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# Flicker Observer Effect: Guiding Attention Through High Frequency Flicker in Images

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**Abstract**

*Drawing the user's gaze to an important item in an image or a graphical user interface is a common challenge. Usually, some form of highlighting is used, such as a clearly distinct color or a border around the item. Flicker can also be very salient, but is often perceived as annoying. In this paper, we explore high frequency flicker (60 to 72 Hz) to guide the user's attention in an image. At such high frequencies, the critical flicker frequency (CFF) threshold is reached, which makes the flicker appear to fuse into a stable signal. However, the CFF is not uniform across the visual field, but is higher in the peripheral vision at normal lighting conditions. Through experiments, we show that high frequency flicker can be easily detected by observers in the peripheral vision, but the signal is hardly visible in the foveal vision when users directly look at the flickering patch. We demonstrate that this property can be used to draw the user's attention to important image regions using a standard high refresh-rate computer monitor with minimal visible modifications to the image. In an uncalibrated visual search task, users could in a crowded image easily spot the specified search targets flickering with very high frequency. They also reported that high frequency flicker was distracting when they had to attend to another region, while it was hardly noticeable when looking at the flickering region itself.*

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Computer Graphics]: User Interfaces—Evaluation/methodology

## 1. Introduction

Many types of media and applications use mechanisms to attract the user's attention. Examples are advertisements, desktop notifications, visualizing responses to human interaction in interactive systems, and guiding the user's attention along a narrative through a dynamic scene. In highly complex scenes with a lot of colors, heterogeneous shapes, motion, and audio, the entire content often needs to be visually compressed – for instance, darkened [KMFK05], blurred [KMH02], or scaled down [Fur86] – to make an item of interest stand out effectively. This may be undesirable due to information loss [ZWSK97], distorted perception of the scene [GF04], or simply because users feel disrupted when the entire content is modified.

In order to gently attract the user's attention, very subtle techniques are employed, for instance modulation of visual saliency [MB16, KV06, VMFS11]. However, subtle techniques, in turn, can be easily missed. What would be desirable is a technique that effectively catches the user's attention only when the attention is currently directed somewhere else, and ceases to be noticeable when directly looking at it.

In the past, such an effect was achieved by using an eye tracker to detect whenever a user initiated a saccade towards the image's area of interest and to remove the modulation [BMSG09] . However, an eye tracker may restrict the user's freedom of movement and limits the application to a single user. In this paper, we describe a method for attracting an observer's gaze using flicker on high frequency monitors – which we call the *flicker observer effect*. These monitors are becoming more widespread nowadays to provide high refresh-rate technology or the possibility to interpolate between movie frames in order to decrease motion blur. We thereby make use of the fact that sensitivity to flicker varies across the retina [Tyl87], with sensitivity being higher in the periphery. This means that at a certain frequency, flicker can only be perceived in the visual periphery, but fuses to a stable signal when the blinking image area is directly looked at. However, whether or not a user can detect flicker depends on several other factors than the flicker frequency, such as size and luminance [Dav12]. We therefore performed multiple experiments to investigate the suitability of high frequency flicker to efficiently and non-distractingly attract

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the user's attention in images. As a result, our contributions are as follows:

- Determined through a psychophysics experiment, we present target region size and luminance ranges for targets flickering with 60-72 Hz so that the desired flicker observer effect can be achieved.
- We demonstrate that, using these settings, flickering items indeed can be reliably detected in the visual periphery, but are rarely seen in the foveal vision.
- We showcase the usefulness of the flicker observer effect on a visual search task in a complex scene. We show how to modify the images to integrate the flicker observer effect and report subjective feedback by 14 observers, which indicates that the flicker observer effect is highly effective, yet hardly noticeable – and therefore minimally disturbing – when directly looking at the flickering target.

## 2. Related work

Using some sort of highlighting or "attention retargeting" technique [MB16] to direct the user's attention to semantically important image regions is a common task in various domains, such as user interface design [ZWSK97, BWC03, GBM07, HBW08], visualization [War12, Rob11], or augmented reality [VMFS11]. Highlighting of important scene elements can deepen the observers' insights by strengthening their engagement [HE12] and improving recall [Low03]. We will first give a concise overview of existing highlighting techniques and then present highlighting techniques using flicker.

### 2.1. Highlighting Techniques

A large variety of highlighting techniques have been used in graphical interfaces, visualizations, or images to effectively guide the user's attention. Taken literally, a highlight effect can be achieved by making the target brighter (or, in turn, by making the surrounding context darker [KMFK05]). Others use distinct colors [SOK*16], spatial distortions [Fur86], artificially added leader lines [HBW08], or blur less important elements [KMH02] to make elements of interest visually stand out. A less common form of highlighting involves the usage of motion [BWC03] or stereoscopic effects [AHKMF11].

While a common goal of highlighting is to make elements of interest clearly distinct from their context [War12], others try to achieve subliminal attention guidance by using very subtle highlighting methods. For instance, subtle modulations of image features to selectively increase or decrease the local saliency were used to direct the user's attention in videos [VMFS11] and volume visualizations [KV06]. In contrast, the goal of our flicker observer effect is not to be subliminal. Our intention is rather to keep the visible modifications of the image to an absolute minimum, while still generating a strong attention guidance effect.

### 2.2. Highlighting Using Flicker

While there are only a few attempts at using flicker to attract the observer's attention, they can be sorted into three groups. The first group highlights items of interest by modulating their luminance with a constant amplitude and a constantly low frequency around 1 to 3 Hz [BWC03, WB04, HBW08, GBM07]. Depending on the chosen amplitude and frequency, users described the use of flicker as attractor either as disturbing or as rather ineffective.

To reduce the nuisance introduced by stable flicker, the second group uses what can be described as a decaying flicker. The flicker is initiated with a high frequency and amplitude and quickly decays into a smooth pulsation using a lower frequency and amplitude [WLMB*14]. This way, the attention is effectively attracted at signal onset, but the signal is quickly turned into a clearly visible yet not alerting visual indication. However, balancing the highlight strength and subtleness is also always a compromise – either in terms of signal effectiveness or in terms of visual quality.

Another method to reduce the discomfort when using flicker is to make it gaze-dependent. *Subtle gaze direction* (SGD) uses an eye-tracker to turn off the flicker when the user initiates a saccade towards the flickering region of interest [BMSG09]. Studies have demonstrated the effectiveness of SGD for static image regions [BMSG09] as well as narratives through artwork [MBS*12] without users even noticing the flickering. Further research indicates that this kind of gaze manipulation also increases memory recall [BMC*12]. SGD is barely noticeable, but requires a setup with an eye-tracker – something that is not widely available, limits the user's freedom, and can only be used for a single observer.

In this paper, we use a physiological property of the human visual system to achieve the advantages of SGD without having to use a restricting eye tracker. In an experiment we show that we can achieve a similar effect as SGD – namely, attracting the user's attention in the visual periphery and "hiding" the attractor for the foveal vision – without even knowing where the user is currently looking.

## 3. Physiological Background

Davson describes flicker as a sensation *"evoked when intermittent light stimuli are present to the eye"* [Dav12]. Flicker is an interesting visual feature since regular flickering is rarely employed in visual scenes, such as movies, websites, or computer applications. It could be shown empirically that blinking targets can be easily discriminated from moving distractors [POT08]. This implies that flicker is attracting the observers' attention even when watching a dynamic scene. In human-computer interaction studies, however, it has been shown that flicker is not only effective, but also considered annoying [GBM07, HBW08].

When increasing the frequency of flicker, it "fuses" for the observer and becomes a continuous signal. The frequency at which the signal is perceived as continuous is called *"critical fusion frequency"* (CFF) [Dav12] or *"flicker fusion threshold"*. The CFF is not stable, but rather depends on numerous factors, such as fatigue [Dav55] and training [SNHW05] of the observer, amplitude and luminance of the flickering target [Dav12], and its size (*Granit-Harper Law*) [RR88]. Upon reaching the CFF, the brightness of the flickering (yet steadily perceived) target is the mean of the brightness of one flicker cycle (*Talbot-Plateau Law*) [Tal34], but not necessarily at even higher frequencies.

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The CFF additionally depends on the eccentricity of the visual field at which it is perceived. In a bright environment, the CFF increases with eccentricity [Fuk79, TH90, TH93, Sid97, HV33]. In other words: a high frequency flicker might be perceivable in the peripheral visual field, but the flicker fuses in the foveal area (i.e., when directly looking at it). In the fovea, the CFF can range between <10 Hz and ~45 Hz, depending on the retinal illuminance (*Ferry-Porter Law*). In the periphery, CFF up to 60 Hz or 70 Hz have been observed [TH93]. This effect is well-known from old CRT monitors whose 60 Hz refresh rates could be perceived mainly in the peripheral vision [Sid97, Far86].

Bauer et al. [BCP*09] showed that a 30 Hz flicker signal could be more easily spotted than a 50 Hz flicker signal, but that the orientation effect was stronger for the 50 Hz flicker signal. However, in their experiment, targets were arranged on a small circle, covering $6^\circ$ of the human visual field. Eccentricity effects on CFF were obtained for much larger visual angles [TH93]. For instance, Sidebottom observed a large effect for a $30^\circ$ viewing angle [Sid97].

Tyler [Tyl85] measured temporal-frequency characteristics as a function of retinal location, and found that the temporal-frequency limits increase linearly by a factor of two from the fovea to $45^\circ$ of eccentricity. Modern monitors cover a visual angle of $60^\circ$ and more. While there was an attempt to use high frequency flicker at 50 Hz to try and attract attention [MB14], it was unsuccessful. Users had been instructed to determine whether the flicker was on the left or right side of an image they presented. The flicker was in an area that had lower contrast. The authors did not detect any effect by the flicker. However, in contrast to us, they used a 21 inch CRT monitor with a resolution of $1024 \times 768$ and a chin rest 70 cm away, while we use a 27 inch LC monitor with a LED backlight and a resolution of $2560 \times 1440$ and a chin rest 50cm away, allowing for larger visual angles along with a significantly higher resolution. While a display device being able to generate attention-attracting flickering (sub-)images with 75 Hz has been proposed in the past [Eva92], there has been – to the best of our knowledge – no empirical demonstration that the desired flicker observer effect actually works on moderately large monitors, and how users experience this kind of attention guidance.

## 4. Overview

To explore the applicability of high frequency flicker for guiding the user's attention in images, we split our research into two major blocks. First, we investigate whether we can find parameters to generate our anticipated flicker observer effect – namely that we can attract the users' attention letting an item flicker in the visual periphery, while going unnoticed when triggering the flicker in the foveal vision – in a fully controlled, artificial scene.

We first performed a psychophysics experiment to determine the size ranges and necessary luminance matchings for targets flickering with 60 Hz or 72 Hz (Section 5). Subsequently, we used these personalized settings and performed an experiment to test whether flickering targets in the peripheral field of view can be detected more reliably than targets flickering in the foveal vision (Section 6).

Second, we demonstrate the effectiveness and usefulness of the flicker observer effect to attract the users' attention in images through a use case. 14 users were asked to spot characters in a crowded comic scene from the famous "Where's Waldo" series and report their subjective impressions of the flicker observer effect (Section 7). We present further potential applications of the flicker observer effect and describe how images can be modified to smoothly integrate this effect (Section 8).

## 5. Experiment: Flicker Fusion Parameters

We conducted a psychophysics experiment to investigate two parameters influencing the perceived stimulus intensity and visual appearance of an item flickering with a high frequency: size and luminance. The amplitude was always set to maximum (i.e., full luminance range from black to white). We only investigated achromatic flicker since chromatic flicker has been shown to be less effective in the past [BMSG09]. The frequency was set to either 60 or 72 Hz, i.e., the refresh rate of the monitor was 120 or 144 Hz. As default, we used 60 Hz. However, people can detect flicker to varying degrees, and some of our users (3 out of 14) performed exceptionally well. In these cases, the user could detect flicker in the center at below $2^\circ$ degrees. For these three users, we used 72 Hz throughout the entire experiment. Since the measurements obtained for those participants were not outliers, we included them into our analysis.

The goal of this experiment was to find high frequency flicker settings so that the flicker observer effect could be achieved, and to compare these settings across the participants. In particular, we were interested in finding the following settings for simple circular targets:

- A luminance offset that needs to be applied to the non-flickering circles so that their brightness is perceived as equal to the flickering circle.
- The maximum size of an item in the foveal vision so that the circle's flickering just cannot be perceived in the peripheral regions of the circle.
- The minimum size of a circle in the peripheral vision so that users can just perceive the flickering.

The first step is necessary since it has been shown that the *Talbot-Plateau Law* does not necessarily apply for very high flicker frequencies, and that the sensation magnitude of brightness may be inverse to the flicker period [NB64]. This observation was also confirmed in our early pilot experiments, where the brightness of the high frequency flicker circle was perceived as clearly higher than of the remaining circles by all observers. We therefore included the luminance step to our experiment to compensate for the potential brightness differences between flickering and non-flickering image regions.

To compare flicker sensitivity between the foveal and peripheral vision, we defined three target eccentricities. Thus, the experiment was split into multiple blocks:

1. *Brightness Matchings (BM)* to find the luminance offset so that the brightness of the non-flickering half of a circle is perceived equal to the flickering circle half.
2. *Maximum size (MaxS)* to find the largest size of a circle in the foveal vision so that the flicker just cannot be perceived.

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3. *Minimum size* to find the smallest size of a circle in the peripheral vision so that the flicker just can be perceived. This step was divided into two sub-blocks:
   a. *Minimum size in close periphery (MinSCP)* to find the smallest size of a just visibly flickering circle in the peripheral vision, close to the foveal vision. The visual angle between the center of the monitor and the nearest point of the circle is $7.8^\circ$. This angle allows the use of a stimulus of up to 1.5 times the fovea [Est10] later.
   b. *Minimum size in far periphery (MinSFP)* to find the smallest size of a just visibly flickering circle in the peripheral vision, with the circle edge at the vertical boundaries of the monitor at the vertical axis (up to $37^\circ$ visual angle) with equal distance along the horizontal axis.

We only roughly sub-divide the visual field into three target eccentricity regions to find a size threshold so that the flicker is still clearly perceivable in the peripheral vision, but does not exceed the less sensitive foveal vision. Previous research suggests that the flicker sensitivity is higher in the far periphery than in the close periphery [Sid97, Far86]. However, our goal is to attract the attention in the entire peripheral vision to encourage users to directly look at the region of interest. Therefore, we added the presumably less sensitive close periphery block as second peripheral condition.

Users performed the blocks always in the order as listed above. This way, the brightness matching could be applied to all subsequent blocks.

### 5.1. Apparatus

The monitor used was a 27 inch Asus PG278Q, calibrated to sRGB with the D65 illuminant using the i1 Display Pro. The refresh rate was set either to 120 Hz or 144 Hz, if the user could detect flickering of circles smaller than $2^\circ$ visual angle. The room did not allow any daylight, and the ceiling lights were on at the highest setting. The users' heads were fixated on a chin rest 50cm from the monitor. The resulting visual angle of the monitor was a total of $62^\circ$ from left to right and $37^\circ$ from top to bottom.

### 5.2. Stimuli

In all blocks, the stimuli were composed of one or four circles on a black background. In the BM block, the user was presented with two half-circles next to each other, i.e., they formed a complete circle. The diameter of the circle was set to $3.2^\circ$ of visual angle. One half of this circle flickered, the other did not. The flickering half-circle was modulated between the extreme RGB-values [255,255,255] (white) and [0,0,0] (black) to achieve the maximally possible flicker amplitude on the monitor. The non-flickering half-circle was initially white.

In the MaxS-block, we showed a single circle in the center of the screen (see Figure 1a). As we used an interleaved staircase procedure, as described further below, we had to choose two initial sizes for this block. The initial sizes of the circles were set to $5.8^\circ$ and $1.9^\circ$ of visual angle. The circle was flickering between white and black to achieve maximum amplitude.

For the MinSCP- and MinSFP-blocks, we used the same initial circle diameters as in the MaxS-block. In these blocks, four circles were shown – two along the horizontal axis, left and right of the center, and two above and below. In both blocks, all four circles were placed equally far away from the center fixation cross. In the MinSCP-block, the distance of the circle boundary to the screen center was fixed to $7.8^\circ$ (see Figure 1b). In the MinSFP-block, the top and bottom circles were always touching the screen edge (see Figure 1c). This means that, as the user adjusted the size of the circle, the distance to the screen center was varied. In each trial, one randomly selected circle out of the four was flickering. As in the MaxS-block, the target circle was flickering between white and black. The non-target circles were shown in the gray value found in the BM-block.

For all blocks, users were asked to keep their gaze fixated to the center of the screen and not to move their heads. In the MinSCP- and MinSFP-blocks, a fixation cross was rendered to the center of the screen.

### 5.3. Task and Procedure

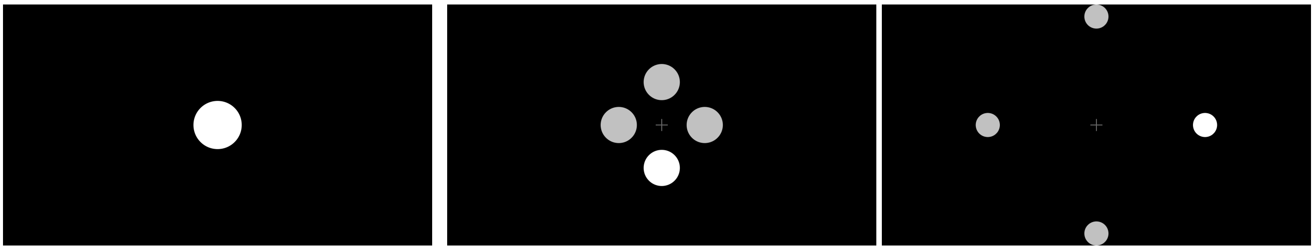
In the BM-block, we used a method-of-adjustment to find the optimal luminance offset. Users could adjust the brightness of the non-flickering circle half by scrolling the mouse wheel to increase or decrease the brightness by as little as one RGB step, i.e., $1/255$. If they desired, they could also use the up and down arrow keys to make very small adjustments. However, only one user used the arrow keys. The luminance value of the non-flickering circle half was stored when the user was finished.

In the MaxS and MinS-blocks, interleaved staircase procedures were used. In each trial, users had to press a mouse button when they perceived flickering in one of the circles, and the "f"-key if not. After pressing a mouse button (i.e., positive response), the size of the circles was decreased, after pressing the "f"-key, it was increased. The step size altered the radius of the circle and was decreased over the course of the experiment, starting with $1/20$ of the height of the screen and decreasing to $1/200$ of the screen after four trials, after which it remained constant. Thereby, we left the distance of the circle boundary to the screen center (in the MinSCP block) and screen edge (in the MinSFP block), respectively, constant. This means that the center of the circle was shifted whenever the diameter changed.

The number of trials was dependent on the user's responses. In total, we continued to show the stimuli until we, for each of the two interleaved staircases, gathered ten responses that differed from the previous one (five "reversals" from "not perceived" expressed by the "f"-key to "perceived" expressed by a mouse click, and five reversals from "perceived" to "not perceived"). The size threshold per block was then determined by averaging the size values for all trials where the user's response changed from "perceived" to "not perceived".

In summary, in the MaxS and MinS-blocks, the following procedure was used:

1. show central fixation cross for 1 second,
2. show stimulus for 1 second,
3. show blank screen with response request until a mouse button or the "f" key has been pressed,



**(a)** **(b)** **(c)**

**Figure 1:** *Stimuli of the flicker fusion parameters experiment for the MaxS (a), MinSCP (b), and MinSFP (c) conditions. The flickering circle is indicated by higher luminance. During the experiment, the luminance of the target was adjusted so that the perceived brightness was equivalent for all circles.*

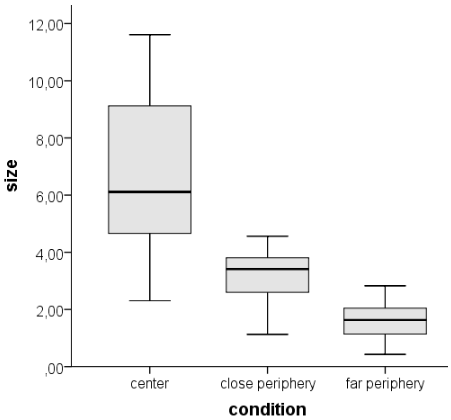



**Figure 2:** *Box plots of maximum visual angles in degrees obtained for the center circle (MaxS) and minimum visual angles obtained for the close (MinSCP) and far periphery (MinSFP) (boxes for first to third quartile and whiskers up to 1.5 IQR).*

4. show inverse stimulus image (gray background with black circles) for 100 milliseconds to avoid after-images,
5. adjust circle size according to staircase protocol and repeat, or stop if ten reversals per staircase were recorded after reaching the minimum step size change.

### 5.4. Subjects

We recruited 14 volunteers from a local university (13 males, 1 female, aged 28 to 54, average 33), each with normal or corrected-to-normal vision and naive to the purpose of the experiment. Six users rarely play computer games, three play weekly, and five daily. All users use a computer on a daily basis.

### 5.5. Results

For the BM-block, users applied a considerable luminance offset to the non-flickering circle half to achieve equal perceived brightness. On average, the RGB values were [189,189,189] (which corresponds to a luminance value of 76.5 in CIEL*a*b*), with a standard deviation of 4.7. This rather small standard deviation indicates that the perceived brightness differences were fairly consistent between users.

We performed a repeated-measures ANOVA to compare the size thresholds between the center, the close and the far periphery. The obtained size thresholds are significantly different from each other ($F_{2,26} = 36.319, p < .001$). Bonferroni-adjusted post-hoc comparisons showed that the MaxS-block leads to significantly larger circles (6.55° visual angle, on average) than the two MinS-blocks (3.13° and 1.60°, respectively). As visualized in Figure 2, the resulting MaxS-diameters ranged from 2.31° to 11.61°, while minimum diameters for the peripheral circles were ranging between 1.13° and 4.56° in the close periphery and 0.43° and 2.83° in the far periphery. Mind that these visual angles are given as seen from the user's perspective, focusing to the center of the screen. This means that the effectively seen visual angle of a circle with equal screen size is getting smaller towards the periphery. To find the potential size ranges of flicker circles, we therefore compare the obtained size thresholds in screen pixels. For each user, the usable size range for the flicker observer effect is defined as $[\max(MinSCP, MinSFP), MaxS]$. In Figure 3, we juxtapose these size ranges for all participants, where the usable size range is the difference between the blue and the orange line. As we can see, there is no complete overlap between the resulting size ranges of the users. This means that the effectiveness of the flicker observer effect also depends on the user – and potentially even the personal conditions of the user, as suggested in previous CFF-research [Dav55, SNHW05].

## 6. Experiment: Flicker Detection in Fovea and Periphery

The purpose of this experiment was to test the underlying hypothesis of the flicker observer effect: *A target flickering with high frequency (60-72 Hz) can be spotted much more reliably in the peripheral vision than in the foveal vision.* Not being able to detect whether or not a target that is currently being fixated is flickering would imply that the distraction introduced by the flicker is negligible.

To verify this hypothesis, we conducted an experiment using the same apparatus and subjects as for the previous experiment (Section 5). We presented users with very short stimuli containing multiple circles with one circle flickering in some of the trials. Users

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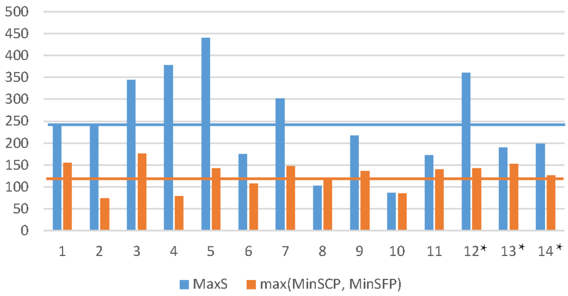


**Figure 3:** *Size thresholds of circle diameters (in pixels) per participant (indicated by participant number) obtained for MaxS (blue) and the maximum of MinSCP and MinSFP (orange). The horizontal lines show the average values. (* Users 12 to 14 were tested with 144 Hz.)*

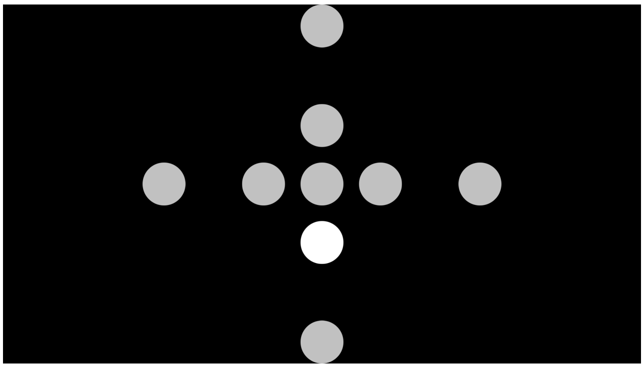

**Figure 4:** *Example stimulus with nine circles. The target circle in the close periphery (bottom) is indicated by increased brightness for illustration purposes.*

were asked to indicate whether they saw one of the circles flickering. We expected to see more correct responses for circles in the peripheral monitor regions than in the center of the monitor.

### 6.1. Stimuli

The stimuli consisted of nine circles placed in three rings: one circle was placed in the center of the monitor while the others were placed top, bottom, left or right of the center, in the near and far periphery, as in the MinSCP and MinSFP blocks in the previous experiment. Figure 4 shows an example stimulus.

The size of each circle was set to the user's maximum size threshold obtained in the MaxS-block of the preceding experiment (see Figure 2), or a maximum visual angle of 7.5°. The circles in the near and far periphery were placed as in the MinSCP and MinSFP blocks of the previous experiment (see Section 5). It is important to note that all circles had the same screen size in pixels. This means, that they were not equal in visual angle, which shrinks towards the periphery. The luminance was set according to the personally adjusted luminance values in the calibration step. The background was black as before.

### 6.2. Task and Procedure

In each trial, the users' task was to indicate whether they saw one of the circles flickering or not. Each stimulus was preceded by a fixation cross presented for two seconds on the center of the screen. After that, the stimulus (as shown in Figure 4) was presented for 0.75 seconds. Finally, a blank screen was shown, with a text asking the users to press a mouse button in case they detected a flickering circle, or the "f"-key if not. After giving the response, an inverse image (i.e., black circles on gray background) was shown for 0.1 seconds before showing the fixation cross again.

### 6.3. Design

For this experiment, we utilized a within-subjects design with four experimental conditions: *center*, *close periphery*, *far periphery*, and *target absent*, depending on if a one of the circles was flickering and at which eccentricity. In the target absent condition, there was no flickering target. The presentation sequence of the stimuli was randomized. The dependent variable was the correctness of response. For each condition, we aggregated the responses into a correctness ratio between 0 (no correct response) to 1 (all responses correct). Each condition was repeated nine times. In the close and far periphery condition, the location of the target (top, left, bottom, right) was chosen randomly.

### 6.4. Results

For each user, we determined the ratio of correctly answered questions per condition. Since the normality assumption was violated for this correctness ratio, we performed a non-parametric Friedman test (see also Figure 5). The test showed a significant difference in correctness depending on the test condition ($\chi^2(3) = 30.179, p < .001$). Bonferroni-corrected pairwise post-hoc comparisons for the three target-present conditions were performed using Wilcoxon-Signed Rank tests. We found significant differences between center and close periphery ($Z = -3.112, p = .002$) and between center and far periphery ($Z = -3.309, p = .001$). Also, there is a significant difference of correctness between close and far periphery ($Z = -2.668, p = .008$). On average, targets in the far periphery were the ones most correctly detected (95.2%; median: 100%), while targets in the center were missed in around 80% of all cases (21.4% correctness on average; median: 11).

These results confirm our hypothesis that high frequency flicker can more easily go unnoticed in the foveal than in the peripheral vision. While we could show that high frequency flicker in the periphery can be detected in almost 100% of all cases, our results suggest that high frequency flicker can sometimes be perceived even in the foveal vision. Mind, however, that we did not use an eye tracker and therefore cannot guarantee that users were indeed looking at the center of the screen (i.e., the center target) during the trials. The true positive responses for the center condition may be caused by fixations outside the center screen region. Also, improper calibration in the preceding experiment may have caused this effect – in particular for the single user scoring around 89% correct responses in the center condition (see outlier dot in the first column of Figure 5).

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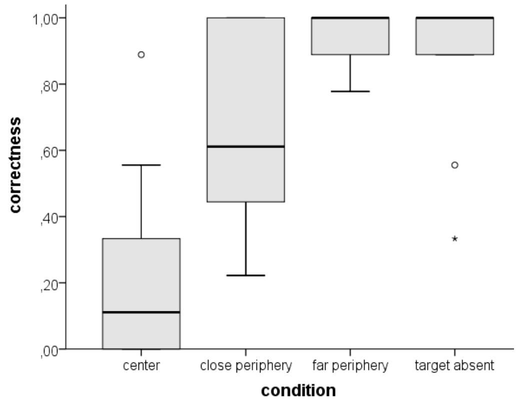


**Figure 5:** *Box plots of correctness rate of responses for the four conditions (boxes for first to third quartile, whiskers up to 1.5 IQR, and outliers as individual dots).*

## 7. Use Case: "Where's Waldo"

High frequency flicker beyond the CFF for the foveal vision can be used to attract the user's attention to image regions in the peripheral vision. To explore the effectiveness and user satisfaction with this technique, we invited the same 14 users to find hidden characters in a crowded scene. We used an image out of the series of "Where's Waldo", an illustrated children's book showing colorful images of scenes crowded with numerous characters. Each image contains one instance of the main character Waldo, wearing a red-white striped pullover and hat, and some of his friends. The image we used was "The Gobbling Gluttons" from the book "Where's Waldo: The Fantastic Journey." It has been shown that unguided detection of "Waldo" can take up to several minutes [BOZ*14]. The flicker observer effect was used to sequentially guide the user's attention to different characters in a single image.

As we used the findings from our psychophysics study (see Sections 5 and 6) to generate the flicker observer effect, we expected that users would easily spot the indicated characters, while expressing little discomfort caused by the flicker. User feedback was gathered quantitatively (through a questionnaire using a five-point Likert scale) and qualitatively through an unstructured feedback session. Our goal was not to keep the user's gaze permanently fixated at the target, but to provide effective, yet unobtrusive support for target detection. Therefore, we let users report the location of the search target verbally instead of using an eye tracker.

### 7.1. Stimuli

To guide the users to the characters, we used the flicker observer effect: each character was surrounded by a 330 pixel region of interest, subject to high frequency flicker, of which 44 percent is affected by the dithering described below. The size of this region was the same for every user. The flicker effect was achieved by alternating between the original pixel colors and black. This effectively darkens the perceived brightness of the flickering patch (→ *Talbot-Plateau Law*). To compensate for this brightness difference, users had to adjust the brightness level of the remaining scene with respect to the flickering patch interactively at the beginning. Using the mouse scroll wheel, the CIEL*a*b* luminance component of all non-flickering pixels could be increased or decreased. The frequency of the flicker was the same as in the preceding experiments.

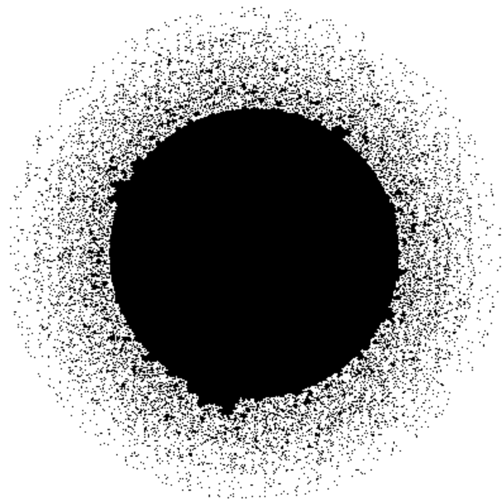

**Figure 6:** *Image of dithering mask for seamlessly integrating high frequency flicker patches into images. The black pixels are flickering, the white pixels are not flickering.*

To avoid sharp boundaries between the flicker region and the context, we used a dithering mask for the flicker. The flickering area can be viewed as a circular region centered at the point $c$, with two radii, $r_1$ and $r_2$, where $r_2 > r_1$. If the distance $d$ between a point $p$ and $c$ is smaller than $r_1$, then the pixel at $p$ is flickering. If $r_2 > d > r_1$, then the probability that the pixel at $p$ is flickering decreases linearly from 1 at $r_1$ to 0 at $r_2$. We calculate this in a fragment shader by comparing the distance to a point in a texture with random values generated with Matlab. An example dithering mask can be seen in Figure 6.

### 7.2. Task and Procedure

The users were asked to find five different characters in the following order: The Wizard Whitebeard, Odlaw, Wenda, Waldo, and a Waldo Watcher. These characters were presented to them on a sheet of paper, as well as in a sidebar of the image (see Figure 7a). The area around the character that the user was currently looking for was flickering. When the users found a character, they had to click on it. The flickering area was then moved to the next character to be searched for. After the user found all the characters, a random section of the image was flickering, and the user was asked to describe different parts or characters in the image. Afterwards, the user was asked questions about how distracting the flickering area was, and whether he or she could detect it when looking directly at it.

### 7.3. Subjective User Feedback

As expected, all users could easily spot the characters indicated by the high frequency flicker within a few seconds. In comparison, earlier studies by Brown et al. [BOZ*14] show that without

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**(a)** **(b)**

**Figure 7:** *The image used for the search task ("The Gobbling Gluttons" from the book "Where's Waldo: The Fantastic Journey"). On the left, the positions of the targets have been marked with black circles. On the right a cutout contains the Wizard Whitebeard and a Waldo Watcher.*

any attention guiding effect, users need around 500 seconds to find Waldo. All users reported that the flicker signal was clearly visible, even though the size of the flickering patch was fixed for all participants. This can be seen as an indication that an averagely sized flicker patch size can yield a satisfactory solution for a wide range of users. Most users also reported that high frequency flicker was distracting when attending to other image regions than the one currently flickering (average response for "It is easily possible to work when there is flicker in the periphery" was 3.64 on a five-point Likert scale). However, the discomfort generated by the high frequency flicker when directly looking at the image was rated as very low (with an average response for "The flicker was causing discomfort when looking at it" of 1.42). When asked specifically about it, most users reported they could not recall any discomfort or visual distortion associated with the image regions around the characters of interest.

According to this user feedback, high frequency flicker indeed seems to be a strong visual attractor – even in very cluttered scenes – while not having a strong influence on the perceived image quality. However, it can cause discomfort when users aim to direct their attention to other, non-flickering screen regions. Like other highlight techniques that have a strong effect on the surrounding image regions (like darkening [KMFK05], blurring [KMH02], or size compression [Fur86]), it is therefore not recommendable for longer exposure, or to indicate image regions of low degree of interest through high frequency flicker.

## 8. Applications of the Flicker Observer Effect

Since flicker does not strongly interfere with color or motion perception [POT08], it can be used for a variety of scenarios beyond our static use case presented above. For instance, high frequency flicker can direct the user's gaze to the current ball location in a TV broadcast of a football match. It can draw the user's attention to the notification area of a large display to inform the user about a recently arrived e-mail. It could also be employed for advertisement purposes, so that the user is explicitly made aware of sponsored products placed in videos.

Previous research [Dav12] and our psychophysics experiments have shown that the flicker observer effect is restricted to a certain size range to work effectively. It is therefore necessary to define a region of interest (ROI) around the item to be highlighted that should be subject to high frequency flicker. To avoid sharp boundaries, we used dithering in our use case to smooth the transition between flickering and non-flickering regions. Each pixel in the ROI then has to be rendered bright and dark in alternating frames to create a flicker sensation, where the frame rate has to be twice as high as the CFF in the foveal region (around 60 Hz [TH93]). In practice, the higher the amplitude (i.e., the luminance difference between the bright and the dark color within the ROI), the stronger the effect [WLMB*14]. Thus, the technique works best for ROIs containing mostly pixels with medium brightness, which can be generated by alternating between very bright and very dark colors. The pixels in the ROI can be preprocessed to reduce the contrast of the ROI if the resulting luminance amplitude would be too low. This can be achieved by standard image contrast adjustment techniques.

To achieve a 60 Hz flicker, a display with a refresh rate of at least 120 Hz is necessary. Modern LCD and OLED TVs often provide 120 Hz or even 240 Hz refresh rate to reduce motion artifacts by interpolating between successive frames, while the normal TV signal is still 25 Hz (or 60 Hz in case of HDTV). Modern TV standards could add the possibility to specify a ROI for each TV frame that can be evaluated by suitable TV sets with sufficiently high refresh rate. The TV sets could then perform the required modifications of the ROI pixels and create the flickering sensation on-the-fly.

Computer monitors capable of active stereo rendering (i.e., producing stereoscopic 3D scenes with synchronized shutter glasses) could provide driver-based functionality to create high frequency flicker, as they are capable of high refresh-rates. The driver software could query operating system events like the mouse cursor position

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or the pop-up of a notification window. It could then specify a ROI around the cursor to help the user keep track of the cursor on a large screen. It could make pop-up windows flicker to make them more evident for the user – without making them bigger (to avoid occlusion) or darkening the remaining display content (to avoid visual distortion of the remaining screen content).

## 9. Conclusions

In this paper, we have explored high frequency flicker as a means to effectively guide the user's attention in an image without noticeable changes to its visual appearance and without having to track the user's gaze. In a controlled experiment, we could demonstrate the *flicker observer effect*: on a consumer high frequency monitor, users are clearly aware of high frequency flicker in the peripheral vision, but rarely perceive the flicker when they are directly looking at it. We demonstrated the usefulness of this visual property by guiding users to hidden characters in a crowded scene using the flicker observer effect. With a fixed flicker patch size, users could easily find the characters, yet reported negligible discomfort or distraction caused by the high frequency flicker when looking at the image regions containing these characters, indicating that an average size flickering patch may be used for a wide range of users.

From our first experiment, it seems that a personal calibration routine is required to find the optimal flicker patch size and luminance offset. However, in the "Where's Waldo" use case, we could show the effectiveness of the technique even for a fixed patch size. More in-depth experimentation is necessary to explore patch size and brightness settings that work across a wide range of users to support walk-up usage. We also plan to explore the interaction between flicker amplitude and patch size to unobtrusively highlight larger targets. Finally, it will also be interesting to formally investigate the effectiveness of the flicker observer effect in dynamic scenes, such as movies, games, or virtual environments.


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In Figure 7, the image "The Gobbling Gluttons" is Copyright ©1989 Martin Handford **From WHERE'S WALLY? THE FANTASTIC JOURNEY by Martin Handford.** Reproduced by permission of *Walker Books Ltd*, London SE11 5HJ

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