Effects of motion picture frame rate on material and texture appearance

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***Abstract*—High frame rate film should decrease motion blur and temporal aliasing allowing viewers to see more detail. Here we assessed how frame rate affected perception of detail in fabrics and costume ornamentation in three experiments. Live action footage with a fashion show theme was captured at all combinations of two resolutions (2k and 4k), three frame rates (24, 48 and 60 fps), and two shutter angles (180° and 358°). In the first experiment, participants rated the sharpness of a clip of a moving garment relative to a stationary clip. In the second experiment, participants rated (1) image sharpness and (2) quality of motion of 20-s sequences of costumed actors walking on a catwalk. In the last experiment, observers viewed pairs of image sequences and made direct pairwise comparisons while attending to the quality of motion, realism and detail in the garments. As expected, fabric detail became noticeably less distinct when in motion. Motion quality and image sharpness ratings improved with increasing frame rate, especially from 24 to 48 fps. Sharpness ratings were higher for 180° than for 358° shutter angle but the effect was small except at the lowest frame rate. Given the relatively weak effects of shutter angle, we conclude that aliasing and judder were stronger determinants of perceived detail than motion blur. Our results show that naïve observers perceive enhanced detail in HFR film sequences of moving fabrics. We argue that this improved perception of detail could underlie both the positive and negative reactions to HFR film, depending on the nature of the content and whether it lends itself to such high fidelity.**

***Index Terms*—high frame rate, perception, acuity, blur, texture perception, natural imagery**

I. Introduction

NEARLY 100 years ago the movie industry standardized cinema frame rates at 24 frames per second (fps) in part to facilitate stable audiovisual synchronization [1]. The 24-fps standard was a compromise that provided acceptable visual quality under technical and economic constraints of the time. The quality of a motion picture image sequence depends on a number of factors including the spatial and temporal resolution of the images. Modern digital cinema is technically capable of delivering higher quality resolution and frame rates. However, although the spatial resolution of digital cinema has been steadily improving, cinema frame rates have remained unchanged since the 1920s. In spite of its objectively lower image quality, the universal adoption of the 24 fps standard has resulted in a particular expectation for cinematic motion quality, which is a large part of what is known as 'the film look' [2]. This aesthetic distinguishes cinematic content from crisper content typical of higher frame rate applications like simulation, games and video.

As a motion picture is a sequence of discrete still images, its fidelity depends critically on the temporal sampling rate (frame rate). Visual sensitivity is described by the spatio-temporal contrast sensitivity function which describes the contrast required to detect a pattern as a function of spatial and temporal frequency [3]. Sampling artefacts will be visible to the viewer if they fall within a range of spatio-temporal conditions that the observer is sensitive to, conditions that have been referred to as the 'window of visibility' [4], [5]. Thus, in the case of a moving image of an object across a camera sensor, low frame rates are more likely to insufficiently sample the motion. Inadequate temporal sampling results in jumps in apparent object position, which break the sense of smooth motion (judder). Increasing the sampling rate can push potential artefacts outside the visible range, making the motion appear relatively smooth. In addition to the effect of the temporal sampling rate, the sampling technique will impact the spatio-temporal characteristics of the image sequence. That is, camera sensors do not capture images instantaneously and any image movement that occurs during the exposure will produce motion blur. The degree of motion blur in an image is directly related to both the length of time it is exposed and to its speed.

Thus increasing the temporal sampling rate (for matched capture and display), should result in content that appears 'crisper' or of higher resolution [6], [7]. Further, motion induced artefacts such as strobing and judder, which are common in 24 fps content, should be reduced. Given the likelihood of spatio-temporal artefacts arising from the use of current (relatively low) frame rates outlined above, high-frame rate (HFR) film protocols would seem to be an obvious path to improving viewer experiences. However, although the technical impact of HFR on motion quality has been widely recognized, there have been few attempts to assess its impact empirically. Marianovski et al. [8] evaluated the legibility of text in images captured from a moving camera and found significant degradation with camera motion at low frame rates but a small effect of shutter angle. Observers in that study were not asked to evaluate image blur. Although the physical constraints of stroboscopic image sampling can be modeled,

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and blur can be quantified, there is evidence that these calculations do not directly predict perceived blur. For instance, Burr and Morgan [9] showed that moving objects are perceived as less blurry than would be expected from predicted motion blur. Other researchers have contrasted perceived blur in static and moving images that contain equivalent blur to show that moving objects appear sharper than equivalently blurred static objects [10]. These studies create a strong foundation for understanding the effect of de-blurring on visual acuity. However, in all cases simple stimuli such as moving bars or sinusoidal gradients were used. Similarly, text is usually well defined and high contrast, and reading it often challenges acuity, so it is not clear if results with text generalize to natural textures and other visual judgements. For instance, several studies examined the effects of frame rate on visual *preference* and generally found that viewers preferred higher frame rates [6], [7], [11].

In preparing stimuli for our preference experiments, we noticed that the subtle motion and detail of clothing and complex natural materials like hair seemed to be of higher fidelity when viewed in HFR compared to SDR. The goal of the present series of experiments was to evaluate the impact of frame rate on the perception of these materials under well-controlled motion conditions. As outlined below, here we filmed footage under conditions in which we manipulated frame rate, shutter angle and image speed to quantitatively assess their impact on the perception of material properties. While previous research has shown high-frame rate improvements for fast motion/action sequences, here we demonstrate its benefits during shots filmed well within cinematic norms. We find that high-frames rate can improve the perceptual quality of material and fabrics in this type of content.

II. General Methods

A. Participants

Participants were recruited from the Department of Psychology Undergraduate Research Participant Pool at York University and received course credit and a small stipend as compensation. All participants provided informed consent prior to the experiment, had normal or corrected to normal acuity, and wore their prescribed corrective glasses/lenses. Testing was conducted in a screening room with multiple viewers in each session.

B. Apparatus

1) Capture: The stimuli were filmed by a professional film crew at a film set located at Sheridan College's Screen Industries Research and Training (SIRT) Centre. The 4k footage was captured at a native resolution of 4096x2160 pixels with a Sony F65 cameras. The 2K footage was captured under identical conditions with an Arri Alexa XT Plus camera.

Image generation and data recording: The clips were arranged in a playlist in a pre-specified order and displayed. The image generation PC was a HPZ820 Workstation (Intel Xeon E5-2637 v2 @ 3.5GHz, 64 GB, Windows 7 Pro 64-bit) with an NVidia Quadro K6000 graphics card (Direct X 10). Images were streamed from a high-speed SSD array and buffered in memory for real-time playback using a custom application created in Derivative Touchdesigner (Derivative, Toronto, Canada).

Participants recorded their responses using ResponseCard LCD electronic clickers made by Turning Technologies, LLC. A corresponding receiver and polling software (TurningPoint® 5) was used to record responses.

2) Displays: Testing was conducted in a screening room with multiple viewers arranged in rows of seating. As specified by typical image assessment protocols (e.g. ITU-R BT.500-13 and ISO 3664) ambient illumination was indirect (via floor lamps) and was much dimmer than the display. Average luminance of the display when showing an all-black image was 0.11 cd/m^2 in Experiments 1 and 2 and 0.13 cd/m^2 in Experiment 3.

Stimuli in Experiment 1 and 2 were presented on a Sony Bravia model XBR-65X930C 65″ class (64.5″ diagonal) 4K Ultra HD TV set for BT.709 colour space, gamma of 2.4, and an average screen luminance for full white of 168 cd/m^2. Digital processing features of the television (including motion interpolation and local dimming) were disabled.

The display had native resolution of 3840x2160 pixels and displayed the central 3840 pixel wide area of the 4096x2160 pixel images. The display was driven by the image generation PC through the TV's HDMI 2.0 port via a dual-link DVI to HDMI 2.0 convertor.

Observers were seated in two rows of five chairs centred on the screen with the first row at a distance of 1.95 m and the second row at 2.8 m from the screen. Two additional chairs were centred in a third row at a distance of 3.63 m. The viewable area of the screen was 1.44 x 0.80 m and subtended 40.5° (H) from the centre seat of the front row (and a pixel in the centre of the display subtended 0.66 minutes of arc).

In Experiment 3, only 2K stimuli were used and these stimuli were rear-projected onto a cinema screen (Stewart Filmscreen 150 Rear Projection, image size 3.56 x 2.00 m) using a Christie HD6K-M projector set for BT.709 colour space, gamma of 2.4, and an average screen luminance for full white of 179 cd/m^2.

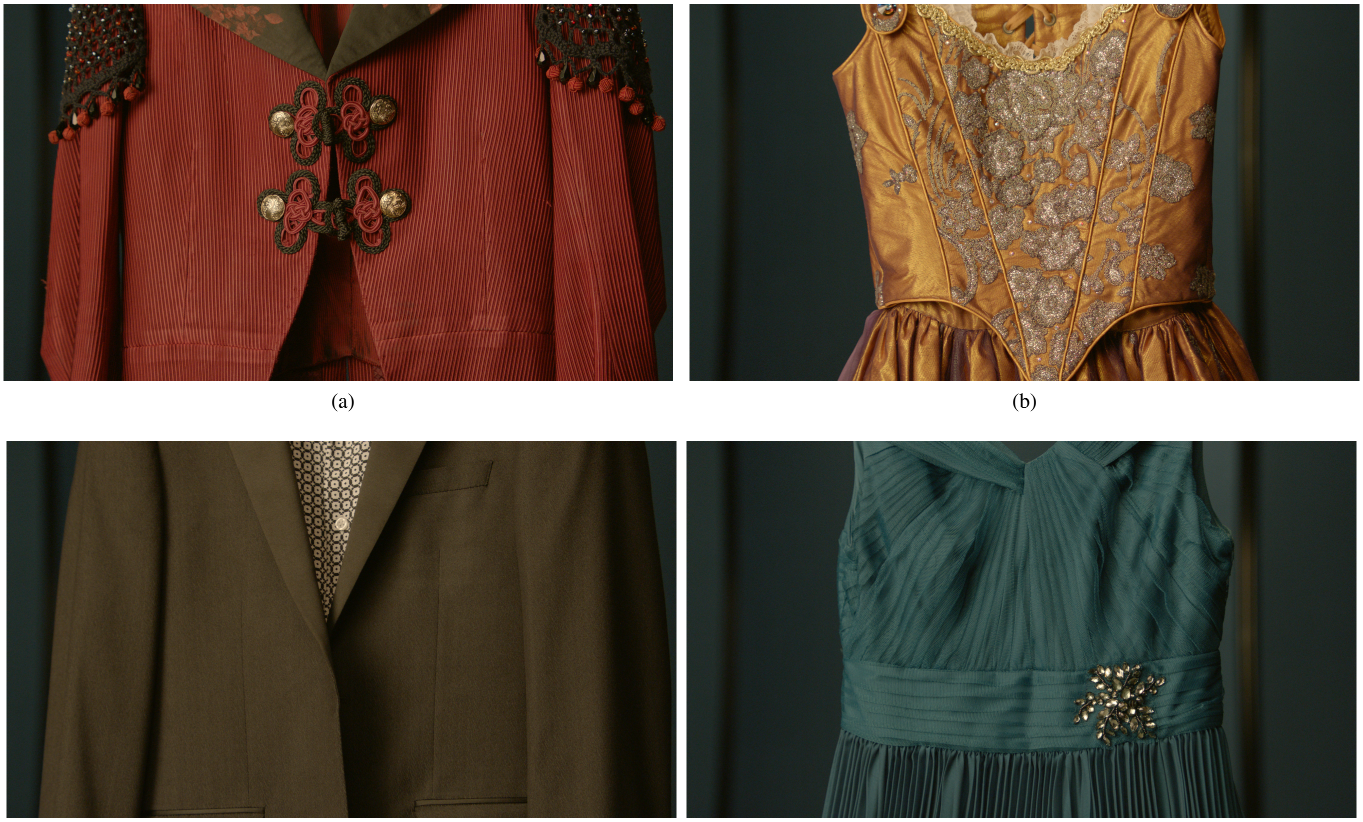
The display had native resolution of 1920x1080 pixels and 2K images were cropped to display the central 1920 pixel area of the 2048 x1080 pixel images. The display was driven by the image generation PC through a dual-link DVI interface.

Observers were seated in two rows of seven chairs (row width 3.5 m) centred on the screen with the first row at a distance of 4.27 m and the second row at 5.11 m from the screen. The viewable image was 3.56 x 2.00 m, which subtended 45° (H) from the centre of the front row (and a pixel in the centre of the display subtended 1.49 minutes of arc).

C. Stimuli

The test stimuli were short clips all related to a fashion show theme. The details of the clips were specific to the experiment and will be described separately for each experiment.

Each shot was filmed by each camera (i.e., at both 2k and 4k) under all combinations of three frame rates (24, 48 and



(a) (b)

(c) (d)

Fig. 1. Garments used in the experiments. Close-up view as used in Experiment 1 where the garment was lowered and raised smoothly during the shot. The garments were labeled (a) garment 1, (b) garment 2, (c) garment 3, and (d) garment 4.

60 fps) and two shutter angles (180° and 358°). The sets were professionally lit and in some cases two levels of lighting were used to determine the effects of direct versus indirect lighting. Four different garments were used to provide a variety of texture and material samples.

The footage was color corrected on a Quantel Pablo Rio and encoded for a target colour space corresponding to ITU-R Recommendation BT.709. Each frame was exported as 16-bit uncompressed TIFF format images to avoid compression loss and artifacts.

III. Experiment 1 – Impairment Judgements

During motion of the photographic subject relative to the camera, motion blur and motion artefacts should degrade viewers' ability to resolve detail in the image compared to a motionless shot of the subject. In the first experiment we assessed the degree of this impairment as a function of shutter angle, frame rate, lighting and speed of subject motion. We asked the viewer to assess the impact of motion on their ability to discern detail in fabrics and costume decorations (Fig. 1) compared to when the same material was stationary in the image.

A. Methods

A total of 31 observers participated in Experiment 1 (mean age 20.7). The observers were run in three sessions with 8, 11 and 12 observers, respectively.

Stimuli were captured at all combinations of two resolutions (2k and 4k), three frame rates (24, 48 and 60 fps), two shutter angles (180° and 358°) and two lighting conditions (A and B, direct versus indirect).

For every combination of these parameters the same shot was captured and edited to provide three image sequences for the testing. Each shot started with the camera centred on the top of the garment. The garment hanger was then pulled upward by a computer-controlled motion stage with a trapezoidal velocity profile (1 s acceleration, 2 s of constant velocity of approximately 350 pixels per second, and 1 s deceleration—the impression was that the camera panned downward over the garment). Following this motion sequence, the garment was held stationary with the camera centered on its midpoint for 4 s. Finally, the garment was lowered by the motion controller back to the start position (1 s acceleration, 1 s at constant speed and 1 s deceleration—giving the impression of an upward pan of the camera). This shot was then edited to produce three test sequences of 2 s each centered on each of these three phases of the shot: one with the garment moving up (the slow condition), one with the garment moving down (the fast condition, velocity was 1.5 times the slow velocity), and one with the garment still (the reference condition).

On each trial, participants viewed two clips of the same garment with a blank interval in between (500 ms viewing of a dark blank screen) as shown schematically in Fig. 2.

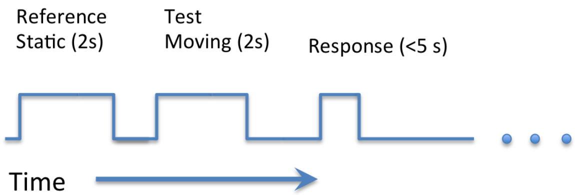


Fig. 2. A timeline of the experimental procedure for each trial in Experiment 1. The pair of clips was separated by a brief display of a blank screen and the response screen displayed the impairment scale until all participants responded (typically less than 5 s).

The first clip showed the garment while it was stationary in front of a stationary camera. As there were no motion blur, judder or other motion artefacts possible in this image sequence it was treated as the unimpaired reference as in the double-stimulus impairment scale (DSIS) method of ITU-R BT.500-13 [12]. The second sequence was the test sequence and showed the same outfit while the hanger was either moved up or down (the impression was that the camera was panning over the garment). The parameters of the test image sequence and reference sequence were always matched in terms of camera sensor, resolution, frame rate, focus, lighting, shutter and other parameters. The only difference was the motion of the garment. Thus any observed impairments can be attributed to the effect of camera motion under the conditions under test.

We tested spatio-temporal material perception for four different garments.

1) A period costume men's jacket (Fig. 1a, top left) of red corduroy with black, red and brass decorations and jewels. The garment had repeating texture and rich ornamentation.
2) A period dress (Fig. 1b, top right) of shiny gold fabric with sequins, lace, piping and other texture.
3) A finely textured men's suit jacket over a geometrically patterned shirt (Fig. 1c, bottom left).
4) A blue-green dress (Fig. 1d, bottom right) of lightweight and finely textured and slightly transparent material. The dress had folds, pleats, and a silver ornamental broach.

In all cases we tested all combinations of 2 resolutions x 3 frame rates x 2 speeds for a total of 24 conditions. To manage the number of conditions and to maintain session length at approximately 30 minutes in accordance with best practice for this type of procedure (e.g. as specified by ITU-R BT.500-13), we tested shutter angle effects and lighting effects in separate subsets of conditions. To evaluate the effects of lighting we fixed shutter angle at 180° and tested the 24 combinations of the other variables for garment 1 and 4 at each lighting level. To evaluate the effects of shutter angle we used only lighting level A (the direct lighting) and tested the 24 combinations for garments 2 and 3 at shutter angles of both 180° and 358°. This resulted in 48 trials in each of the lighting and shutter angle subsets for 96 trials per session. These trials were presented in a different pseudo-randomized order for each session.

On each trial, observers rated the quality of the moving clip relative to the stationary clip in terms of degradation of sharpness using the clicker buttons. We asked observers to view the clips in their entirety and responses were only permitted after the trial was completed. After each trial, observers were presented with an image showing the mapping of an impairment scale to the clicker buttons A–E:

(A) The same (rating = 5)
(B) Slightly degraded (rating = 4)
(C) Moderately degraded (rating = 3)
(D) Significantly degraded (rating = 2)
(E) Extremely degraded (rating = 1)

The experimenter waited for all responses to be registered before proceeding to the next trial.

Prior to beginning the main experiment, the procedure was explained and two practice trials were provided so that the observers could familiarize themselves with the task and the clicker operation. Each test session lasted approximately 30–40 minutes including informed consent and debrief.

B. Results and Discussion

In many cases (e.g. low frame rate and long shutter) the detail in the fabrics became very noticeably less distinct when in motion and thus the observers found the task easy to understand and perform.

The scale used in the experiment was mapped to a numerical impairment score from 5 (no impairment) to 1 (extremely degraded). Separate analyses were performed on the lighting and shutter angle subsets of the data. Mean impairment scores are shown in Fig. 3.

Fig. 3a and 3b show the subset of data where the shutter angle was varied. Linear mixed effects models with stepwise incremental model selection were used in R (package lmertest, https://cran.r-project.org/) to analyze the effects. As can be seen in the figure, increasing frame rate increased mean impairment scores (indicating increases in quality, $F(1, 1447) = 4.56, p = 0.0328$, F-tests use the Satterthwaite approximation for degrees of freedom). Shutter angle had little effect except at the lowest frame rate where increased shutter angle was associated with more impairment (frame rate x shutter interaction $F(1, 1447) = 8.94, p = 0.002$; main effect of shutter $F(1, 1447) = 11.14, p = 0.0009$). Speed was also a factor with increased speed generally resulting in more impairment although the effect was typically small. The garment used in the trial played a significant role, with garment 2 (the gold dress) showing more impairment (main effect, $F(1, 1447) = 4.56, p = 0.033$), a stronger effect of frame rate (garment by frame rate interaction $F(1, 1447) = 9.74, p = 0.0018$), and a larger shutter effect (garment by shutter interaction $F(1, 1447) = 4.47, p = 0.035$), than garment 3 (the suit).

The effect of frame rate was expected since, as frame rate is increased, temporal resolution is enhanced and motion blur and aliasing are reduced. It is possible that aliasing and judder played a more significant role in this degradation than motion blur. Evidence for this conclusion comes from the fact that the shutter angle effects were smaller than expected if motion blur drove the frame rate effects. For example, the within frame

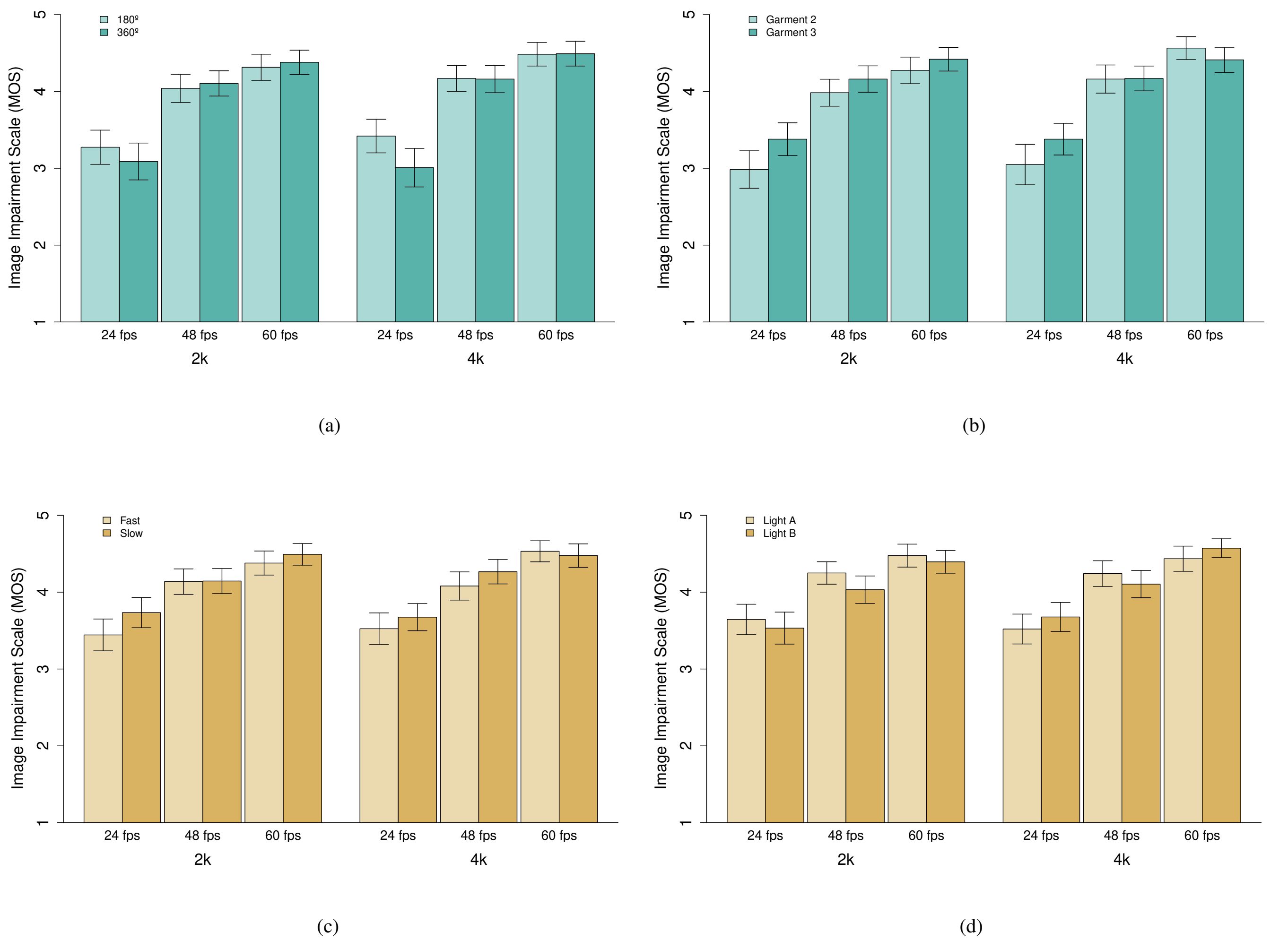


Fig. 3. Mean impairment scores for Experiment 1 (with 95% confidence intervals). The subset of data where lighting was fixed and shutter angle was varied is shown in (a + b) with (a) showing the effects of frame rate, resolution and shutter angle collapsed across speed and garment, and (b) showing the effects of frame rate, resolution and garment collapsed across speed and shutter angle. The subset of data where shutter angle was fixed and lighting varied is shown in (c + d) with (c) showing the effects of frame rate, speed and resolution collapsed across lighting and garment, and (d) showing the effects of frame rate, resolution and lighting collapsed across garment and speed.

motion blur in the 48 fps 358° case (exposure 20.72 ms) is approximately the same as in the 24 fps, 180° case (exposure 20.83 ms) but the reported reduction in quality is much more severe in the latter condition (e.g., Fig. 3a).

The motion blur in the camera image is an important source of image degradation but there are additional factors that must be considered. For instance, in a panning shot such as the ones used in this experiment, the eyes are expected to track the subject of the shot as it moves across the frame. Two related factors are involved when the eyes move. First the image has a finite hold time during which the image is present on the display. The extent and nature of this image hold depends on the type of display. If the eye moves smoothly during this hold-time (for instance when tracking the average velocity of an object) then the image of the object will move across the retina. This can produce retinal image blur analogous to the camera image blur. Second, when the refresh rate of the display does not equal the frame rate the images must be repeated one or more times to match the refresh rate (or interpolated to increase the effective frame rate). Eye movements under these conditions can result in retrograde motion signals as the repeated image appears ‘behind’ the expected motion of the target.

Fig. 3c and 3d show the subset of data where lighting was varied. Once again there were significant effects of frame rate ($F(1, 1452) = 265.6, p < 0.001$) and speed ($F(1, 1452) = 6.40, p = 0.012$). However there were no significant interactions or main effects of lighting or garment.

In the set of images we used to assess the impact of shutter angle we found an effect of the garment. Garment 2 was an elaborate dress (Fig. 1) with rich, fine detail and shiny features that were easily degraded by motion blur and artefacts. In contrast, the most salient feature of garment 3 was the periodic check pattern on the shirt, which was prone to aliasing artefacts, as a result its overall visibility was more robust to changes in shutter and frame rate. The other significant feature of garment 3 was the very fine texture in the suit jacket which, unlike the check pattern, was degraded by any motion, even at the highest frame rate. Given that the test garments were selected with an eye to including a wide range of textures and detail this result is not surprising. It is informative however, in that it confirms that the impacts of shutter and frame rate depend on the nature of the texture; in this case the texture of the gold dress was fine enough for the degradation to be apparent but coarse enough that it could still be discerned under motion, given sufficient temporal resolution.

In contrast, in the image sequences used to assess the effects of lighting, we found no differences in the effects of frame rate or shutter angle between garments 1 and 4. While these two garments were very different in appearance and material, they both had features on a similar scale due to ornamentation, ribbing, and pleating and a similar vertical/ oblique orientation bias in the visible features.

IV. Experiment 2 – Single Stimulus Quality Judgements

In the first experiment observers rated the impairment of the moving image relative to a stationary reference. In this case, we expect that observers should be very sensitive to degradation in the image sequence, even if the overall quality of the image was still relatively high. To understand how perceived quality varies as a function of the capture parameters, in Experiment 2 we asked viewers to rate absolute quality while over trials we varied the shutter angle, frame rate and sensor resolution.

A. Methods

A total of 26 observers participated in Experiment 2. The observers were run in three sessions with 11, 7, and 8 observers, respectively.

The shot used for this experiment showed a view of a runway stage (Fig. 4). A runway model entered the scene from behind a curtain, walked to one side of the stage, turned, walked to the opposite end, turned and walked back to the centre of the stage. These stimuli were filmed at all combinations of two resolutions (2k and 4k), three frame rates (24, 48 and 60 fps), two shutter angles (180° and 358°) and two actors (actor 1, female, and actor 2, male, in different costume, see Figure 4) for a total of 24 conditions. Professionally trained actors were used to ensure that timing and sequences were repeatable (i.e., that marks were reliably hit). All clips were edited to 20 s in length.

On each trial, observers viewed one of these 24 conditions. These trials were presented in a different pseudo-randomized order for each session. They were asked to watch the clip carefully and to rate the quality of imagery on two properties: (1) its sharpness or level of detail and (2) the quality of the motion. Prior to testing, the participants were told that motion quality was to be judged based on the smoothness and naturalness of the motion of the actors and their clothing. They were also told that the differences between the clips would be most pronounced when the actor was moving and so they should pay particular to these intervals. Observers were requested to view the clips in their entirety and responses were only permitted after the trial was completed.

After each trial, observers were presented first with an image showing the mapping of an image quality scale for motion quality to the clicker buttons A–E (corresponding to the single stimulus quality adjectival scale in ITU.R BT.500-13 Table 3):

(A) Excellent (rating = 5)
(B) Good (rating = 4)
(C) Fair (rating = 3)
(D) Poor (rating = 2)
(E) Bad (rating = 1)

The experimenter waited for all responses to be registered before proceeding. Following the ratings of image sharpness a slide prompting the motion quality ratings was presented. The mapping of clicker buttons to rating scale was the same as for both judgements. Once the software registered the motion quality ratings from all observers the experiment proceeded to the next trial.

Prior to beginning the main experiment the procedure was explained and two practice trials were presented so that the observers could familiarize themselves with the task and the clicker operation. Each test session lasted approximately 20–30 minutes including informed consent and debrief.

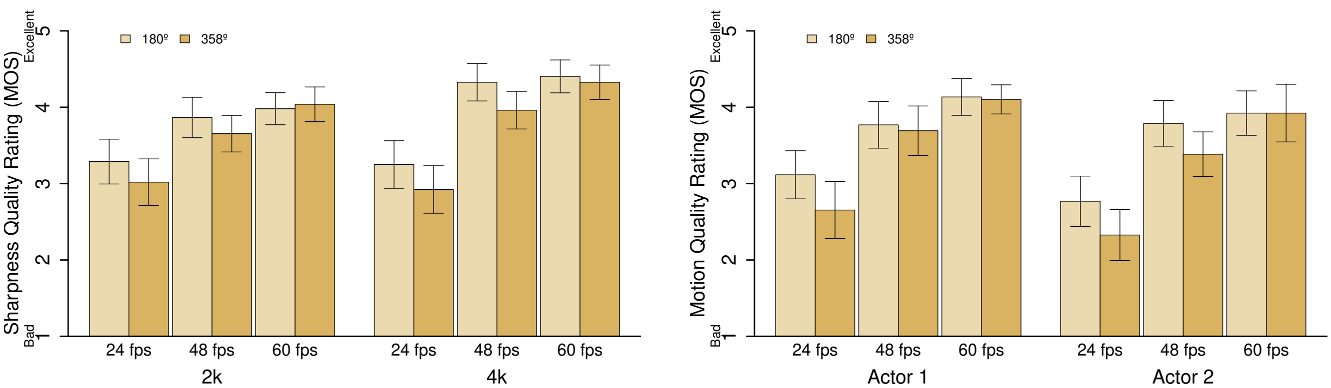
B. Results and Discussion

Mean opinion scores for the motion quality and sharpness ratings are shown in Fig. 5. Linear mixed effects models with incremental model selection were used in R (packages lme4 and lmertest, https://cran.r-project.org/) to analyze the effects. All models incorporated a random-intercept factor for the participant (to model the repeated measures). For each dependent variable, fixed effects (main effects of Frame Rate, Shutter Angle, Resolution, and Actor as well as the interactions of included main effects) were added starting from the initial random-intercepts-only model. Terms to add were chosen based on maximal improvement in Akaike information criterion (AIC). The resulting larger model was adopted if there was a significant improvement compared to the model without the added term, based on a likelihood ratio test. This process was repeated until no significant improvements could be found.

For sharpness ratings (Fig. 5a), this process arrived at model including Shutter Angle and the main effects and interaction of Frame Rate and Resolution. Adding Actor as factor did not improve the model (likelihood ratio test $\chi^2(1) = 0.604, p = 0.437$). Sharpness ratings increased significantly with increasing frame rate ($F(1, 594) = 190.96, p < 0.001$ using the Satterthwaite approximation for degrees of freedom) especially from 24 to 48 fps. The ratings of sharpness for a shutter angle of 180° were higher than for 358° ($F(1, 594) = 9.13, p = 0.003$) consistent with the smaller motion blur expected in the former case. Also, consistent with the higher pixel resolution, there were higher ratings of sharpness for the 4k compared to 2k images at the higher frame rates of 48 and 60 fps. However, the benefit of higher resolution depended on frame rate; there was a significant interaction between these factors ($F(1, 594) = 8.44, p = 0.004$). At the lowest frame

(a) (b)

Fig. 4. Sample frames from the stimuli used in Experiment 2 showing actors 1 (a) and 2 (b).



(a) (b)

Fig. 5. Mean opinion scores for Experiment 2 (with 95% confidence intervals) for (a) sharpness ratings and (b) motion quality. The data was collapsed across actors in (a) and across resolutions in (b).

rate of 24 fps, ratings of sharpness for the 4k sequences were similar to or even lower than ratings for the 2k sequences. It is possible that the reduction in image sharpness due to motion blur was more apparent in the low frame rate 4k condition because it could be judged relative to the high resolution static portions of the image or compared to portions of the sequence where the actor was moving more slowly.

For motion quality ratings (Fig. 5a), the model included the main effects and interaction of Frame Rate and Shutter Angle, and a main effect of Actor. Adding a Resolution term did not improve the model (likelihood ratio test $\chi^2(1) = 0.447, p = 0.504$). As we found with motion quality, frame rate had a significant influence on motion quality ratings ($F(1, 594) = 5.13, p = 0.024$) with quality increasing with frame rate, especially from 24 to 48 fps. There was also a significant interaction between frame rate and shutter angle with the degradation in motion quality at 358^o compared to 180^o shutter being most pronounced at the lowest frame rates (interaction $F(1, 594) = 4.35, p = 0.038$; main effect of shutter $F(1, 594) = 8.57, p = 0.0036$). The motion quality ratings also depended on the actor with lower ratings on average for actor 2 compared to actor 1 ($F(1, 594) = 7.39, p = 0.0067$). This could be due to the alternating fast motion of the legs, which were visible for actor 2 but were hidden under the fluid motion of the dress for actor 1.

There was a moderate correlation between the sharpness and motion quality ratings (Kendall's tau = 0.52). On average, sharpness ratings were higher than motion quality ratings perhaps indicating that observers found motion artefacts more disturbing than loss of detail during motion.

V. Experiment 3 – Pairwise Comparisons

In the final experiment we had observers make direct comparisons of the quality of the same shot under different capture conditions. This allowed us to obtain an indication of viewer preference as a function of shutter angle and frame rate. This experiment also differed from Experiment 2 by approximating a theatrical rather than television viewing setting and using a dolly shot rather than a fixed camera. Thus, Experiment 3 allowed for an estimation of the degree of preference (or indifference) to the frame-rate differences in quality and for an assessment of the generality of our findings across variations in technology and cinematography.

A. Methods

A total of 26 observers participated in Experiment 3. The observers were run in two sessions with 14 and 12 observers, respectively.

The shot used for this experiment showed a side view of the models walking down the catwalk in different wardrobes. The female actor (Actor 1) wore either the blue-green dress (Actor 1, Wardrobe 1, dress is shown as garment 4 in Fig. 1) or the gold dress (Actor 1, Wardrobe 2, worn as shown in Fig. 4). For one wardrobe, Actor 2 wore the same the jacket, jeans and shoes as in experiment 2 (Actor 2, Wardrobe 1, see Fig. 4). For the other, he wore the red jacket (shown as garment 1 in Fig. 1) with ribbed, tight pants and high boots (Actor 2, Wardrobe 2).

For this experiment all image sequences were 2k resolution and were three captured at all combinations of three frame rates (24, 48 and 60 fps), two shutter angles (180° and 358°) and with two different actors, each in two different garments. Thus there were 24 different clips (6 for each garment). The shot was close-up showing the actor from the waist down and the camera tracked the actor walking down the runway so the actor stayed centred in the shot. Professionally trained actors and a motion controlled camera dolly were used to ensure repeatable timing and that marks were reliably hit. All clips were edited to 3 s in length corresponding to several steps along the same portion of the catwalk.

On each trial, observers viewed two pairs of clips sequentially and rated their relative quality. All comparisons were made between clips with the same actor wearing the same garment. For each garment there were 15 possible (unordered) combinations of the six conditions. Thus, in the first session we presented 60 trials (all 15 combinations for each of the four garments) in pseudorandom order and then presented these trials in a counterbalanced order for the second session. Observers were asked to view the clips in their entirety and responses were only permitted after the trial was completed.

Observers were instructed to base their judgements on the detail and motion of the actors and the fabric of their garments, specifically whether the fabric appeared sharp, smoothly moving and natural looking. After each trial, observers were presented with an image showing the mapping of a quality preference scale to the clicker buttons A–E:

(A) Strongly prefer clip 1
(B) Somewhat prefer clip 1
(C) No preference
(D) Somewhat prefer clip 2
(E) Strongly prefer clip 2

Prior to beginning the main experiment the procedure was explained and two practice trials were presented so that the observers could familiarize themselves with the task and the clicker operation. Each test session lasted approximately 20 minutes including informed consent and debrief.

B. Results and Discussion

Mean preference scores are shown in Fig. 6. Fig. 6a shows the preference for the larger shutter angle when the frame rate was the same in the two clips. As can be seen there were no strong preferences, with smaller shutter angle preferred (negative values on the graph) for some conditions and the larger for others (positive values on the graph). This absence of shutter effects held across frame rates.

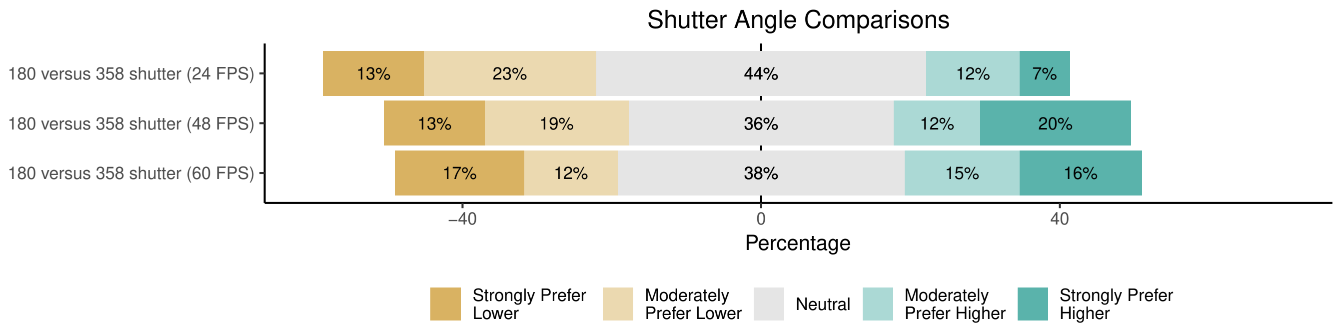
Fig. 6b shows the preference for frame rate (positive numbers indicate preference for the higher frame rate in a pair) when shutter angle was equal in the two clips. As can be seen 48 and 60 fps clips were consistently preferred over 24 fps clips. There was no strong preference between 48 and 60 fps. However, there was a modest bias for 60 over 48 fps for one condition (Actor 2, Wardrobe 2) and a consistently larger preference bias for 60 over 24 fps compared to 48 over 24 fps.

Conjoint analysis [13] using the R package prefmod (https://cran.r-project.org/package=prefmod) indicated a significant effect of frame rate ($\chi^2(1) = 273.54, p < 0.001$) and a significant interaction between shutter and actor ($\chi^2(3) = 9.82, p = 0.0017$) but there was no significant interaction between shutter and frame rate or between frame rate and actor or outfit. Inspection of the coefficients confirmed that the actor by shutter interaction corresponded to the pattern of results observed in Fig. 7 with observers slightly preferring the smaller shutter angle for actor 1 (and their garments) and the larger shutter for actor 2 (and their garments).

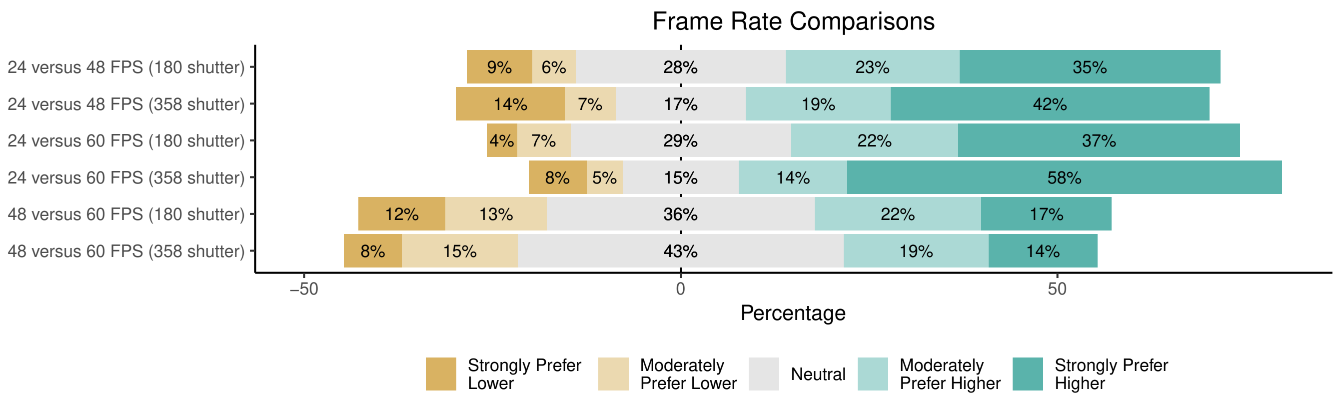
The conjoint analysis treats preference as a binary outcome (prefer the first or second interval) while allowing for ties (no preference) but not distinguishing between weak and strong preference. To determine if the results were the same when the degree of preference was taken into account, we repeated the analysis using the ordBTL package in R (https://cran.r-project.org/package=ordBTL) which implements an extension of the Bradley-Terry-Luce model to allow for ordinal (as well as dichotomous) response variables [14]. The results were compatible with the conjoint analysis and in increasing order of preference ranked the conditions as 24fps-358°, 24fps-180°, 48fps-180°, 48fps-358°, 60fps-180° and 60fps-358°. Higher frame rate was associated with greater preference, with the 24 fps conditions having significantly lower coefficients than the 48 and 60 fps cases ($p < 0.0001$) and with the 60 fps conditions having significantly larger coefficients than both the 24 and 48 fps cases ($p < 0.01$). Consistent with the conjoint analysis, the effect of shutter angle was inconsistent and dependent on the actor.

VI. General Discussion

Using film content captured with a professional film crew and equipment we found that increasing frame rate improved the perceived quality of moving clothing and fabrics relative to a static clip (Experiment 1), without a reference (Experiment 2), and when comparing clips (Experiment 3). The effects of frame rate on motion has been previously documented with simple stimuli. Our results with natural textures generally confirm and extend these findings with simple stimuli. For example, Burr et al [15] used drifting sinusoidal gratings. In their study for the lowest spatial frequency grating of 0.07 cycles per degree moving at the fastest speed of 171 deg/s (temporal frequency of 12 Hz), the frame rate needed to be

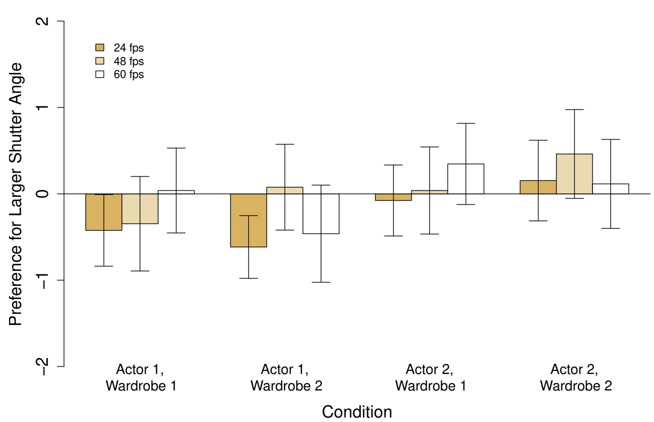


(a)

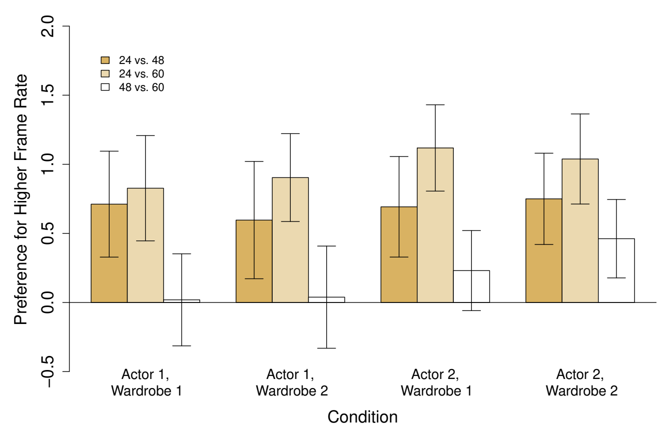


(b)

Fig. 6. Distribution of preference responses for comparisons between shutter angles at a fixed frame rate (a) and between frame rates at a fixed shutter angle (b). In all cases, responses are collapsed across actor and wardrobe. The distributions are centred on the middle of the neutral response so the bias in responses is reflected in the left-right balance of the bars.



(a)



(b)

Fig. 7. Mean preference ratings in Experiment 3 for comparison between shutter angle at a fixed frame rate (a) and between frame rates (b).

at least about 60 Hz to appear smooth to their two subjects. Some models of image quality incorporate a decreasing rate of improvement of quality with increasing frame rate [16], [17] and our data were consistent with this showing less improvement from 48 to 60 fps than between 24 to 48 fps in all three experiments. These results are generally consistent with previous studies of viewer preference which also reported diminishing returns with higher frame rates [6], [7], [18], [19].

However, the acceptable frame rate depends critically on the image content and the characteristics of the motion [6], [19]. De Bruyn and Orban [20] reported that the maximum velocity at which direction discrimination was possible increased with frame rate (at least until the highest frame rate of 100 fps that they tested). More recently, Kuroki et al [21], [22] found that the smoothness of perceived motion during free head/eye movement while viewing a high-refresh rate CRT improved with increased frame rate up to 250 Hz, at which point responses plateaued. Mackin et al [23] used a strobed physical stimulus and confirmed that increasing the frame rate improves perceived motion smoothness up to at least several hundred frames per second for rapidly moving stimuli. In their study the stimulus was a simple black bar on a white disk background. The stroboscopic display technique ensured that all stimulus blur was due to the observer' visual system and not to display characteristics. However, the method resulted in the occurrence of multiple images or banding under some test conditions (e.g. when the spatial displacement of the line was greater than the width of the line). Mackin et al found that multiple imaging often limited perceived motion quality confirming observations of [8], [10]. In the present study we found a small effect of image velocity (Experiment 1) although we used a very limited range of movements consistent with cinematic convention. Even within this limited range we found appreciable improvements with increased frame rate. Faster, more dynamic scenes would be expected to show even more improvement of increased frame rate [6], [7], [23], [24], [25].

Motion has been shown to be important in distinguishing surface material properties, particularly for shiny materials where the motion of specular highlights and reflections is a characteristic feature [26], [27], [28]. Many materials bend or otherwise deform in specific ways as they move, providing information about their underlying properties. Fleming and colleagues have explored this in the context of viscous liquids and shown the importance of visual motion in materials that flow [29], [30] and in elastic deformations [31]. Fabrics and materials such as hair, often exhibit gloss and also deform and 'flow' with movement and the appearance and dynamics of this deformation are important to material perception [32]. Consistent with this observation, motion has been demonstrated to be important in distinguishing these materials [33], [34] and in particular the uniformity of motion appears to be important to estimating material stiffness [35]. One of the motivations for the present study was our previous observation that it is difficult to distinguish flexible light-weight materials from stiffer materials under low frame rate. Similarly complex real-time simulations of hair, fur and fabrics involve a tradeoff between the fidelity of the simulation in each frame and the frame rate; such issues highlight the importance of understanding the relative impact of frame rate [36], [37].

In contrast to the strong effect of frame rate seen here, the effects of shutter angle were modest. While observers on average judged quality as higher for 180^o compared to 360^o shutter in all three of our experiments, these effects were small compared to the frame rate effects. This suggests that motion smoothness and aliasing are key determinants of video quality for fabrics in our experiments rather than motion blur.

As outlined in the Introduction, disruptions of motion smoothness are perceived as 'judder'. Daly et al [38] identified four components of judder: motion blur, non-smooth motion, multiple edges, and flickering. They found that frame rate was the most important determinant followed by speed. In a recent follow-up, Chapiro et al [39] looked at the influence of frame rate, panning speed, luminance and other factors on judder in 2D images translated across the screen. They asked participants to rate judder on a 9-point scale (normalized to full range). At 30 fps judder increased with image speed and average luminance although little judder was seen under any condition at 60 fps or higher. Consistent with our weak effect of shutter angle the authors found no effect of computationally generated motion blur on judder.

Our subjects always had a foreground stimulus (the subject of the shot) that was either moving (Experiment 1 and 2) or tracked by the camera (Experiment 3). Given our instructions they would be expected to attend to it and follow it with their eyes. This would result in less retinal motion in the foreground object relative to the image motion (and more in the background in Experiments 2 and 3). The reduced retinal motion should result in an increased sensitivity to motion blur in the tracked content but should reduce aliasing effects in the foreground as well [40], [41]. Daly et al [38] also compared judder when the eyes were stationary compared to tracking the stimulus. Consistent with expectations, observers experienced less judder when the eyes tracked the stimulus than when they fixated. We expect that observers in our experiments would have experienced more judder in the background than the foreground although this would be less noticeable as they were attending to the actors and their garments.

With given bandwidth constraints, spatial resolution and frame rate trade off and it is important to understand the relative importance of these factors [42], [43]. Our data suggest that often, at least for the frame rate range studied here, the quality of displayed textures is more dependent on temporal than spatial resolution confirming earlier reports [44]. For example, in Experiment 2, doubling the frame rate from 24 to 48 fps had a much larger effect on perceived quality than doubling resolution from 2k to 4k. This pattern of results echos Janowski and Romaniak's [16] conclusion that perceived quality is particularly tied to frame rate in movies with high spatial detail.

The experiments presented here are the first to empirically evaluate the impact of HFR on material and texture perception in cinema content. We have shown that, in general, higher frame rates, higher resolution and smaller shutter angles should be used when the goal is to emphasize details in moving image although the effect of frame rate was more important than the other two factors under our conditions.

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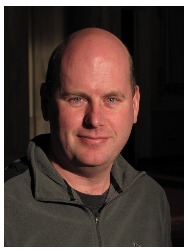

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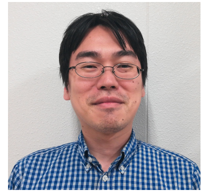

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