When Does the Hidden Butterfly Not Flicker?

Jing Liu[1], Soja-Marie Morgens[1], Robert C Sumner*[1], Luke Buschmann[1], Yu Zhang[2], and James Davis†[1]

[1]University of California Santa Cruz
[2]Nanjing University

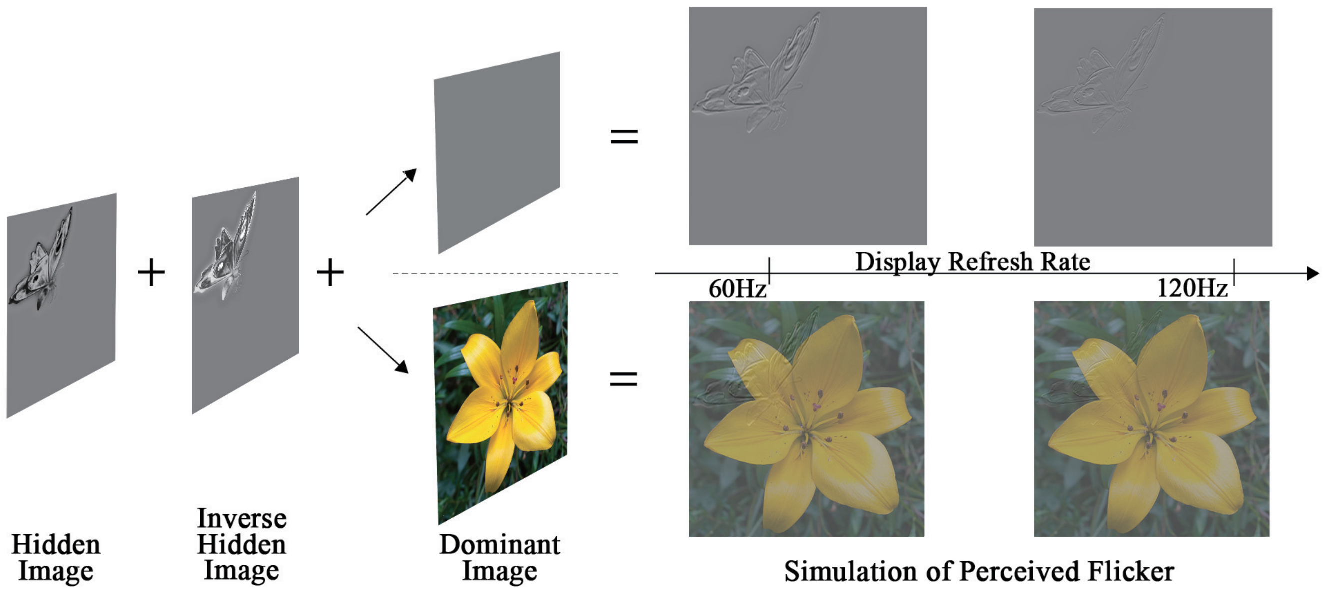

Figure 1: *Hidden channel displays rely on a flicker fusion rate of 60Hz to hide the hidden channel from the naked eye. This figure shows a simulation of the observed structural flicker in hidden channel displays. The* Hidden Image *frame, when displayed in rapid sequence with the* Inverse Hidden Image *frame, should integrate into a gray field and become invisible to the human eye. Viewers should perceive a flicker-free* Dominant Image*, either a gray field (top row) or a flower (bottom row). However, our user study shows that the flickering structure is obvious even at frequencies above the traditional flicker fusion rate of ∼60Hz. In addition to temporal frequency, the image content in the* Dominant Image *has significant impact on the perceived amount of flicker.*

CR Categories: I.3.3 [Computer Graphics]: Picture/Image generation—display algorithms

Keywords: Flicker, Computational Displays

1 Introduction

The emergence of high frame rate computational displays has created an opportunity for viewing experiences impossible on traditional displays. These displays can create views personalized to multiple users, encode hidden messages, or even decompose and encode a targeted light field to create glasses-free 3D views [Masia et al. 2013].

Yet as these displays break new ground in functionality, they also bring complex display patterns that have never appeared on traditional displays. Commonly accepted standards for traditional displays might no longer apply to these new displays. For example, under what conditions do viewers no longer perceive flicker?

Flicker is the ability of the eye to perceive each frame as distinct rather than as a blended entity. It is a perceptual effect caused by temporally alternating brightness values, and depends fundamentally on the differences of the brightness and the temporal display rate. The Critical Flicker Fusion (CFF) threshold, the frequency at which alternating brightness differences are no longer perceived by the average viewer, is widely accepted to be at a 50-90Hz refresh rate [Kelly 1974; Varner et al. 1984].

While 60Hz CFF is used as the standard for traditional displays, this threshold may no longer be accurate for emerging computational displays with complex coded temporal structure.

In this paper we investigate computational displays with temporally encoded hidden channels. This particular class of display has many applications, ranging from augmented television, where imperceptible patterns are hidden from human eyes but can be reconstructed by a synchronized camera [Grundhofer et al. 2007], to encryption of confidential information on displays [Wu and Zhai 2013], to simultaneous 3D and 2D viewing of stereoscopic content [Scher et al. 2013].

Hidden channel displays show sets of images in sequence; each set contains a dominant channel, a hidden channel, and an inverse

*The first three authors contributed equally
†e-mail:{jingliu, smorgens, rcsumner, lnbuschm, davis} @soe.ucsc.edu

hidden channel, as indicated in Figure 2.

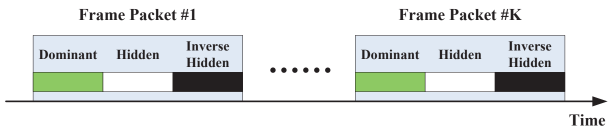

Figure 2: *Frame packets contain a set of images to be displayed rapidly in sequence. In our study, frame packets contained three images each:* Dominant Image*,* Hidden Image *and* Inverse Hidden Image*.*

The *Inverse Hidden Image* is the luminous complement to the *Hidden Image*. These two frames, when alternately displayed, are intended to produce a spatially uniform gray field when integrated by the human eye, thus effectively "hiding" their image content. Here we define the *frame packet rate* as the rate at which the frame sets are refreshed. A 60Hz frame packet rate is equal to 60 frame packets per second, or 180 total image frames per second shown on the display.

We performed user studies to investigate the necessary frame rate for flicker fusion on this type of display. In our studies we found that the required frame packet refresh rate for displays with a hidden channel can be much higher than the widely accepted $\sim$60Hz CFF rate. Depending on content, flicker artifacts are easily perceived on these displays even at a 120Hz frame packet rate. Since the actual effect can only be seen on a high speed display, Figure 1 shows a simulation produced by image processing mimicking our hypothesis that this content dependent flicker is caused by eye saccades.

In order to ground our perceptual findings, we investigated their application to 3D+2D TV, one of the many applications of hidden channel displays. On these displays, viewers with synced glasses see 3D content while viewers without glasses simultaneously see 2D content.

We conducted additional studies to investigate the presence of flicker in the special case of stereoscopic content, as found on these devices. We found that the structural similarity of the stereoscopic content in these images has a masking effect that reduces the perception of flicker.

Based on these results we built a prototype 3D+2D TV and tested it with users. When using the widely accepted CFF rate the prototype was observed to flicker. When temporal frequency and luminance ratio parameters were set according to the results of our perceptual studies, flicker was no longer observed.

The primary contributions of this paper are:
1. Perceptual studies on a computational display that indicate that the flicker fusion threshold is content dependent, and can be higher than for traditional displays.
2. A prototype 3D+2D TV configured according to our user studies, on which users reported no flicker.

2 Related Work

Flicker Phenomenon: The Critical Flicker Fusion (CFF) threshold is the point at which successive light flashes are perceived as continuous. Light flashes operating below the CFF are seen as flicker, while any light flashes operating above the CFF are perceived as a single blended image. Flicker was noticed as early as 1740 and was brought into perception science in 1953 [Landis 1953]. Displays operating below the CFF can cause discomfort and eye fatigue to their viewers [Baccino et al. 2001; Tam et al. 2011].
[Farrell et al. 1987] identified display luminance and the refresh rate as the two critical factors in determining the CFF for displays. In their equation, increasing a display's luminance makes flicker easier to see while increasing a display's refresh rate makes flicker harder to see. The spatiotemporal video displays of that time were thus rated as having a CFF of 50-90Hz and many studies and display standards have maintained these findings. However when testing for flicker, studies have generally used spatially uninteresting images [Robson 1966; Kelly 1974; Farrell et al. 1987]. These images were either uniformly black and light fields, or simple codes of alternating black and white. Modern computational displays use far more complex coded images.

Motion and Phantom Arrays: More recent studies have found that when the point of interest is in motion, humans perceive flicker at display refresh rates above the currently used CFF thresholds. Researchers attribute this to rapid eye movements known as saccades, in which the eyes rapidly change gaze direction [Watson 2013]. An additional effect known as the phantom array causes viewers to see flicker in point light sources modulated at high frequencies [Hershberger and Jordan 2012]. While we believe these effects are related to the one we study, none of the prior work provides any discussion of the frame rates required for content on coded computational displays.

Flicker due to hidden channels: Grundhofer et al. designed a hidden channel display with the purpose of embedding a coded message discernible by a camera but not by a human viewer [Grundhofer et al. 2007]. They identified flicker as a problem and measured the luminance ratio at which it could be suppressed on their display. However, many displays with hidden channels simply assume a 60Hz refresh rate is sufficient for avoiding flicker. In building a 3D+2D display, Scher et al. proposed a 3 frame packet with refresh rate of 60 Hz [Scher et al. 2013]. Similarly, the temporal psychovisual modulation display for multiple view points uses a 4 frame packet at 60Hz [Wu and Zhai 2013]. Neither experimented with the appropriate frame packet refresh rate for hidden displays.

3 User Study

We designed user studies to explore how some important display parameters and image content affect the level of flicker perceived in hidden channel displays with static images.

Study design: In this study, we displayed static hidden channel scenes to users and asked them to subjectively rate their perception of flicker. We showed the users different scenes multiple times with randomly chosen parameter values for the frame packet rate and the luminance ratio of hidden content to dominant content.

Each scene consisted of a frame packet as displayed in Figure 3. Each contained a *Hidden Image* which was originally the right view of a stereoscopic pair and an *Inverse Hidden Image* to cancel it out. The *Dominant Image* was either the left stereoscopic view or a flat gray image, chosen with equal likelihood. This choice was to compare the perception of flicker when there is no structural content in the *Dominant Image* to when it has similar structural content to the *Hidden Image*. We hypothesized this would help mask the flickering. Furthermore, the study design lends itself directly to understanding 3D+2D displays.

Our data set contained 10 pairs of stereoscopic images, of which 7 were natural images and 3 computer generated scenes. All individual image frames were shown in 6-bit grayscale. Frame packet rate was uniformly sampled at 60, 80, 100 and 120Hz. The luminance ratio (as defined in Equation 1) was sampled at 0.1, 0.4, 0.7 and 1.0

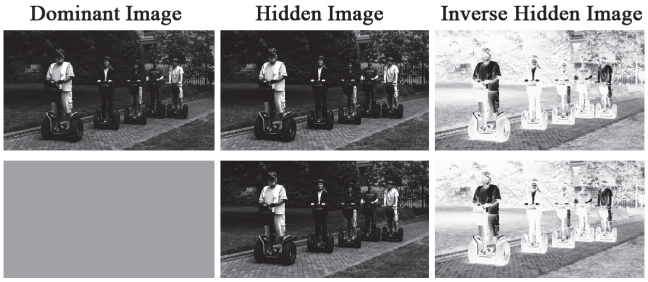

Figure 3: *Example Test Frame Packets. (top row)* Dominant Image *as left eye stereoscopic view; (bottom row)* Dominant Image *as a spatially uniform gray field. In both cases the* Hidden Image *is the same: the corresponding right eye stereoscopic view.*

$$\textbf{luminance ratio} = \frac{\textbf{max\_intensity}(\ Hidden\ Image\ )}{\textbf{max\_intensity}(\ Dominant\ Image\ )} \quad (1)$$

In order to minimize learning bias, each user was initially shown the same four practice images which reflected the test's total range of flicker. In the actual test, the ordering of parameters and the image choices were randomized for each user.

We conducted the study on 10 users. Each user test was conducted in a dark room, with participants sitting at a distance of 1m away from the screen (40cm x 25cm). The screen was illuminated by a TI Lightcrafter 4500 projector with a measured luminance of 90 cd/m^2. Standard description and instructions were given to every participant in this user study.

Participants were asked to rate the flicker at integer ratings from 0 to 3, with 0 being no flicker, 1 being a little flicker, 2 being obvious flicker and 3 being severe flicker. In order to reduce biasing from after-images on the viewer's retina, each participant was asked to close their eyes for two seconds between test images. For each setting in the two-dimensional parameter space, 40 data points were collected and averaged scores are shown in the result figures.

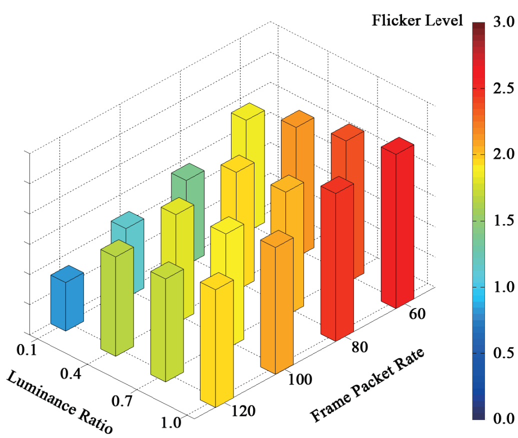

Figure 4: *Average user perception of flicker when the* Dominant Image *is a uniform gray field. Users reported 0-3, with 3 being very annoying flicker and 0 being no flicker. Users perceive flicker more as the luminance ratio increases or the frame packet rate decreases.*

Study results: Though all of our test conditions fell above current display CFF standards, all users reported seeing flicker for at least some of the tested conditions.

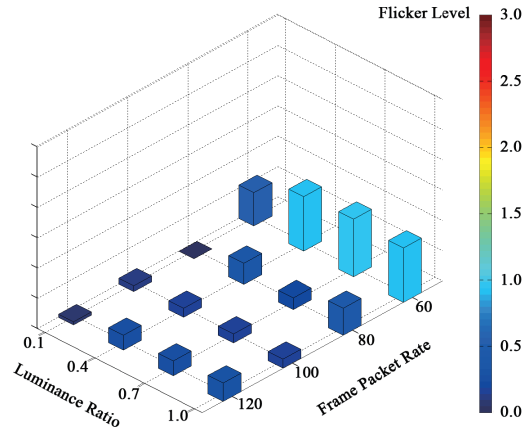

Figure 5: *Average user perception of flicker when the* Dominant Image *has (stereoscopic) content similar to the* Hidden Image*. Compared to the case of dissimilar content as reported in Figure 4, the perceived flicker is significantly less at all parameter settings. While, the average user sees flicker at 60Hz, most perceive no flicker at higher frequencies.*

Figure 4 shows the results for tests where the *Dominant Image* is a flat grey field. Observe that an increased frame rate lowers flicker visibility and an increased luminance ratio increases flicker visibility. This is consistent with previous CFF related perceptual studies. However, everywhere in this luminance-frequency space, multiple users perceive flicker. This contradicts the standard $\sim$60Hz CFF frame packet rate currently used in hidden channel displays. At a full luminance ratio, most users found the flicker obvious, even at 120Hz.

Figure 5 shows the results for tests where the *Dominant Image* is the left eye stereoscopic image corresponding to the right eye hidden image. It is obvious when compared to Figure 4 that having a non-trivial *Dominant Frame* significantly reduces the perception of flicker. While most users perceive "a little flicker" at 60Hz, 90% of users reported seeing no flicker at 80-120Hz when the luminance ratio was 0.7 or less.

These studies indicate that not only is the flicker fusion rate higher than the standard but it is also content dependent for hidden channel displays. Structure in the *Dominant Image* effectively distracts the viewer from perceiving flicker as severely, even at the same luminance ratio and frame packet rate. Moreover, we hypothesize that the strong content similarity of the *Dominant Image* to the *Hidden Image* due to their being a stereoscopic pair enhances this effect due to sharp image edges (the main culprit in the perceived flicker) being in roughly similar places in the pair of stereoscopic images.

4 Prototype for 3D+2D Display

We built a prototype of the 3D+2D TV presented in [Scher et al. 2013]. In this method, a 3D viewer wears shutter glasses to provide left and right viewpoints, while a 2D viewer wears no glasses and sees the integral of all light on the screen. The original work demonstrated a multi-projector prototype using polarization to provide a non-modulated *Inverse Hidden Image*, but hypothesized that the method will be most applicable to and best implemented on temporally multiplexed displays. The authors use the conventional CFF rate and therefore hypothesized that a 180Hz displays (60Hz frame packet rate) would be sufficient. The perceptual studies presented here contradict this assumption, and using our prototype we indeed found that the original proposed rate was insufficient to provide a flicker free display.

Implementation: Our prototype, as seen in Figure 6, used the same DLP Lightcrafter 4500 to provide grayscale three-frame packets (*Left Eye/Dominant Image*, *Right Eye/Hidden Image*, and *Inverse Hidden Image*). An Arduino Uno synchronized a pair of stereoscopic Sony SSG-4100Gb 3D Active glasses to the projector. The left lens is synchronized with the *Left Eye Image*, the right lens with the *Right Eye Image*, and the *Inverse Hidden Image* is blocked from both lenses.

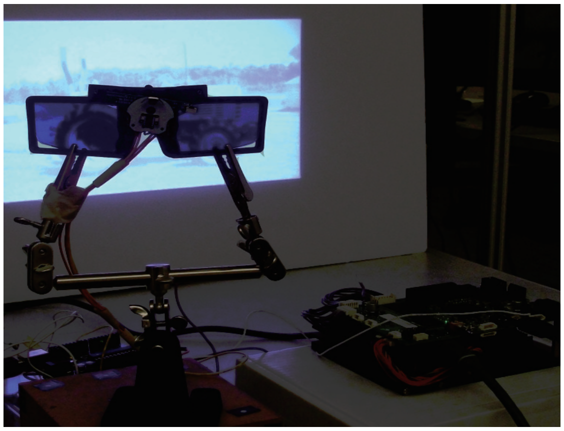

Figure 6: *Prototype 3D+2D TV built using parameters derived from our perceptual studies. A pair of stereoscopic glasses allows a user to see a 3D image while viewers without glasses see a 2D flicker-free image.*

Parameter selection: A 3D+2D display must balance the desire of the 2D viewer with that of the 3D viewer. The 2D viewer prefers a *Right Eye/Hidden Image* with a low luminance ratio to increase 2D image contrast, while the 3D viewer would prefer the left and right eyes to have equal brightness, i.e. a luminance ratio of 1.0. The work of [Scher et al. 2013] found a luminance ratio in 0.25-0.40 to be acceptable to both classes of viewers. We chose a ratio of 0.40 in our prototype. Referring to our perceptual studies using stereoscopic content with this luminance ratio, we found that viewers see flicker at 60Hz but not at 80Hz or above. Thus, our prototype used a frame packet rate of 120Hz.

Evaluation: We evaluated our prototype with viewers who did not participate in our previous user tests. We first asked viewers to use 3D glasses and report whether they see acceptable 3D. All viewers reported 3D viewing. We next asked viewers to view the video in 2D without glasses and report the presence or absence of flicker. At the 60Hz frame packet rate proposed in prior work, the majority reported flicker. At the 120Hz frame packet rate set based on our perceptual studies, no viewers reported flicker.

5 Conclusion and Future Work

This work has shown that computational displays with temporally coded content sometimes have critical flicker fusion (CFF) rates well above the textbook rates of traditional displays. In addition we demonstrated that CFF is content dependent, a fact usually ignored in display design. We found that CFF was much higher using flat field dominant images than when using stereoscopic-pair dominant images. We used our findings to investigate one type of recently proposed computational display, and demonstrate a prototype 3D+2D TV without flicker.

Our studies were performed on relatively simple hidden channel displays, and investigated only two types of content. An important area of future work is to quantify the CFF for other types of displays and for other applications. In addition, we offer no quantification of the perceptual masking that apparently occurs under some conditions. Future work will hopefully provide a theoretical framework for masking allowing display and application designers to know in advance at what rate they must drive hidden channel displays to avoid flicker artifacts.

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