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Window of Visibility in the Display and Capture Process

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***Abstract*—In normal conditions, the Critical Flicker Frequency is usually 60Hz. But in some special conditions, such as low spatial frequency and high contrast between frames, these special conditions have high probability to occur in some TPVM-based applications. So it's extremely important to verify if a visual signal with a combination of temporal and spatial frequency can be recognize by human eyes. Based on the research in the last paper ' 'Window of Visibility' inspired security lighting system', this paper introduces the measuring method of WoV of human eyes. In this paper we will measure critical flicker frequency in low spatial frequency and high contrast conditions, and we can witness a different conclusion from the normal conditions.**

***Keywords*—Window of Visibility(WoV), DLP, Temporal Psychovisual Modulation(TPVM)**

I. Introduction

THERE is a new information display technology introduced in the last article at IWSSIP [1]. The new technology can prevent the visual information from being taken by photos while remain complete and clear for human eyes. The techniques of temporal psychovisual modulation(TPVM) and window of visibility(WoV) are applied into the security lighting system [2]. So we may introduce some knowledge of these techniques.

TPVM makes use of the phenomenon that human eyes cannot recognize visual signal with a higher frequency than 60Hz.[3] This frequency is usually called critical flicker frequency(CFF). However, the technology development in the recent decades makes it possible for modern displays to operate at frequencies much higher than CFF, such as 240Hz [4]. Because of the feature of human visual system(HVS), fusion occur when human eyes viewing high frequency visual stimuli[5], and redundancy takes place. Because of that, there is extra capacity in modern display, which is called psychovisual redundancy [6]. Making use of that we can design new display system to deliver multiple signal to different audience or hide some information into what we see[7][8]. The security lighting system is the later kind of application.

Some kinds of TPVM application are composed of high-speed display and synchronized receiver[9][10]. In this condition, viewers with glasses can see the modulated views while others may see the normal view. But the devices required make this application not economical. There is another method to modulating the illumination of what you want to protect. You can add noise or some patterns in the illumination while increasing its frequency. So that the human eyes won't notice the hidden pattern but the camera will take them in the photo[11][12]. And they are introduced in the last IWSSIP article.

Although the CFF is 60Hz in normal conditions, it's not 60Hz in some special conditions, including TPVM-based applications. The reason of this phenomenon is that while the contrast of images is higher, the CFF becomes higher[13][14]. And in some special conditions, even the frequency raises to as high as 500Hz, human eyes can still sense the flicker. In the TPVM-based applications, the neighboring two frames may be completely converse, which is similar with the special condition mentioned by James Davis, Yi-Hsuan Hsieh and Hung-Chi Lee [15]. For instance, the first frame is named frame A, the second frame is frame B and the third frame is 1-B [16][17]. As the result of that, its necessary for us to measure the WoV of human eyes and digital camera to choose the temporal and spatial frequency of the hide information instead of set the CFF at 60Hz as a default.

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II. Related Principles

A. The Process of Taking Photo of Screen

The process of image display is composed of several individual steps, including motion, blur, expose, sample, filter, down-sample, flicker and hold, which was introduced by Andrew B.Watson in 2013 [18]. The whole process in that article is recording a lines motion and display it so its kind of different from the original process. The most simple condition of motion image is a moving line for one side to the other side, and the function $m(x,t)$(Eq.1) represent the location of the line which determined by the time. We all know that in the real world there is not a line with zero width, in other words, all lines must have width. This phenomenon can be characterized by next function. The function $o(x)$ represent the process of blur, which usually is a Gaussian blur. And to represent the movement of a blurred line, the motion function is convolved with the blur function.

Its known to us all that although videos are continuous for human eyes, theyre actual discrete. So next step is sampling for display discretely(Eq.3). In the sampling function the parameter w_s represent the frame rate of the display.

$$m(x,t) = \delta(x - rt) \tag{1}$$

$$o(x) = \frac{1}{b} exp\left(-\pi \frac{x^2}{b^2}\right) \tag{2}$$

$$s(t) = \frac{1}{w_s} \coprod\coprod(tw_s) \tag{3}$$

For avoiding of flicker while keep the frame rate from increasing, every single frame in a video is usually displayed for multi times, for instance, 3 times. Then the actual frame rate is 72Hz. And every frame has a duration time, this and previous procedure can be described as Eq.4 and Eq.5. And now the process of image display has been over.

$$f(t) = \frac{1}{3}\Big(\delta\big(t+\frac{1}{nw_s}\big)+\delta(t)+\delta\big(t-\frac{1}{nw_s}\big)\Big) \tag{4}$$

$$h(t) = \frac{nw_s}{p}\prod\left(\frac{tnw_s}{p}\right) \tag{5}$$

The final purpose of security display is adding hidden information that cameras can record, so the last step is taking photo of content displayed. This expose procedure can be represented by convolve the whole function with a pulse (Eq.6). The complete version of this display-capture process is Eq.7 and its Fourier transformed version is Eq.8.

$$e(t) = \frac{w_s}{d}\prod\frac{tw_s}{d} \tag{6}$$

$$l(x,t) = \Big(\big(m(x,t)*o(x)\big)s(t)\Big)*f(t)*h(t)*e(t) \tag{7}$$

$$L(u,w) = \Big(\big(M(u,w)O(u)\big)*S(w)\Big)F(w)H(w)E(w) \tag{8}$$

Although the functions of steps are similar with what Andrew B. Watson raised, the whole procedure is different with his conclusion. In Andrew B. Watsons article, the movement of the line is continuous and the final output is a video. This can be called a capture-display process. But in this article, the so-called movement of the line is discrete and the final output is a photo. And the flow diagram of the display-capture system is shown in Fig.1.

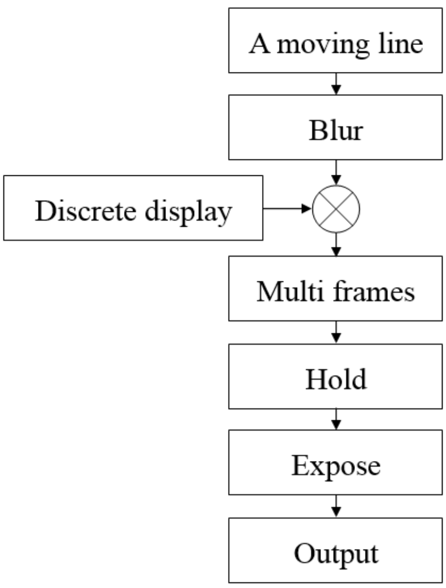


Figure 1. The flow diagram of the display-capture system

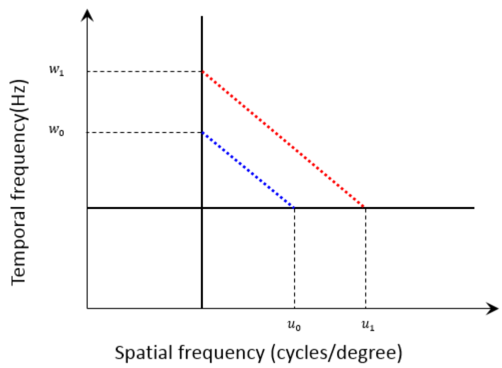


Figure 2. The window of visibility of human eyes (blue line) and camera (red line)

B. *Window of Visibility*

Human visual system has plenty of complex mechanisms and one of them is the limit of sense of spatial and temporal frequency. Both spatial frequency and temporal frequency human visual system can recognize have upper limit and lower limit. However, the upper limit of spatial and temporal frequency may not be reached at the same condition [19]. In other words, while the temporal frequency is increasing, the most spatial frequency human visual system can recognize becomes lower. And the temporal frequency upper limit decreases as well when the spatial frequency becomes higher.

To describe the visual stimuli that can be noticed by human visual system, we can represent each kind of visual stimuli with its spatial and temporal frequency is a two-dimensional coordinate system. The final area of visual stimuli that can be seen is the Window of Visibility(WoV), and its shape is usually rhombus. If we used the third axis to represent the contrast of the visual signal, we can get different diamond-shaped area at different height. The complete version of this model is the pyramid of visibility, but in this application, we just need the contrast be a constant.

Just like human visual system, camera and other artificial visual systems has them WoVs as well, and they are usually different from human eyes WoV. More precisely, the WoV of camera is bigger than it of human visual system. As the Fig.2 shows, the WoV of camera has higher spatial and temporal frequency. If we add some visual stimuli in the area between the red line and the blue line, the special stimuli will be unnoticeable for human eyes but can be recorded by camera. Measuring the WoV of human visual system more precisely is what need to be done.

III. Experiment Design

In the security lighting application, what we need is the effect of interference to be better. So in the experiment, we set the contrast as 100%. Ten spatial frequencies from 2 cycles/degree to 20 cycles/degree will be tested. In each group of spatial frequency, 15 temporal frequencies from 20Hz to 1000Hz will be tested to calculate the CFF at each spatial frequency. The last step is calculating the linear fitting result

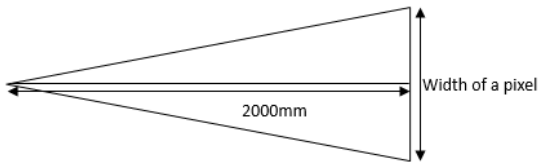


Figure 3. Method to calculate visual angle of one pixel

Table I
SPATIAL FREQUENCY OF EACH GROUP

Number of pixel	8	10	12	16	20
Spatial frequency(cyc/deg)	15.65	12.52	10.44	7.83	6.26
Number of pixel	24	36	48	72	108
Spatial frequency(cyc/deg)	5.22	3.91	2.61	1.74	1.16

from the ten pairs of spatial frequency and temporal frequency.

A. Procedure

The distance from the eyes of participants and the screen is around 2000mm, while the distance from the DLP to the screen is 900mm. The angle of the light from the DLP is a constant, so the length and the width of the projection area are constants as well, precisely, 535mm and 300mm separately. The number of pixel in two directions are known (1920 and 1080). Then the width of a single pixel can be calculated as shown in Eq.9. Then we can calculate the visual angle of a single pixel using the method shown in the Fig.3. The smallest spatial cycle can be displayed by this DLP is two pixels per cycle, which can be transformed to 62.61 cycles/degree.

$$w_0 = \frac{535mm}{1920} = 0.279mm \tag{9}$$

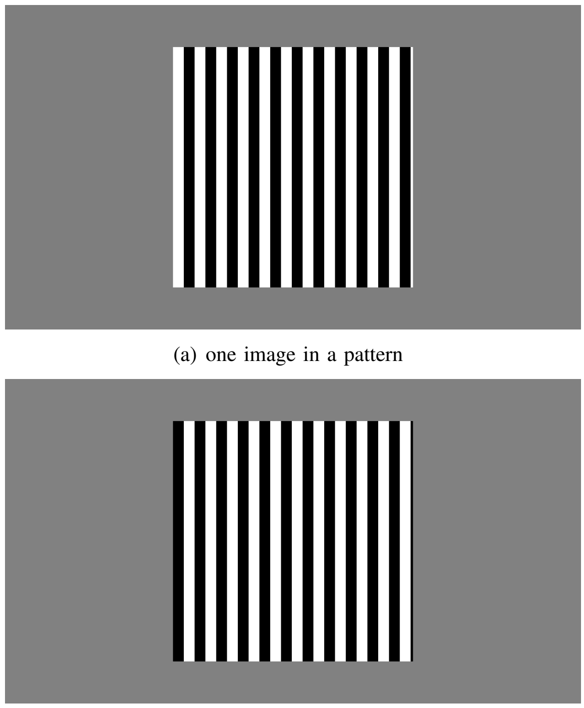
$$\alpha_0 = 2arctan\frac{w_0}{2L} = 7.986 \times 10^{-}3degree \tag{10}$$

In this experiment, we will concentrate on CFF when spatial frequency is lower than 16 cycles/degree. We choose the width of stripe to be 8, 10, 12, 16, 20, 24, 32, 48, 72 and 108 per cycle. Then we can calculate the actual frequency of each group. The results are shown in Table I. And to measure the CFF at each spatial frequency, the subjective experiment will be taken. We also choose 15 temporal frequencies from all the groups. The frequencies and time cycles are shown in Table II.

Now we get 150 images with 10 different patterns. Each pattern consists of two related images. One of them is black-white stripes in the square area in the center with gray in the outside area. And the other image is the reverse image of the previous just mentioned. There is one pattern shown as an example in Fig.4. Within each pattern, each image will be displayed at different frequency, so there are 150 different samples. Then we randomize these samples and shown them to one of the participants. The viewer watches the image display in order and records whether he or she can notice the flicker or not. Here we use 1 to represent that the viewer can notice the flicker and 0 for not. At last we get 150 numbers meaning how many participants can notice the pattern.

Table II
TEMPORAL FREQUENCY AND THEIR DISPLAY TIMES

Frequency(Hz)	20	50	80	100	150
Times(us)	50000	20000	12500	10000	6667
Frequency(Hz)	200	250	300	350	400
Times(us)	5000	4000	3333	2857	2500
Frequency(Hz)	450	500	600	750	900
Times(us)	2222	2000	1667	1333	1111



(a) one image in a pattern

(b) the reverse of (a)

Figure 4. Two images of a pattern(spatial frequency = 1.74cyc/deg)

B. The Method of Data Analysis

Because of the subjective factor of the participants and the psychology factor, the number of how many participants can see the flicker may not change suddenly. So what we exactly need is a threshold to represent the CFF. To do this we use a concept of psychometric function. By taking the experiment, we get the percentage of how many participants can notice the flicker at each temporal frequency in each group of spatial frequency. Then we fit the 15 points in each group into one curve and get the threshold where the percentage is 50%. In other words, when 50% of the participants can notice the flicker, the temporal frequency is the CFF.

$$S(x) = \frac{1}{1+e^{-x}} = \frac{e^x}{e^x+1} \tag{11}$$

The psychometric function used in this experiment is the Sigmoid function(Eq.11) and one of a typical curve is shown in Fig.5. The actual curve generated by data fit using the result of the experiment is kind of different from the curve in Fig.5. Its reversed and has an offset(Fig.6). The X axis represent the temporal frequency in log scale and the Y axis represent the percentage of participant that can notice the flicker. The blue point is the original result of the experiment and the red dash line is the curve of fit.

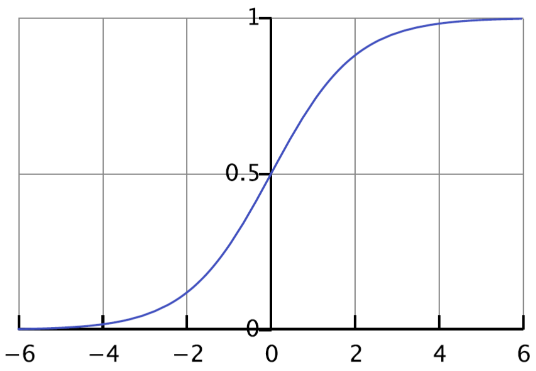


Figure 5. Sigmoid function curve

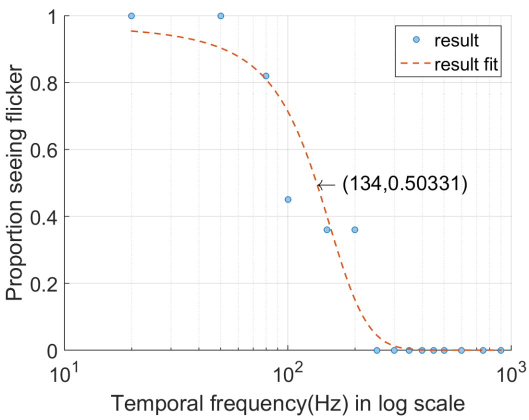


Figure 6. One of the result curves

IV. Experiment Result and Analysis

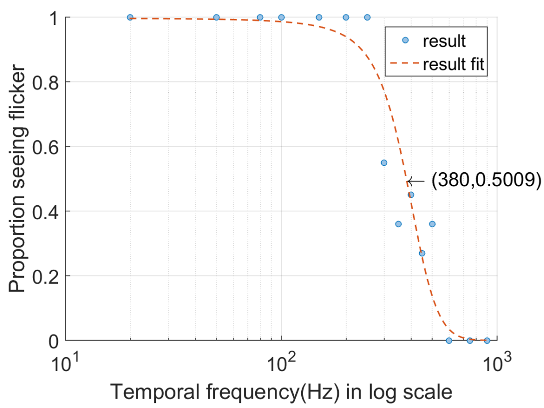
Some of the curve results of ten groups are shown in Fig.7. We can notice that almost all the groups have a downward trend when spatial frequency increases. When temporal frequency is lower than 100Hz, almost all the participants can notice the flicker of the stripe pattern. Then the probability to notice the flicker decreases while the temporal frequency increases. When temporal frequency is as high as 900Hz, almost all the participants cannot notice the pattern. The data of the sixth group (6.26cyc/deg) has plenty of deviation so it wont be use in subsequent analysis. Then we still obtain 9 pairs of spatial frequency and their critical flicker frequency, as shown in Table III. For more direct demonstration, we plot the 9 points in one figure. We can notice that when spatial frequency is higher than 5 cyc/deg, the critical flicker frequency increases when spatial frequency decreases, which is the same as what we have mentioned in previous section.

However, when spatial frequency is lower than 5 cyc/deg the trend of CFFs change is different from that when spatial frequency is higher than 5 cyc/deg. In this interval when spatial frequency decreases, the critical flicker frequency doesn't increase, even decreases slightly. One possible reason of this phenomenon is that the frequency interval from 500Hz to 700Hz is too big, then the subjective factor of participant generates errors. The other possible explanation of this may be that the spatial frequency sensitivity of human eyes decreases when spatial frequency is lower than 5 cyc/deg, so the critical flicker frequency becomes lower.

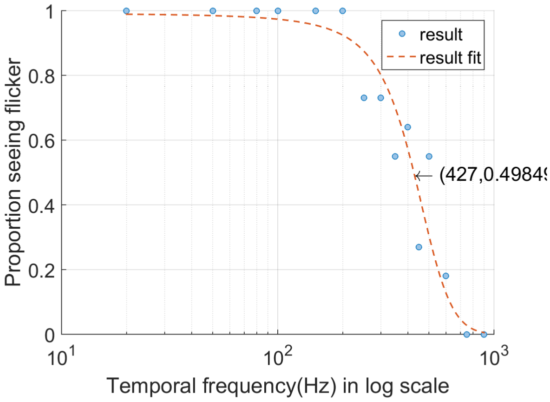
Table III
Ten Pairs of Spatial and Temporal Frequency

No.	Spatial frequency(cyc/deg)	temporal frequency(Hz)
1	1.16	380
2	1.74	427
3	2.61	452
4	3.91	449
5	5.22	486
6	6.26	509
7	7.83	394
8	10.44	259
9	12.52	177
10	15.65	134

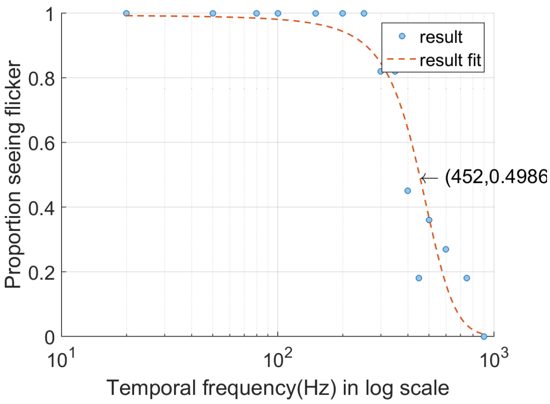
At last we perform linear fit for the five points at right side and get the red line in Fig.8, this red line can be regard as a part of window of visibility when contrast is 100%. And this red line has a similar trend with the two lines in the Fig.2. The area above the red line represents all the stimuli that cannot be recognized while the area below represents them that can be recognized.



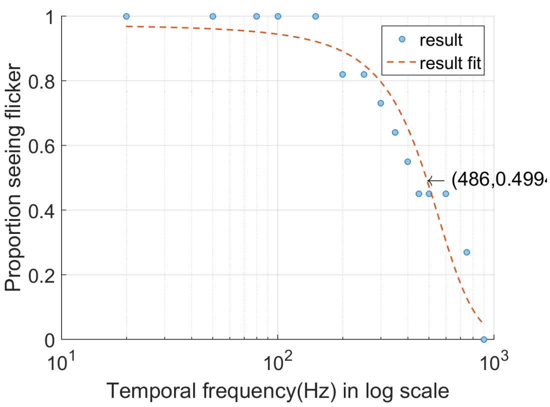
(a) spatial frequency: 1.16cyc/deg



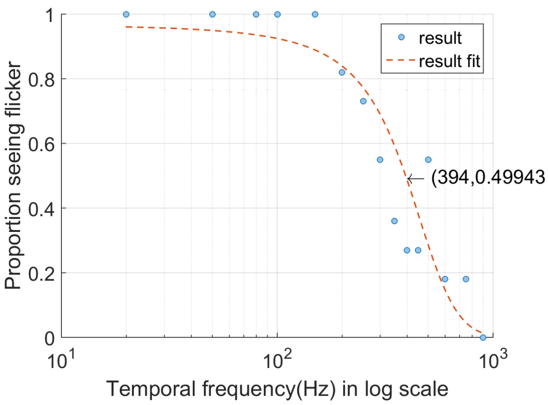
(b) spatial frequency: 1.74cyc/deg



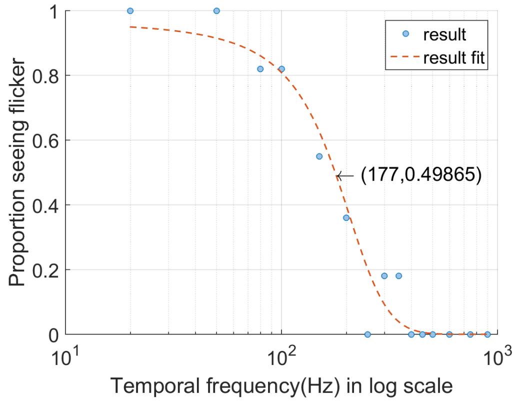
(c) spatial frequency: 2.61cyc/deg



(d) spatial frequency: 5.22cyc/deg



(e) spatial frequency: 7.83cyc/deg



(f) spatial frequency: 12.52cyc/deg

Figure 7. The fitting sigmoid curves of some groups

V. CONCLUSION

Because of the redundancy in modern displays frame rate, the technique of TPVM and related applications appeared. However while old standard of frame rate such as 24Hz or 60Hz may be fine for traditional displays, the new standard of frequency with new display techniques becomes higher and higher. Especially in applications using TPVM, the neighbor frames can be completely reverse. In these condition, much higher frame rates are necessary to insure a comfortable experience for viewers.

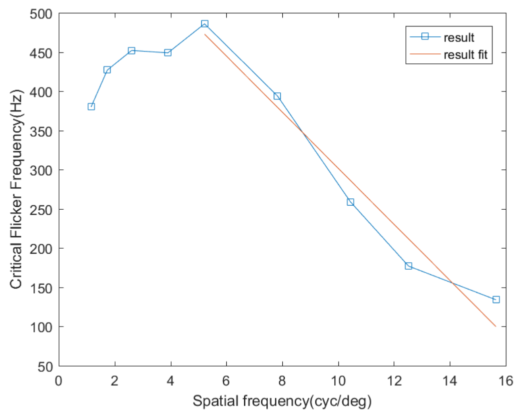


Figure 8. The linear fit result of Window of Visibility

In this paper, experiments are done to measure the window of visibility of human visual system at spatial frequency lower than 15 cyc/deg more precisely. When contrast is around 100% and spatial frequency is lower than 15 cyc/deg, the CFF is much higher than 60Hz, even around 400Hz-500Hz sometimes. This result can be regarded as a guidance for applications involving TPVM. In some TPVM-based applications, such as dual-view medical image visualization and invisible QR code [20], the information that need to be hide can choose its spatial and temporal frequency higher than the red line but not too much higher, to remain visible for cameras.

There are plenty of other details that can be research deeply, such as critical flicker frequency at spatial frequency higher than 15 cyc/deg, critical flicker frequency at different contrast and critical flicker frequency at special conditions, for instance, head movement or eye movement. Additionally, the amount of temporal sample can also be improved to get more data from curve fitting. Another major research topic is the window of visibility of cameras, with the result of these two researches, a more precise standard of choosing spatial and temporal frequency of hidden information can be provided.

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