

## 4. Increase in the Number of Shades Due to High Speed

A PWM waveform is generated to create multiple gradations. Assuming a flashing period $T$ and a data transfer time of $t_d$, the gradation $G = T/t_d + 1$, therefore, if the data

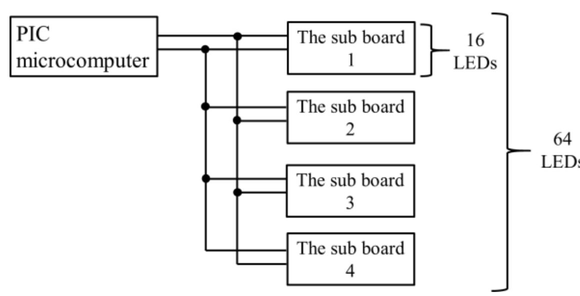


**Fig. 2** Configuration diagram of line display.

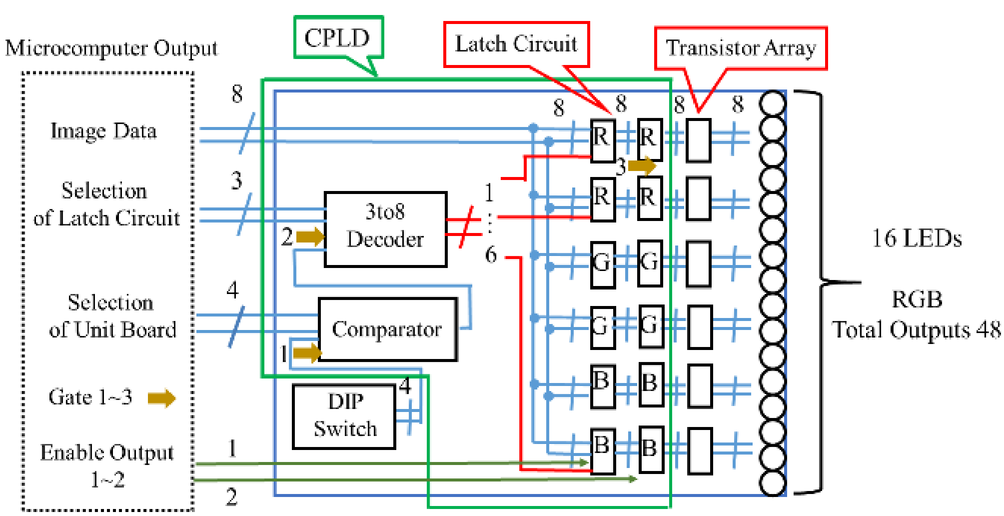


**Fig. 3** Configuration diagram of the sub board.

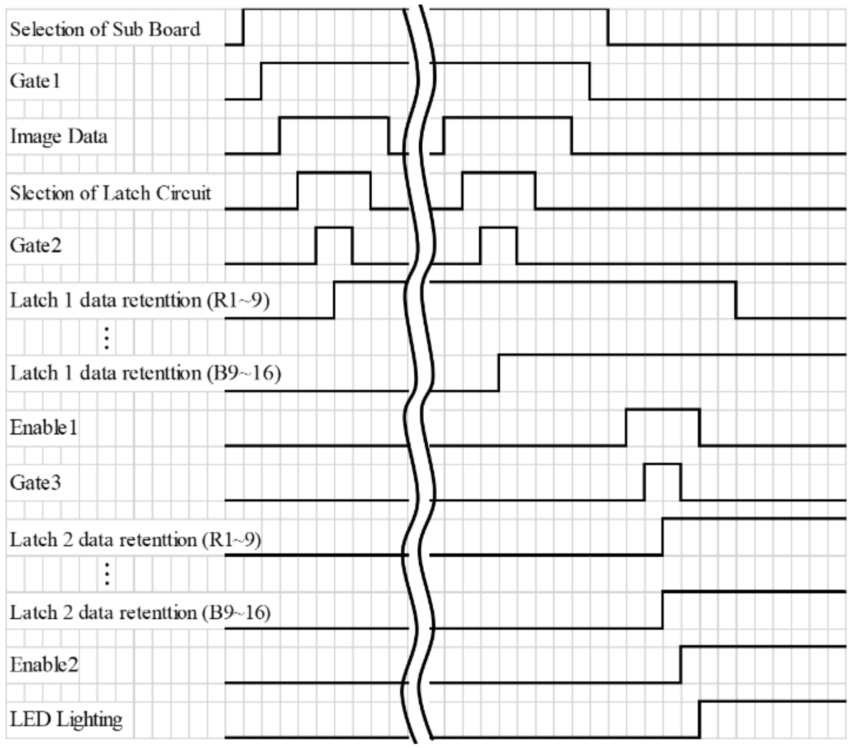


**Fig. 4** Timing diagram of data transfer for LEDs.

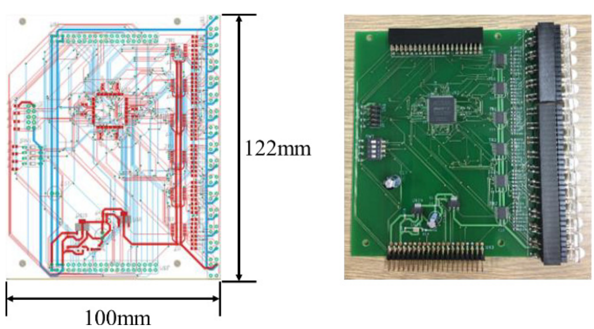


**Fig. 5** Pattern diagram designed by CDA software Eagle and the developed sub-board.

**Fig. 7** Developed high speed line display.

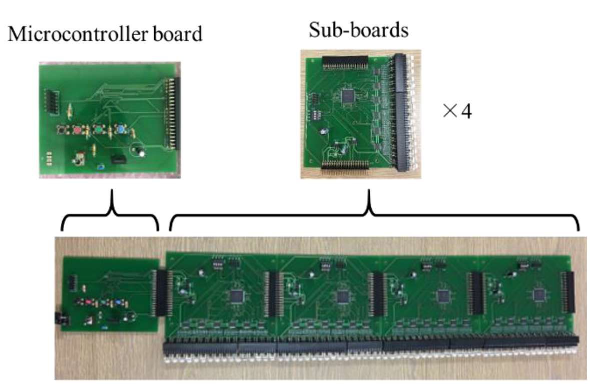


**Fig. 6** Connected the microcontroller board to the sub board.

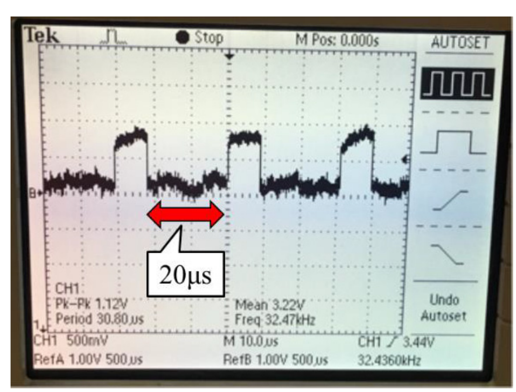


**Fig. 8** Observation results by the oscilloscope.


**Fig. 9** Displayed gray scale images by our developed line display.

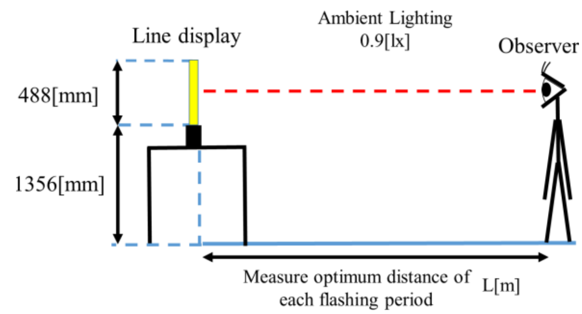


**Fig. 10** Experimental condition for optimal distance.

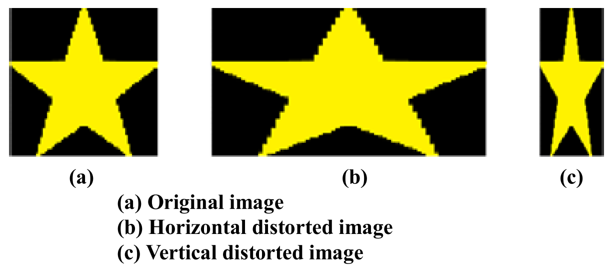


**Fig. 11** The evaluation criteria for image perception.

**Fig. 12** The images used in the experiment captured by a digital camera.

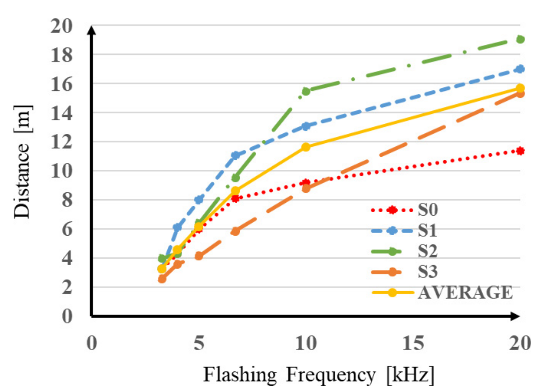


**Fig. 13** The relationship between flashing frequency and optimal distance.

transfer time is 20 $\mu$s and the most visible flashing period is 0.3 ms [8], the gradation can be increased to 16 levels. The 16 levels pixel value was determined by Eq. (2), which transforms the usual linear 256 levels pixel value $E$ into an exponential 16 levels pixel value $R$, taking into account of perceptual sensitivity based on the Weber-Fechner law.

$$R = 255\left(\frac{E}{15}\right)^{\alpha} \qquad (2)$$

In an experiment on image visibility considering perceptual sensitivity using a line display, it was confirmed that visibility was improved by correcting the perceptual sensitivity [32]. $\alpha$ is the correction value, which was set to 1.7. Face images with multi-leveled colors of 5 and 16 displayed by a flashing line display are shown in Fig. 9. This picture was taken by moving a digital camera to simulate eyeball movements. By increasing the number of grayscales, the image of the face is displayed more clearly.

## 5. Experiment

The experiment was conducted to evaluate the flashing period and perceivable distance of images. The experimental condition is shown in Fig. 10. The experimental environment was outdoor at night, the illumination was 0.9 lx, and a 64x64 pixels yellow star image. The evaluation criteria for image perception are shown in Fig. 11. Four subjects (S0-S3) were tested to measure the distance L, which is the optimum distance to perceive the displayed image with the least distortion, at each flashing period. The experiments were conducted with a flashing period ranging from 0.05 ms (20 kHz) to 0.3 ms (3.3 kHz). A photograph taken by moving a digital camera in the same way as the eye movement when the line display was actually operated to output the image used in the experiment is shown in Fig. 12.

## 6. Results

The measurement results of the four subjects (S0-S3) and their average values are shown in Fig. 13 and Table 1. A graph of the mean and standard deviation of the measurements from the results is shown in Fig. 14. The vertical axis is the perceptible distance and the horizontal axis is the flashing frequency. The results showed that the optimal distance for perception was longer as the flashing frequency was higher, and shorter as the frequency was lower. When the flashing frequency was 20 kHz, the maximum and minimum values were 19.1 m and 11.4 m, respectively, and the average value was 15 m. As the flashing period was decreased, the visible distances became shorter, with a maximum of 4.0 m, a minimum of 2.6 m, and an average of 3.3 m at 3.3 kHz. Figure 14 shows that the standard deviation increases as the flashing frequency increases.

**Table 1** The measurement results of the four subjects (S0-S3) and their average values.

| | 3.3 kHz | 4.0 kHz | 5.0 kHz | 6.7 kHz | 10 kHz | 20 kHz |
|---|---|---|---|---|---|---|
| S0 | 3.3 m | 4.3 m | 6.0 m | 8.1 m | 9.2 m | 11.4 m |
| S1 | 3.3 m | 6.1 m | 8.0 m | 11.1 m | 13.1 m | 17.0 m |
| S2 | 4.0 m | 4.4 m | 6.4 m | 9.6 m | 15.5 m | 19.1 m |
| S3 | 2.6 m | 3.6 m | 4.2 m | 5.9 m | 8.8 m | 15.4 m |
| Average | 3.3 m | 4.6 m | 6.2 m | 8.7 m | 11.7 m | 15.7 m |

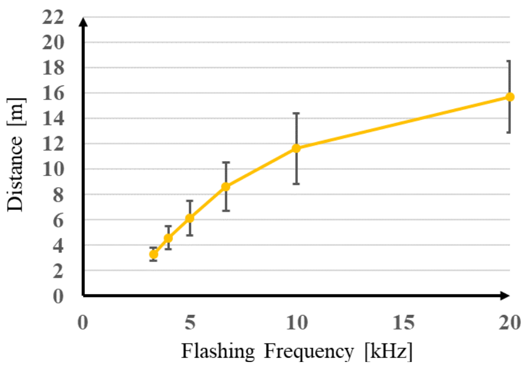


**Fig. 14** The average and standard deviation of the relationship between flashing frequency and optimal distance.

## 7. Discussion

According to Ref. [2], when the saccade amplitude is $\theta$ deg and the width of the light source in the field of view is $D$ deg (for example, $D = 0.1$ deg for an LED with a light source of 5 mm observed from 3 m away), the maximum number of horizontal pixels $X$ that can be displayed is given by the following equation.

$$X = \theta / D \tag{3}$$

Let $\ell$ be the distance the light source moves on the retina during the flashing period $t_m$, then

$$\ell = V \times t_m \tag{4}$$

Where V is the eye velocity in saccades. When the moving distance on the retina $\ell$ is larger than or equal to the width of the light source $D$ ($D \leqq \ell$), the lights can be perceived without overlapping, and particularly when the width is the same as the light source ($D = \ell$), the information can be perceived without distortion. When $\theta$ is constant, the maximum number of pixels $X$ depends on $D$. When $V$ and $t_m$ are constant, $D$ is relevant for presenting information with less distortion. The width of the light source $D$ is given by the following equation.

$$D = \tan^{-1}(h/L) \tag{5}$$

where $h$ is the LED size and $L$ is the optimal distance between the device and the subject. From Eqs. (4) and (5), assuming a velocity $V$, we have calculated the optimal visual distance L for each flashing period at $D = \ell$, and compared it with the average of the measured values. Optimal distance and measured values on flashing frequency are shown in Fig. 15.

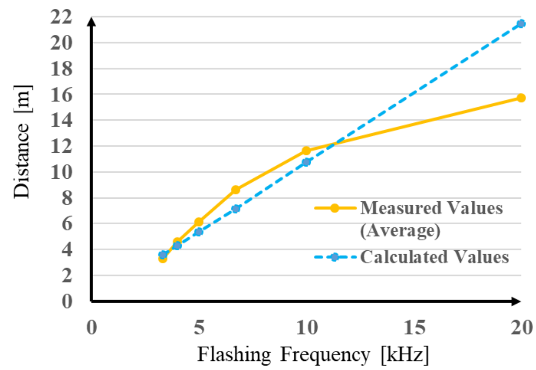


**Fig. 15** Optimal distance and measured values on flashing frequency.

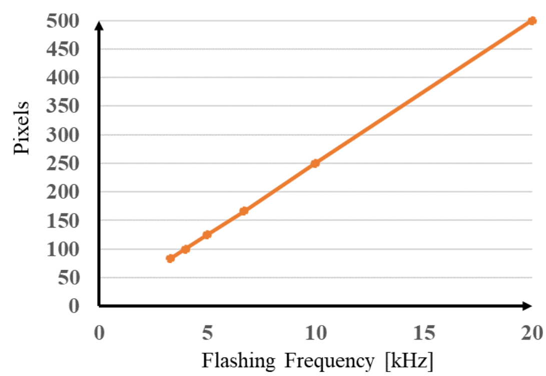


**Fig. 16** Perceivable pixels depending on flashing frequency.

In daily life, saccades of around 10 deg are common [14]. The maximum speed of a saccade at an angle of 10 deg is 400 deg/s [16]. Assuming that the angle of the eye moved by the subject is 10 deg and the speed is 400 deg/s, we calculated the optimal distance at which the image can be perceived. Comparing the measured values in Fig. 15 with the calculations, the two are close at distances shorter than 12 m, but the measured values are saturated at distances longer than 12 m, and the difference from the calculated values increases. This is thought to be because the visual acuity deteriorates as the distance between the subject and the display increases, so that the optimum perceptual distance is saturated due to the limitation of visual acuity. Figure 16 shows the result of calculating the maximum number of pixels for each flashing frequency from Eq. (3) using the optimum distance for each flashing frequency in the experimental results. It shows that the number of perceivable pixels increased as the distance and the flashing frequency increased.

## 8. Conclusions

In this paper, a high speed flashing line display was developed using a CPLD and PIC microcontroller. The flashing period was reduced to 20 $\mu$s, which was less than half that of our previous system. The relationship between the flashing frequency and the optimum distance that can be perceived with the least distortion was clarified. The results show that the higher the flashing frequency is, the more information can be perceived from a farther position. Calculated values, which were based on the relationship between the flashing period and the width of the light source, were almost identical with measured values at the flashing frequencies from 3.3 kHz to 10 kHz. Due to short flashing period, the developed line display not only was visible at distance of 15 m or more, which is suitable for outdoor use, but also realized 16 gray levels.

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