Critical Flicker Frequency (CFF) at high luminance levels

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Abstract

The critical flicker fusion (CFF) is the frequency of changes at which a temporally periodic light will begin to appear completely steady to an observer. This value is affected by several visual factors, such as the luminance of the stimulus or its location on the retina. With new high dynamic range (HDR) displays, operating at higher luminance levels, and virtual reality (VR) displays, presenting at wide fields-of-view, the effective CFF may change significantly from values expected for traditional presentation. In this work we use a prototype HDR VR display capable of luminances up to 20,000 cd/m^2 to gather a novel set of CFF measurements for never before examined levels of luminance, eccentricity, and size. Our data is useful to study the temporal behavior of the visual system at high luminance levels, as well as setting useful thresholds for display engineering.

Introduction

The Critical Flicker Fusion Frequency (CFF) is an important measure of human temporal contrast vision. It is quantified as the frequency in Hertz at which flickering stimuli become perceptually stable. Similarly to closely related spatial models like the *contrast sensitivity function* (CSF) The value of the CFF is known to be affected by several properties of the stimulus, including mean luminance level, contrast in relation to the background, retinal eccentricity, spatial characteristics (such as frequency for a Gabor-type stimulus), color or wavelength for chromatic stimuli, size, viewing distance, and surround luminance conditions [1, 2, 3, 4, 5]. The high number of factors leads to an exponential growth in possible combinations, and as a result it is challenging to perform a comprehensive study of the CFF [6].

Although the CSF has been studied across a wide range of luminances [7], there is little CFF data at very high luminance levels. With HDR (High Dynamic Range) display technology rapidly improving and consumer displays often reaching peak values over 1,000 cd/m^2 [8], there is an acute need for characterising temporal vision at high luminance levels. This need is further exacerbated to avoid visible flicker in wide field-of-view displays (in particular, virtual reality, or VR displays), as unlike most visual thresholds there is evidence pointing to higher sensitivity for flicker outside the fovea [1, 4]. Finally, modern display use may involve activities in which large, bright stimuli are presented routinely during activities like web-browsing. As stimuli of larger size are known to increase the CFF [1], exploring the impact of very high sizes on flicker is important to avoid presenting visible artifacts to users.

The goal of our work is to bridge the gap in the CFF literature by investigating the relationship between sensitivity to flicker and very high photopic luminances under natural viewing conditions (natural pupil) for a variety of retinal eccentricities. In addition, we explore a unique full field-of-view condition and contrast results to traditional disk stimuli.

Related work

The most popular model of CFF in relation to luminance is the *Ferry-Porter law*, which dictates that the CFF increases with the logarithm of increasing luminance [10, 11]. However, most studies that corroborate this finding are limited to low to moderate light levels. The data from Porter's 1901 study [11], and Ives' 1912 study [12] show good adherence of experimental results to the Ferry-Porter model up to $\sim$ 0.8, 0.5 cd/m^2, respectively.

The only study examining the CFF past 1000 cd/m^2 comes from a series of works by Hecht and colleagues, who studied the relationship between CFF and luminance levels for different retinal eccentricities [13], light wavelengths [14] and stimulus sizes [15]. A sigmoidal relationship between the CFF and log luminance for foveal stimuli was shown, the linear part of which (adhering to the Ferry-Porter law) extends up to $\sim$1000 cd/m^2, after which the rate of increase of CFF slows and reaches a peak of about 50 Hz at $\sim$4000 cd/m^2. They also showed a slight increment in the CFF when rigid fixation was not stipulated in their methodology, which can be interpreted as the CFF being higher for less controlled (or more natural) viewing conditions. For parafoveal stimuli, their data shows that the CFF vs. log luminance curve follows a two-part sigmoidal relationship because of the presence of rods in the parafovea and the different luminance activation ranges of rods and cones [13]. Hecht and Smith (1936) have also shown that CFF increases with stimulus size (reaching up to 60 Hz for a 19° foveal stimulus) and shows the same sigmoidal relationship [15]. Brooke has shown a similar plateauing of CFF for high luminance levels at different peripheral locations with a constricted pupil [16].

Hartmann et al. (1979) have shown that the linear relationship between the CFF and retinal luminance is preserved for luminances up to 70 cd/m^2 for foveal and parafoveal stimuli using a natural pupil [1]. Later studies by Tyler and Hamer [3] reported the extent of the linear relationship between the CFF and retinal illuminance to up to $\sim$4 log Td. However, their methodology involved dilating the observers' pupils, making the effective luminance range lie below 1000 cd/m^2. Recent work by Krajancich et al. (2021) employs Gabor patch stimuli to investigate the relationship between the CFF, luminance levels, and spatial frequency. They have also shown adherence to the Ferry-Porter law for luminances below 190 cd/m^2 [4].

The physiological basis of the relationship between CFF and luminance is unclear but several studies have offered some possible explanations. Some studies have showed a plausible link between the temporal properties of the retinal photoreceptors and the approximately linear increase in CFF with luminance level in human [17], cat [18] and primate visual systems [19]. In contrast, a perceptual difference study using dynamic natural scenes has shown that the link between perceived differences and spatio-temporal properties of the stimuli can be explained by cortical temporal (sustained and transient) channels [20].

To conclude, the nature of the relationship between the CFF and high luminances under natural viewing conditions common in practical display usage scenarios has not been fully explored. Studies examining higher luminance ranges indicate that the Ferry-Porter law may provide a good fit up to about 1000 cd/m^2, but further increasing the luminance causes the CFF to saturate or even decrease, but little data is available to model this behaviour. Our study examines the CFF up to 8000 cd/m^2, the highest value ever examined and the first study in 90 years [13] to evaluate this artifact for luminance levels above 1000 cd/m^2.

Our study

Device To study flicker fusion at very high luminance levels, we needed to employ a display capable of both high luminance and dynamically changing refresh rates to enable users to select thresholds with appropriate granularity. To accomplish this, we used a custom high-dynamic-range virtual reality demonstrator capable of peak luminances over 20,000 cd/m^2 [21] (see Figure 1). Flickering stimuli were rendered by showing a constant image of the stimulus on the LCDs. LED backlights were modulated at frequencies up to 100 kHz using Thorlabs DC2200 controllers to simulate target frequencies. Persistence was kept constant at 50%.

Stimuli For the main portion of the study, stimuli consisted of disks of varying luminance placed at one of three retinal eccentricities. A central fixation cross was displayed at a low luminance level for non-foveal stimuli, with the rest of the screen remaining dark. The following combinations of parameters were used:

- Luminances: 10, 100, 173, 299, 517, 894, 1547, 2675, 4626 and 8000 cd/m^2.
- Eccentricities: 0, 10, and 20° along the nasal axis
- Sizes: Kept constant at 1°, or compensated for eccentricity via a cortical magnification model (Rovamo et al. [22]), yielding sizes equivalent to 1° at the fovea as follows: 4.4° at 10° of eccentricity, and 8.2° at 20° of eccentricity.

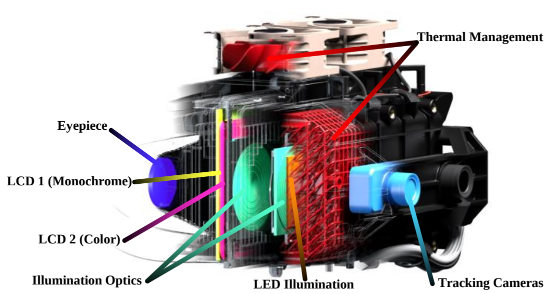

Figure 1. The display used to run our experiment: light from two 60 W chip-on-board LEDs is steered using a pair of fresnel illumination optics. The image is formed via a pair of stacked LCDs, and presented to the user through achromatic doublet lenses. Image courtesy of Matsuda et al. [9]

In addition, we collected data for stimuli consisting of a uniform white field at the same luminance levels as the main study.

Participants 15 observers participated in the main study with disk stimuli. 6 observers took part in the follow-up exploration using full-field stimuli, two of whom ran twice. All the participants were recruited internally at the host institution, had normal or corrected-to-normal vision, and provided informed consent. Users learned experimental protocol and controls in a brief training session, and a qualitative post-study survey was collected.

Procedure Data was obtained using the method of adjustment. Observers adjusted the refresh frequency until they could not perceive the flickering and the disk appeared solid. 50 unique trials were examined (10 luminance levels, 3 eccentricity levels with 2 sizes for non-foveal eccentricities). To avoid hysterisis, each condition was shown twice, starting from either a very high or very low refresh rate, resulting in 100 total trials, which were presented in random order. Study duration was approximately 50 minutes.

Results and discussion

The results of our study are summarised in Figure 2. For the foveal stimuli (top-left plot), the CFF increased from 34 Hz at 10 cd/m^2 to 52 Hz for 1000 cd/m^2 following the Ferry-Porter law. The CFF fluctuates between 45 and 55 Hz as the luminance of the stimulus goes beyond 1000 cd/m^2. The decrease in CFF from $\sim$1000 to 4000 cd/m^2 is comparable to that presented by Hecht in 1933 [13]. The two highest luminance conditions we examined go beyond previous CFF literature, and show an increase in sensitivity past 4000 cd/m^2. Given the noise inherent to our measurement procedure which leads to overlapping error bars in this range, further exploration is desirable before conclusions can be drawn. It is interesting to contrast this data against a comparable high luminance result for a spatial-only CSF dataset gathered by Wuerger et al. [7] (Figure 3). Similar to our foveal measurement, the contrast sensitivity curve shown is measured using a 1 cycle-per-degree Gabor patch with a 1° Gaussian envelope. The contrast sensitivity reaches a maximum at 200 cd/m^2 and starts to decline somewhere between 200 to 2000 cd/m^2. However, unlike our CFF data, this decline extends to 10,000 cd/m^2. This indicates that the change in visual contrast sensitivity with luminance may be inconsistent for spatial and temporal visual mechanisms.

We have fitted straight lines to the linear part of our data (dashed lines in Figure 2). The data intervals with numerical gradient lower than 2 Hz/log luminance were selected for this fit. The values of slopes and the measured maximum luminance level where the Ferry-Porter law is valid are reported in the figure. Tyler and Hamer, (1990) have reported a slope of 9 Hz/log luminance [3], which is comparable to our 8.5 Hz/log luminance (top left in Figure 2). However, the decrease of slopes with eccentricity shown in our data is contrary to the trend shown in the series of work by Tyler and colleagues where the slopes get steeper with increasing eccentricity [23, 3, 24]. Though, it should be noted that the flickering stimuli used in their work were spectrally monochromatic and isolated a single cone system and the surround was uniform 40 cd/m^2 white field. Hecht and Verrijp (1933)

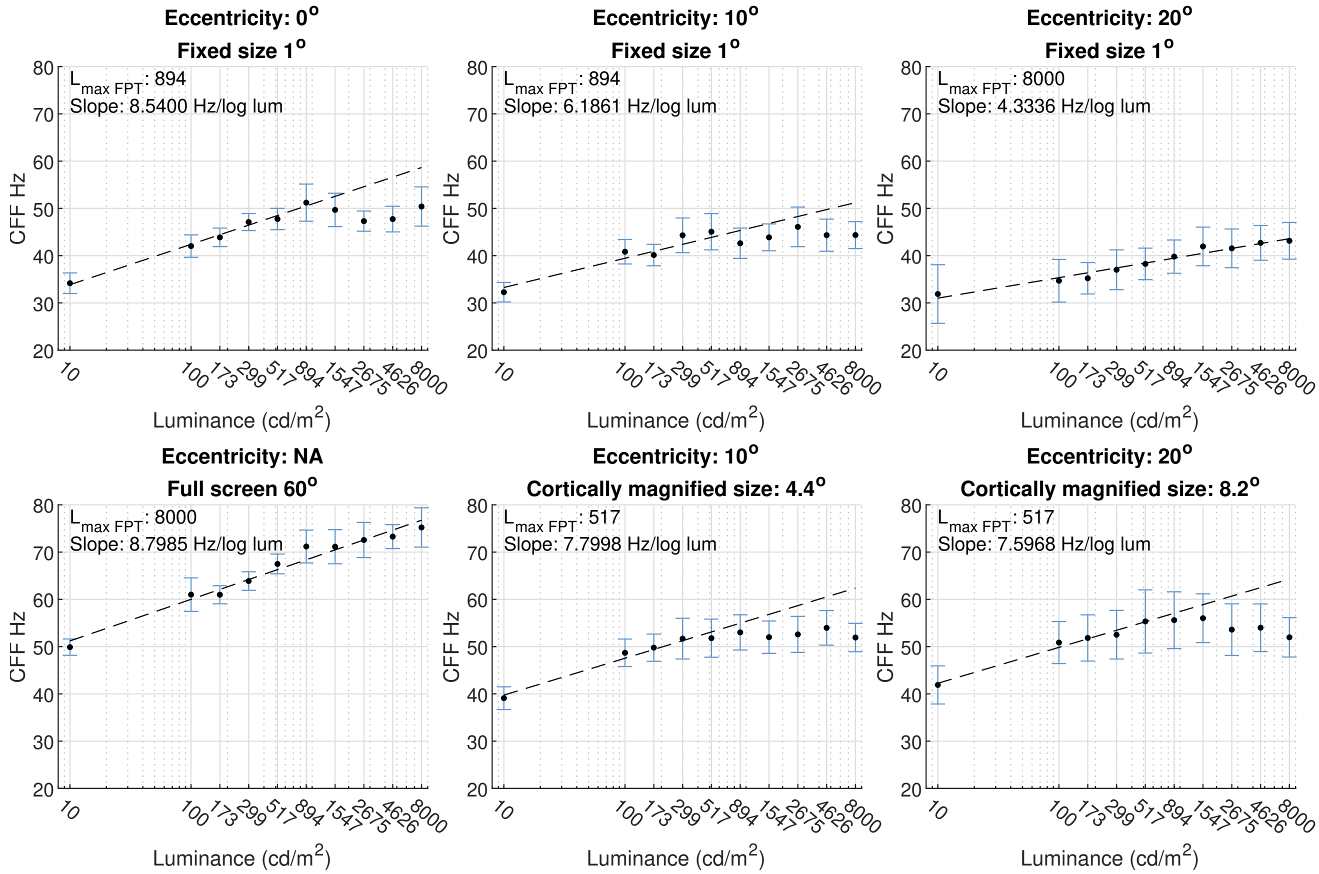

Figure 2. *Results of our studies (bottom-left plot for full field flicker; all other plots for circular stimuli with a dark surround). Each circle shows the mean for the examined condition. Outliers over 2 standard deviations were replaced by the mean to avoid an undue influence. Vertical bars show 95% confidence interval. The black dotted line shows a best-fit straight line for the linear part of the datasets (calculated per plot).* L_{maxFPT} *represents the maximum of the measured luminance range where Ferry-Porter law is valid.*

who have used a much smaller surround of 10° have showed the same trend as ours where the slope decreases with increasing eccentricity [13].

Peripheral measurements were done with either fixed size stimuli (Figure 2, top row) or cortical magnification corrected stimuli (Figure 2, bottom row). As expected, fixed size peripheral stimuli have lower CFF values compared to their counterparts magnified with the eccentricity. This effect is shown in Figure 4 for the 10° (top) and 20° cases (bottom). CFF increases with increased stimulus size are consistent with the Granit-Harper law and results shown in other studies [25, 4]. In particular, Hartmann et al. (1979) [1] have shown a semi-log relationship between the CFF and stimulus area for foveal and near-foveal stimuli. As our study only covers two sizes, we cannot verify this trend. Just going by the means, there is a slight difference in slopes for different luminance levels in Figure 4. However, because of the large measurement noise and only two measured sizes, we can not infer conclusively whether luminance level has an effect on the rate of change of CFF with size. There might be a joint effect of luminance level and stimulus size on peripheral CFF, as demonstrated by Rovamo and Raninen (1984), where they scale both area and luminance by the cortical magnification factor [2].

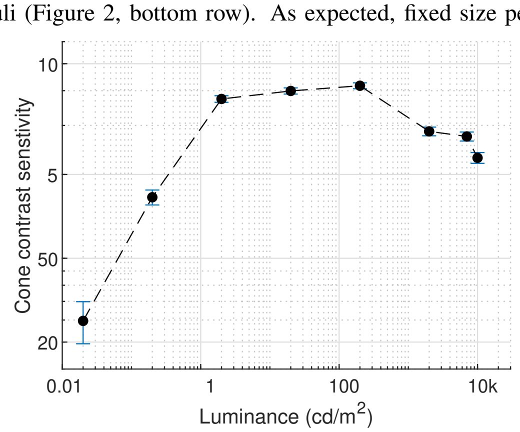

Figure 3. *Contrast sensitivity data for comparison. Stimuli are static black and white Gabor patches of 1 cycles per degree (spatial frequency) and 1° Gaussian envelope. Error bars denote standard errors.*

In addition, the CFF had lower values at higher eccentricities when size was kept constant (Figure 5, bottom), which is similar to what Hecht and Verrijp (1933) have shown as well [13]. This finding is contrary to what some other comparatively recent studies have shown [1, 2, 4]. For parafoveal stimuli with sizes adjusted to compensate for cortical magnification, we observe the opposite effect (Figure 5, top), i.e. the CFF tends to increase with higher

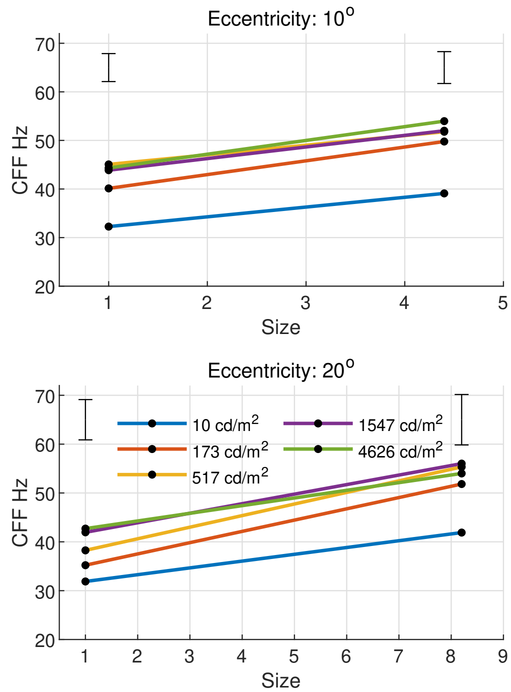

Figure 4. *Results of CFF as function of size. 1° stimuli are without cortical magnification factor applied for peripheral stimuli. The larger stimuli account for cortical magnification. The error bars show the average 95% confidence interval for the data points below them.*

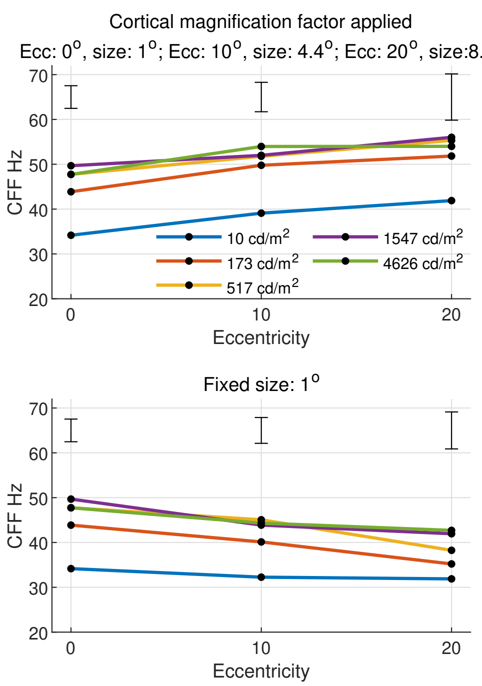

Figure 5. *Results of CFF as a function retinal eccentricity. Top plot shows the results for stimuli adjusted with cortical magnification factor (stimulus size increases with eccentricity), while the bottom plot is for stimuli without cortical magnification factor applied (stimulus size remains constant across eccentricities). The error bars show the average 95% confidence interval for the data points below them.*

eccentricity, in line with what Tyler (1987) had shown in their study with stimuli size adjusted with cortical magnification factor [23]. This effect could be due to a true improvement in temporal sensitivity on the periphery, e.g. due to the relative increase in incidence of magno ganglion cells, which are known to have an effect on flicker fusion [26] in the periphery [27]. Alternatively, this could be due to imprecision in the cortical magnification factor value, or other external influences such as imperfect luminance compensation or artefacts due to the display's optics at higher eccentricities.

Finally, we also measured the CFF for full-field flickering stimuli, which in our display amounted to a field-of-view of approximately 60° [21]. The vignetting introduced by the optics of the display was inverted to produce constant luminance up to 20 degrees of eccentricity, but had a smooth roll-off at further values to avoid excessive dimming in the center. Figure 2 (left, bottom panel) shows that the CFF for full-field stimuli is at least 15 Hz higher then that of disk stimuli in the main study, which can be attributed to the much larger size. No saturation of the CFF value with luminance increase is present. The Ferry-Porter law appears to be valid across the entire range, with CFF values in a log-linear relationship to luminance. This finding means that large high-luminance stimuli, such as those present in e.g. web-browsing applications, may require a higher refresh rate to minimise noticeable flicker. An interesting question is whether the CFF continues to increase beyond the 8000 cd/m^2 value measured in this .

Conclusions

We gather a high luminance CFF dataset for different retinal locations and sizes. We find that the CFF seems to saturate around 1,000 cd/m^2 for disk stimuly, but the same is not true for full field stimuli, which follow the Ferry-Porter law well up to 8000 cd/m^2. Our data shows that the CFF decreases with eccentricity for constant stimulus sizes, but increases with eccentricity if the stimulus size is adjusted using the cortical magnification factor. Future work may investigate additional influences, such as the effect of background luminance and differently coloured stimuli on the CFF.

Acknowledgements

The authors thank Ken Koh and Yu-Jen Lin for help with the experimental software. We thank Cameron Wood and Helen Ayele for their work organising the subjective study, and the anonymous participants for their efforts.

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