Visibility of Motion Blur and Strobing Artefacts in Video at 100 Frames per Second

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Abstract

High frame rates are currently under discussion in the broadcasting industry as part of ultra-high definition standards. Previous subjective tests showed that a substantial improvement in video quality is possible with high frame rates, and there is wide agreement that 100 frames per second (fps) will be a suitable high frame rate for television in Europe. However, details of the relative importance of the two most significant artefacts affected by the frame rate, motion blur and strobing, are not well understood. These complementary artefacts can be controlled with the camera exposure time, but cannot be simultaneously optimised. We conducted subjective tests at 100 fps, measuring the visibility of motion blur during tracked motion, and strobing during untracked motion, with different exposure times. Both artefacts were rated in the same test, allowing the results to be directly compared. Hence we are able to make recommendations on optimising overall motion quality in a 100 fps system.

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Additional key words: Blur, digital video broadcasting, frame rate, high frame rate, high definition video, image resolution, judder, motion, motion pictures, strobing, television, TV broadcasting, ultra-high definition video, video, video signal processing.
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1 Introduction

High frame rate television has the potential to offer viewers much better motion representation than conventional rates of up to 60 frames per second (fps) [5]. The on-going standardisation of ultra-high definition (UHD) television presents an opportunity to make a change to world standards, so the question of frame rate is currently a topic of intense debate in the broadcasting industry.

The initial version of ITU-R Recommendation BT.2020, which defines the video parameters for UHD, included only one higher frame rate, 120 fps. This represented an aim for a single worldwide frame rate standard that would simplify programme exchange, by eliminating the need for frame rate conversion. Whilst this is an appealing prospect, a simple switch to a new frame rate is not possible: a change to high frame rate programme making is likely to be gradual, and there will always be a need to play back archived material, meaning that any high frame rate distribution chain will need to be capable of frame rate conversion. Conversion by non-integer factors is difficult to do [22], and with additional problems of interference from lighting that is modulated at twice the mains electricity frequency [14, section 3.2.4.6], 100 fps is likely to be a more suitable rate than 120 fps for countries with a mains frequency of 50 Hz. It is now included as a footnote in the current version of the ITU-R recommendation [13].

With the aim of optimising video capture for a 100 fps system, we have conducted experiments to quantify the perception of motion artefacts at this frame rate as they vary with different camera exposure times. The two artefacts of primary interest are motion blur, which occurs with a long exposure time, and strobing, which occurs when the exposure time is short compared with the frame period. These artefacts are described in more detail in section 2.

There are other artefacts relating to motion which are of interest, but evidence suggests that flicker is not noticeable at flash rates above around 80 Hz [7] [14, p. 16], so is not an issue for 100 fps video, and problems caused by inaccurate motion estimation either in an encoder or as part of motion-compensated frame insertion (MCFI) in the display are higher level problems that will benefit from a good understanding of the more fundamental sampling artefacts of blur and strobing before they are studied in more detail.

Eye movements are known to have a strong impact on the perception of blur and strobing, so we separate judgements for the case where the eye is following a moving object and the case where the viewer’s gaze is fixed, on the same test sequences. Our main contribution is data that allows the two artefacts to be balanced, which makes it possible to recommend a camera shutter angle that offers the best compromise between blur and strobing. We also show that different subjects have different preferences, and that there is no perfect shutter angle that makes both blur and strobing imperceptible in all cases at 100 fps.

In section 2 we explain motion blur and strobing, and how they are affected by eye movements, then review related work in section 3. We describe our experiments in section 4, then present the results and discussion in sections 5 and 6 respectively. We present our conclusions in section 7.
2 Motion Blur and Strobing

Once the frame rate is above the critical flicker frequency of about 80 Hz [14], at which large area flicker becomes invisible on displays with some blanking between frames, the two most significant motion artefacts are blur and strobing. Motion blur occurs when an object moves relative to the camera during the time that the camera shutter is open. The amount of blur is dependent on the speed of the motion, leading to an unnatural change between sharp and blurred pictures as objects change speed. This effect can be reduced by shortening the time for which the camera shutter is open—often called the shutter angle, where 360° represents a shutter that is open for the full frame period. However, a very short camera shutter is approximately equivalent to sampling with no anti-alias filter, and hence motion in the video sequence is aliased, leading to a juddery appearance or multiple imaging. We use the term strobing to refer to all of these visual effects caused by temporal undersampling. The blur and strobing effects can be traded against each other by changing the camera shutter angle: a large angle produces a high level of motion blur, and a smaller angle reduces the motion blur but increases strobing.

The human eye is also an important part of the end-to-end system [4], and the visibility of blur and strobing artefacts is strongly dependent on the viewer’s eye movements [16, p. 138] [19]. When we track a moving object with our eyes, we are much better able to resolve detail in the object than when our eyes are stationary. Hence, during tracked motion we are very sensitive to motion blur, for example when following a football as it is kicked from one side of the pitch to the other. However, eye tracking reduces strobing effects in the object being tracked. It is in the untracked motion that strobing is most visible, for example in the crowd filling the background of the same football scene. A detailed discussion of these effects is given in [20], together with a more extensive description of blur and strobing artefacts.

The display technology used to present video sequences can also affect the quality of motion [16, ch. 5]. In particular, conventional liquid crystal displays have a display on-time of close to 100% of the frame period, and hence freeze the picture for this time. If the eye is moving, the image of the frozen frame will move with respect to the retina, causing motion blur that is dependent on the speed of eye movement. This is sometimes called retinal slip [17]. In order to minimise the effect, we use a display with backlight blinking for our experiments, which allows us to set a very short on-time (2 ms).

In this article we compare the two critical cases for blur and strobing perception: visibility of blur during tracked motion, and visibility of strobing during untracked motion. This allows the two effects to be quantitatively compared on the same material, which is crucial to an understanding of motion perception in video. Whilst it is possible to reduce either the blur or the strobing to acceptable levels by setting the camera shutter angle appropriately [25], it is only in the comparison of the two artefacts that we can fully understand the advantages and limitations of a high frame rate system.

3 Related Work

Television systems have always been temporally undersampled [4], and higher frame rates were also discussed in conjunction with the introduction of high definition (HD) television in the 1980s [23] [26], although they were not adopted in the final standards [9]. As ultra-high definition is being standardised, we have another rare opportunity to upgrade the television frame rate. Higher frame rates will be an important part of the complete UHD package, allowing the extra spatial resolution to be much better maintained in moving scenes that would otherwise suffer from motion artefacts.

A number of subjective tests have been carried out recently to assess the perceived benefits of higher frame rates. These include a range of experiments [25] by Japanese public broadcaster, Nippon Hōsō Kyōkai, (NHK), that are also summarised in ITU-R report BT.2246 [14]. They report that for an acceptable level of motion blur a camera shutter time of less than 1/320s is needed,
which would correspond to a shutter angle of 112.5° at 100 fps. For an imperceptible level of blur they found that the shutter time should be less than 1/1600 s, corresponding to a shutter angle of 22.5° at 100 fps. Kuroki et al. [17] found that blur reached the limit of perception at around 250 fps with a 360° shutter, an absolute shutter time that is equivalent to a 150° shutter at 100 fps. All of these implied shutter angles for 100 fps that should keep motion blur at an acceptable level are rather short, and hence are likely to cause strobing artefacts.

Both studies also measured strobing perception. NHK show that strobing is still visible at 240 fps for fast moving objects and a 180° shutter [14]. Kuroki et al. [17] found perceptible jerkiness limits at 250 fps with a shutter angle of 180° for all but one of their test sequences, which required a yet higher frame rate. This suggests that at the lower frame rate of 100 fps, strobing will still be visible when the shutter angle is 150° or shorter, as would be required for an acceptable level of motion blur. We confirm this hypothesis with our experiments, which were run directly at 100 fps.

The Broadcast Technology Futures Group led by the European Broadcasting Union conducted subjective tests to measure the overall quality of video at a range of frame rates, without separating blur and strobing effects, and found that 120 fps offered significant perceptible improvements over 60 fps, and some smaller improvements were also seen at 240 fps [5]. The results from Kuroki et al. [17] showed a similar trend. This implies that, although 100 fps may not allow a system to reach the perceptible limit of both blur and strobing at the same time, it will nonetheless offer a significant quality boost to the viewer.

The visibility of blur and strobing has also been studied within the vision science community. Robson [21] and Kelly [15] both present spatio-temporal contrast sensitivity measurements, which quantify acuity (related to blur sensitivity) at different spatial resolutions and velocities, and Barten provides a comprehensive review of contrast sensitivity [1]. Emoto [6] shows that dynamic visual acuity is better correlated than static visual acuity with subjective measures of sharpness for moving images. Bex et al. [2] and Farrell et al. [8] have investigated the strobing effect. However, these experiments have been conducted under diverse experimental conditions, so it is difficult to extrapolate any conclusions about relative preferences for blur and strobing at a given frame rate.

Sugawara et al. opt for 120 fps for their Super Hi-Vision system [24], explaining that this is sufficient to overcome the critical flicker frequency, and motion blur can be reduced using a short shutter. However, Salmon et al. indicate that under these conditions strobing is only removed from tracked motion, but still very much visible in untracked motion [22]. There is therefore a need to better understand the visibility of strobing in untracked motion. Our results allow blur in tracked motion and strobing in untracked motion to be directly compared, and hence they can be used to suggest a suitable shutter angle that provides the optimum balance between the two artefacts at 100 fps.

4 Experiment

To allow for subjective testing of material in relation to motion blur and the strobing effect a number of video clips were created. Each clip had a set speed of motion and shutter angle and the test participants were asked to rate the visibility of the relevant motion artefact. The ratings could then be directly compared to each other to find the best shutter angle for each speed of motion. The test methodology was taken from [11].

4.1 Test Video

We decided to use artificially-generated test material to allow us to have full control over the speed of motion and camera shutter angles. In order to approximate real footage as closely as possible, a still photograph was used as the basis for the test sequences. The video test sequences were created by artificially moving the photograph horizontally, equivalent to a camera pan, and motion blur for a particular camera shutter angle was synthesised by adding an amount of spatial blur
corresponding to the distance the scene would have traveled during the time the camera shutter would have been open. For example, to synthesise motion blur for a speed of 10 pixels per frame and a 360° shutter, each video frame was convolved with a horizontal rectangular window of width 10 pixels. For a speed of 10 pixels per frame and a 180° shutter, a rectangular window of width 5 pixels was used, because the camera shutter would only be open for half the frame period. When the whole image is moving horizontally at the same speed, this is equivalent to adding motion blur. Watson [28] also used this approach to synthesising motion blur due to camera integration. A synthesised shutter angle of 0°, which would not be achievable with real video since it would require a fully-closed shutter, refers to the original still photograph with no artificial motion blur added. This case would be of interest for computer graphics, where it is possible to create moving sequences with no motion blur (or to add blur artificially).

To ensure that the motion blur synthesis was carried out in linear light, a gamma curve was applied to correct for the gamma already in the photograph. After motion blur synthesis, gamma correction was re-applied to match the gamma of the display used in the experiments. The display was found to have a gamma value of 2.2.

The same clips were used for viewing the strobing effect, with the addition of a stationary black cross in the centre of the picture for fixation. Strobing is only visible when the video is seen as a moving sequence, but can be illustrated using a still photograph of the screen, as shown in Fig. 1 (left). The fixation marker can also be seen. For comparison, Fig. 1 (right) shows a blurred sequence that has been photographed in the same way.

At the time of testing the largest high frame rate displays available were HD with 1920×1080 pixels, so our test sequences were also made in HD. Viewers were positioned at a distance of 3 times the screen height (3H), relative to our HD screen. This is equivalent to a quarter of a UHD screen with 3840×2160 pixels, viewed from the recommended UHD viewing distance of 1.5H (see [12] for the derivation of recommended viewing distances). The display used has a height of 0.34 metres, making the viewing distance 1.02 metres.

The photograph chosen was an image of a harbour, which contains a wide variety of different objects, textures and frequencies, including many vertical edges. Vertical edges are the most critical material during a horizontal pan, because they include high horizontal spatial frequencies, and hence would highlight both blur and strobing artefacts. Following some initial tests, it was
reported that an image in motion that fills the entire display could be challenging for people who suffer from motion sickness. With this in mind, only the central part of the image was used and a mid-grey border added above and below for the remaining portion of the display. This final image is shown in Fig. 2.

### 4.2 Shutter Angles and Motion Speeds

The shutter angles chosen for our tests were 0°, 72°, 120°, 180°, 240° and 360°. These values cover the full range of possible shutter angles, and reflect those commonly used in television production, as well as those used in previous studies [17].

We chose the motion speeds to cover a range of values from very slow to beyond the average maximum tracking speed of 80 arc-degrees per second [3]. Tracking a high number of fast moving images is demanding, making viewing and evaluation strenuous. Since it is undesirable to have physical fatigue influencing results, we chose to use a smaller number of fast images compared to slow. Table 1 shows the speeds of motion chosen and their equivalent speeds in arc-degrees per second at the centre of the screen.

### 4.3 Backlight Blinking

To reduce motion blur caused by retinal slip (see section 2), manufacturers have introduced the process of backlight blinking. When this is used the image is displayed for a period of time shorter than a whole frame; the backlight is turned off for the remaining time.

<table>
<thead>
<tr>
<th>Pixels per Frame</th>
<th>Arc-Degs per Second</th>
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<tbody>
<tr>
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<td>40</td>
<td>70.2</td>
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<tr>
<td>60</td>
<td>105.3</td>
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4.4 Methodology

The Double Stimulus Continuous Quality Scale (DSCQS) method described in ITU Recommendation BT.500 [11] was used for the tests. This methodology requires that each test condition is presented as a pair of video clips, one with an artefact and one reference, free of the artefact. Both clips are rated, by placing a mark on a line that represents a continuous impairment scale, as shown in Fig. 3. The positions of the marks are mapped to a scale from 0 to 100, and the difference between the two ratings is then used as the final result. Since blur and strobing are both impairments, it was considered more appropriate to use the adjectives associated with the ITU impairment scale (“imperceptible” to “very annoying”) rather than the quality-related adjectives suggested for DSCQS (“excellent” to “bad”).

As discussed in section 2, eye tracking also makes a difference to the perception of motion artefacts. We wanted to compare the two most critical cases: blur during tracked motion and strobing during untracked motion. Two test conditions were devised, one for motion blur and one for strobing. The test for motion blur required the participant to track the motion of the image. The test for strobing required the participant to keep their eyes at a fixed point on the display. A cross was placed in the centre of the display and on the answer sheet when the participant was to judge strobing rather than motion blur. This allowed the participants to keep track of the artefact they were required to judge and also keep their eyes on a fixed point while watching the video. Laird et al. have shown that viewers are able to reliably choose whether to track a moving object or fixate on a stationary target [18]. To ensure that the blur and strobing ratings could be directly compared, the two types of test were interleaved within the same session, using the same rating scale.

For the reference signals, a video clip with a shutter angle of 0° was used when the participant was judging motion blur. An image with a 0° shutter angle will be completely sharp and free of any blur. A video with a shutter angle of 360° was used as a reference for the strobing effect. This simulation is equivalent to having the shutter constantly open and hence the entire motion captured with minimum strobing.
The tests included 6 different shutter angles and 6 different speeds of motion for both conditions, resulting in a total of 72 tests. The tests were split into two playlists which participants undertook in separate sittings, each lasting 44 minutes.

4.5 Viewing Conditions

The display and lighting conditions were set up according to the typical laboratory environment described in [11]. The display used was an ASUS VG278HE, and two controllable LED tile lights directed at the wall behind the display were the only additional source of light in the room. The orientation of the lights avoided them shining into participants’ eyes.

With backlight blinking enabled on the display, the number of other controllable features was reduced to contrast only. Laboratory viewing conditions were achieved by first adjusting the display contrast using a pluge test image [10] to calibrate the black level, measuring the display peak white, then calibrating the background lighting to maintain the appropriate relative luminance for the display. The display peak white was measured as 95 cd/m$^2$, with a colour temperature of 6860 K. The background illuminance on the right hand side of the display was 13.7 cd/m$^2$ with a colour temperature of 6600 K, and the background illuminance on the left hand side was 13.4 cd/m$^2$ with a colour temperature of 6690 K, leading to relative luminances of 0.144 and 0.141 respectively. Measurements showed some small variations when repeated; reported figures are median values.

The distance between display and participant should be constant for all subjects. Display gamma was found to change with vertical viewing angle so the vertical position is also important. A chin rest was used to maintain head height and viewing distance for all participants. The room set-up is shown in Fig. 4.

5 Results

In total 25 people completed both playlists and 7 only managed one playlist, giving 32 different participants overall. Of the 32 participants, 24 work in BBC Research and Development, so are likely to have some experience of judging picture quality. Of these, 8 are directly concerned with television picture quality as part of their normal work. No participants were excluded.

It was clear that the participants found the subjective test quite physically demanding and a break was always given between completing the two playlists. Some comments from participants
include that one found the strobing effect “more annoying” than the blur, one was not able to track the fast motion 100% of the time and one preferred blur as it was “easier” on their eyes.

The 32 participants completed in total 2052 individual tests. Of these tests a participant was not able to provide an answer on six occasions. Four out of these six were at the highest speed of 60 pixels per frame.

5.1 Mean Values for all Participants

In total 72 mean difference rating values for each clip across all participants were calculated from the results obtained. Fig. 5 shows the mean difference ratings for both motion blur and strobing, together with the 95% confidence intervals, for the six different speeds.

When interpreting the plots in Fig. 5, a mean difference rating value of 0 indicates that there was no perceived difference between the reference clip and the clip with the artefact. The higher the mean difference rating value, the more perceptible and annoying the artefact has become.

It can be seen in Fig. 5a that the mean difference values for motion blur increase as the shutter angle increases. Likewise the mean difference values relating to the strobing effect decrease as the shutter angle increases. This is the expected result for both artefacts as the shutter angle is changed. We can see a similar trend for the other speeds, in Figs. 5b–5f.

The mean difference rating values for motion blur are smaller when the speed of motion is 40 pixels per frame (Fig. 5e), in comparison to lower speeds (Figs. 5a–5d). As seen in Table 1, 40 pixels per frame is less than the average maximum tracking speed of 80 arc-degrees per second specified in [3], so the majority of participants should be able to track this speed. The smaller difference ratings suggest that motion blur is less perceptible at higher speeds.

When the speed is increased to 60 pixels per frame (Fig. 5f), it can be seen that the mean difference rating values for motion blur are almost constant. This speed of motion is equivalent to 105.3 arc-degrees per second and therefore higher than the average maximum tracking speed given in [3]. It is therefore reasonable to believe that a significant number of participants had difficulty in tracking the motion. This would make giving a subjective evaluation of the motion blur much harder. Of those who could track it is likely that motion blur is still more acceptable with higher speeds.

ANOVA tests were carried out on the mean difference ratings for each artefact and for each speed of motion. This shows whether there is a significant difference between any of the mean difference ratings for a particular speed. Tukey’s Honest Significant Difference Tests were carried out to identify where the significant differences occurred.

For speeds of motion of 5, 10, 15, 25 and 40 pixels per frame, the ANOVA tests show that there were significant differences in the mean difference rating values for both blur and strobing (p ≤ 0.05). At 60 pixels per frame there were also significant differences in the mean difference ratings for strobing, but for motion blur at 60 pixels per frame there was found to be no significant difference (p = 0.169).

The results from the Tukey’s Honest Significant Difference test are shown in Tables 2a and 2b, highlighting the shutter angles where the mean difference ratings were found to be significantly different from the reference. For motion blur ratings there are significant differences at low speeds and large shutter angles, whereas for strobing the significant differences occur for higher speeds and small shutter angles. This confirms our conclusions from Fig. 5 that as the speed of motion increases, blur becomes less problematic but the visibility of strobing increases.

5.2 Preferred Shutter Angles

Once a participant has rated both blur and strobing for the image with the same speed of motion, the difference ratings for each shutter angle for both artefacts can be plotted together, as shown in Fig. 6a for one participant. Second order lines were fit to the blur ratings and strobing ratings for each participant who completed both playlists, and the crossing points found. The crossing point
Figure 5: Mean difference rating values for all participants for different shutter angles. 95% confidence intervals are also shown. Speeds are (a) 5, (b) 10, (c) 15, (d) 25, (e) 40 and (f) 60 pixels per frame.
Table 2: Shutter angles (in degrees) with mean difference ratings that are significantly different from the reference ratings, for motion blur and strobing. **Boldface** and asterisks indicate significance.

<table>
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<th>Speeds (Pixels per Frame)</th>
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<td>(a) Motion blur. Reference shutter angle 0°.</td>
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for the participant in Fig. 6a is at 124 degrees, which is then the preferred shutter angle for this participant at a speed of 15 pixels per frame.

The crossing point represents the shutter angle at which the blur in tracked motion and the strobing in untracked motion are equally objectionable, and so can be interpreted as the best balance between the two artefacts for that speed. A balance is required because it is common for different kinds of motion to appear in the same scene, for example objects moving past a background. The viewer will have to select one object to track and all other motion will be untracked. This means that blur and strobing will be visible in the same scene. It is also not known in advance which object a viewer will choose to track.

The crossing points for the same participant as in Fig. 6a for all speeds is shown in Fig. 6b, together with a quadratic curve of best fit. It can be seen that the preferred shutter angle for this participant is almost level at slow speeds and rises at speeds of motion of 40 and 60 pixels per frame. This indicates that this participant prefers blur to strobing as the speed increases.

The preferred shutter angle for each individual at each speed of motion was then calculated. The 25 participants’ preferred shutter angles are shown in Fig. 7, along with the mean result. The majority of participants give similar results to the participant in Fig. 6b, but it can clearly be seen that there are also a number of participants who do not follow the trend. This indicates that, although the mean values can be used to optimise the motion for most people, individuals have differing opinions on preferred shutter angles and it will not be possible to chose one value that will be ideal for all viewers.

We calculated smoothed estimates of the distribution of preferred shutter angles for each speed 1. These are shown in Fig. 8. Vertical lines representing the mean values are also shown.

When looking at the density plots we can see that there is a wide distribution of preferred shutter angles. The mean does not always fall at the peak of the distribution, and there is evidence in some plots (Figs. 8c and 8e) of two peaks in the distribution, which indicates a group that finds strobing more annoying than motion blur (right hand peak), and a group that finds the blur more annoying (left hand peak). Whilst the reasons for this wide distribution are not clear, and may to some extent be content-dependent, it is clear that there is not one optimal shutter angle that will give the best balance for all viewers.

6 Discussion

These results have implications for any future television services running at 100fps. The mean difference rating plots in Fig. 5 show that the crossover point for blur and strobing artefacts is above a difference rating of 20, for all except the very slow speed of 5 pixels per frame (8.8 arc-

1Density estimates were calculated using the density function from the statistical computing package R using the default kernel and bandwidth (http://www.r-project.org).
degrees per second) and the very fast speed of 60 pixels per frame (105.3 arc-degrees per second) that many people were not able to track. On the continuous impairment scale used, a difference of 20 covers a full categorical judgement grade, and so can be a useful threshold for measuring perceptibility. We can therefore conclude that for most moderate to fast motion it is not possible to choose a shutter angle that makes both blur and strobing imperceptible.

This conclusion is based on mean values. Figs. 7 and 8 show how the preferred shutter angle varies with different speeds for different individuals, and suggest that people may have different preferences for blur and strobing. This means that the average optimum shutter angle will not be optimal for all viewers. The only way to make both blur and strobing imperceptible to all viewers for all speeds of motion, without relying on imperfect motion-compensated interpolators, is to further increase the frame rate. These results match earlier conclusions from both experimental results [17] [25] and theoretical studies [19] [27].

Despite this, we do not want to discourage the introduction of 100 fps television. Even if the motion artefacts cannot be made completely imperceptible under all conditions, experiments and demonstrations have shown that this frame rate offers significant perceptible improvements over conventional frame rates [5]. The results of our experiments do not alter the preference for 100 fps
Figure 8: Density plots for preferred shutter angles for all 25 participants at speeds of (a) 5, (b) 10, (c) 15, (d) 25, (e) 40 and (f) 60 pixels per frame. The vertical line (⋅⋅⋅) indicates the mean value.
as the most suitable standard for high frame rate services in Europe for the near future, due to the many additional factors that influence the choice: practicalities of manipulating, storing and transporting the extra data place an upper limit on the frame rate, and the need for compatibility with 25 and 50 fps systems as well as modulated 50 Hz light sources make a frame rate that is a multiple of 50 Hz strongly desirable. Our results can rather be used to help get the best out of a 100 fps system, whilst acknowledging that this frame rate is still a compromise.

Our results show that on average a 180° shutter is a good compromise for most material and most people. If the content contains a lot of fast motion, it may be better to increase the shutter angle to 270° to reduce strobing effects in untracked motion.

These tests were run with the display aperture as short as possible – 2 ms – in order to minimise the impact of the display on our results. At 100 fps and above, a short display aperture is attractive, since it adds minimal motion blur due to retinal slip, and at such high rates perceptible flicker is not problematic [14]. However, it should be noted that a longer display aperture, as is typical of conventional liquid crystal displays, will add blur that is dependent on the speed of eye movement to both tracked and untracked motion [19]. This means that motion blur may be visible even when it is not present in the transmitted signal, and some strobing may be disguised.

It is also important to note that these experiments investigated only large area motion that fills a third of the HD screen area, or a twelfth of the UHD screen area. Full-sized UHD video would also allow the motion to cover a much larger area, that reaches well into the peripheral vision where much is still unknown about the visibility of blur and strobing artefacts. We would expect background strobing to be more visible when the area of movement is larger, which may mean a longer shutter would be preferred.

The test image used was chosen specifically to include a wide range of detail and textures, including water, trees, and man-made structures, and hence we expect the results to be broadly applicable to a range of material. However, further testing on more content would be required to confirm this.

7 Conclusion

We have conducted controlled subjective tests to investigate the visibility of motion blur and strobing artefacts at 100 fps with different camera shutter angles. Our results demonstrate that it is not possible to make both blur and strobing imperceptible for all people at all speeds of motion by varying the camera shutter angle. However, they do provide information that allows the optimisation of 100 fps capture, which has been shown elsewhere to offer significant subjective benefits. We found that a 180° shutter is a suitable compromise between blur and strobing when the scene contains only moderate motion, with 270° being preferred when the motion is very fast.

This work contributes to the overall understanding of motion perception in high frame rate television. Blur and strobing artefacts can easily be individually minimised, but they can appear at the same time in the same scene. To achieve an overall minimisation of motion artefacts, this work takes the crucial step of allowing the two artefacts to be balanced during capture, which provides the knowledge required to give viewers the best possible experience of any future 100 fps system.

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References


