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Evidence that Viewers Prefer Higher Frame Rate Film

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High frame rate movie-making refers to the capture and projection of movies at frame rates several times higher than the traditional 24 frames per second. This higher frame rate theoretically improves the quality of motion portrayed in movies, and helps avoid motion blur, judder and other undesirable artefacts. However, there is considerable debate in the cinema industry regarding the acceptance of HFR content given anecdotal reports of hyper-realistic imagery that reveals too much set and costume detail. Despite the potential theoretical advantages, there has been little empirical investigation of the impact of high-frame rate techniques on the viewer experience. In this study we use stereoscopic 3D content, filmed and projected at multiple frame rates (24, 48 and 60 fps), with shutter angles ranging from 90° to 358°, to evaluate viewer preferences. In a paired-comparison paradigm we assessed preferences along a set of five attributes (realism, motion smoothness, blur/clarity, quality of depth and overall preference). The resulting data show a clear preference for higher frame rates, particularly when contrasting 24 fps with 48 or 60 fps. We found little impact of shutter angle on viewers' choices, with the exception of one measure (motion smoothness) for one clip type. These data are the first empirical evidence of the advantages afforded by high frame rate capture and presentation in a cinema context.

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1. INTRODUCTION

The industry standard presentation protocol for both traditional and digital cinema was determined by the limitations of projection technologies of the early 1900s. Standardization of the frame rate at 24 frames per second (fps) occurred in the 1920s when the addition of sound to film made precise and stable synchronization protocols necessary. While 24 fps was found to support the perception of most continuous motion, such a low flash rate produces objectionable flicker in strobed displays [Engstrom 1935]. Therefore, in a cinema projector, each frame is flashed two or three times reducing flicker without increasing frame rate (and hence the length and cost of the film stock or data transfer)[Armat 1897]. The universal adoption of the 24 fps standard has resulted in a particular expectation for motion blur in 2D and S3D film, which is a large part of what is known as 'the film look'. This aesthetic distinguishes cinematic content from crisper content typical of higher frame rate applications like simulation, games and video.

The possibilities for higher frame rates (HFR) enabled by the move from film to digital cinema have sparked the imagination and filmmaking focus of established large-budget directors such as James Cameron and Peter Jackson. Both Cameron and Jackson have committed to combining stereoscopic (S3D) filmmaking with HFR capture/projection [Giardina 2012a]. High-frame rate photography has been used in movie making for many years but projection is normally at 24 fps producing slow motion effects. High-frame photography with matched presentation frame rate maintains time progression and motion but increases temporal resolution. This theoretically should improve perceived image resolution, as well as reduce motion artefacts such as strobing and judder. However, anecdotally some viewers balk at the hyper-realistic imagery and compare it to watching HD video footage [Giardina 2012b]. This contrasts with studies in simulation [Lindholm and Martin 1993] and gaming [Claypool and Claypool 2007] which show benefits of increasing frame rate, typically to at least 60 fps in these applications.

The growing debate surrounding HFR cinema is currently fuelled mainly by the opinions of industry experts and critics. To date the typical audience member has had little experience with HFR footage, apart from the Hobbit™ franchise movies and the occasional theme park exhibit. The response of professional critics may differ from that of typical young audience members who have grown up with computer games and high-definition video as defining audiovisual experiences. The current study looks at viewer preference for frame rate and frame duration (shutter angle — the amount of the frame period in which the sensor is exposed expressed as an angle) using a variety of film clips.

2. PREVIOUS WORK

Acuity for moving targets differs from spatial resolution of stationary images, particularly when eye movements are considered. For example, Miller [Miller 1958] investigated visual acuity during pursuit eye movements. He found that acuity degraded markedly with the speed of the image, when image speed was expressed in terms of change in visual angle per unit time (note they used relative high speeds 10-170°/s). Increased luminance benefits dynamic visual acuity for high speed motion more than for slow/stationary targets. With higher luminance cinema presentations made possible by the move to laser projection technology, viewers should be more sensitive to both loss of detail and to flicker since sensitivity to both these factors increases with luminance [Sheedy et al. 1984; Winterbottom et al. 2007].

When an object moves relative to a stationary camera, its image moves continuously relative to the sensor. The discrete-time nature of the image acquisition process has several effects on the motion sequence. These effects are determined by the rate of image sampling and the duration of the sampling window.

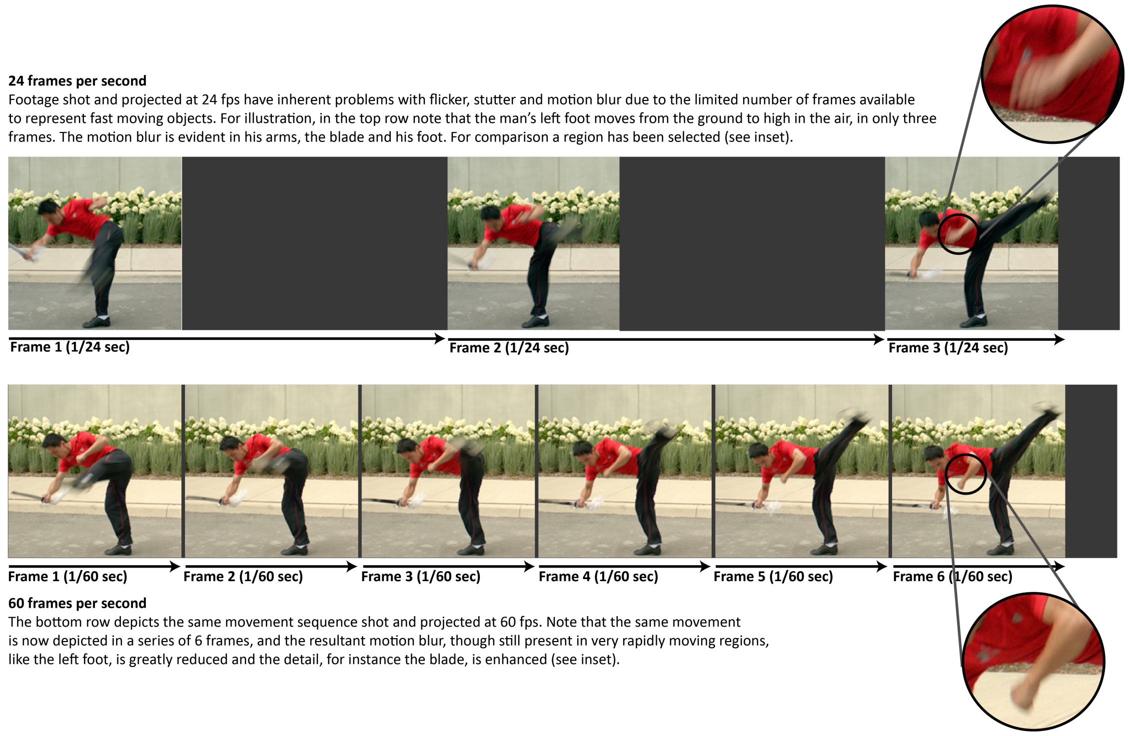

Fig. 1: Illustration of the difference in motion blur present in a sequence shot at 24 fps (upper) vs. 60 fps (lower). Adapted from a Christie Digital white paper on HFR.

First, increasing the frame rate increases the temporal resolution. The discrete temporal nature of sampled (stroboscopic) motion captures information about the motion but also introduces artefacts [Watson et al. 1986]. Considered in the spatio-temporal frequency domain, increasing the frame rate increases the temporal frequency components of an input image that can be faithfully represented in the sampled image. This has been modeled for human vision as a simplified window of visibility that describes whether aliasing and other artifacts are likely to be visible to a viewer [Watson 2013]. Such an analysis appears to work well at predicting artifacts in in both 2D and S3D content [Banks et al. 2012; Hoffman et al. 2011].

Researchers have attempted to quantify the sample rate at which stroboscopic motion appears equivalent to continuous motion (or appears to be smooth and continuous). For example, Burr et al [1986] studied the effects of frame rate on the perception of drifting sinusoidal gratings. Frame rates were based on multiples of the monitor refresh rate of 200 Hz and the displays were fairly bright (400 cd/m2). They found that the minimum frame rate which supported the perception of smooth motion increased with temporal frequency (corresponding to increasing velocity for a fixed spatial frequency) and decreased at higher spatial frequency (increasingly fine features) and was always above the Nyquist rate for the temporal frequency. For the lowest spatial frequency grating of 0.07 cycles per degree (period of 14.3°) moving at the fastest speed of 171°/s (temporal frequency of 12 Hz), the frame rate needed to be at least about 60 Hz to appear smooth for the two subjects. In a related study, De Bruyn and Orban [1989] measured thresholds for discriminating opposite motion of random-dot patterns for different strobe rates. They found that the maximum velocity at which discrimination was possible increased with frame rate (at least until the highest frame rate of 100 fps that they tested).

Judder can also be produced by stroboscopic displays. Kuroki et al [2007] reported that jerkiness during free head/eye movement while viewing a high-refresh rate CRT declined with increased frame rate up to 250 Hz, at which point responses plateaued. More recently, Johnson et al [2014] reported that perception of motion artefacts, including judder, increases with flash repetition at typical frame rates (30, 60 fps).

Second, when exposure time is not infinitesimally short, the image moves across the sensor during the exposure period producing motion smear of the image or motion blur. Conventionally, cinematographers quantify the exposure duration in terms of the shutter angle, which refers to the angular size of the opening between the vanes on a rotating mechanical shutter (i.e. 90° and 180° shutter angles would correspond to the shutter being open for 1/4 and 1/2 of the frame, respectively), even when the shutter is electronic not mechanical. It is common to use a shutter angle of 180° when shooting 24 fps footage and, as described above, audiences have come to expect the resultant motion blur as part of the film look. The relationship between motion blur and exposure duration is made more complex by the fact that projectors present each frame for a finite interval (flash duration) and, even in the absence of motion blur in the images, if the eyes move during this time then the retinal images will have motion blur.

The preceding factors are physical processes and the degree of blurring they produce can be calculated. However there is evidence that for real motion on the retina there is a process of active de-blurring by the human visual system. That is, objects in motion appear sharper and with less smear than expected based on predicted motion blur [Burr et al. 1986; Burr and Morgan 1997]. In their follow-up study, Bex et al [1995] confirmed that moving objects appear sharper than equivalently blurred static images; their results suggest that perceptual sharpening occurs and the visual system does not simply preserve sharp edges in moving images. Thus the relationship between physical blur in a scene and perception of that blur is not easily predicted. Moreover, viewers' preferences may be influenced by complex factors, such as past experience, and therefore may not be predicted simply from image quality.

There has been relatively little evaluation of HFR in a cinema context, and virtually no experimental study. A notable exception is the Showscan system developed and promoted by Douglas Trumbull. The original Showscan system [Trumbull 1985] used 65-mm film projected at 60 fps and the Showscan demonstrations have been influential in promoting the adoption of HFR film. However these evaluations were mainly technical, or they were demonstrations made for industry viewing. More recently, the Cameron-Pace HFR demonstration footage has been used to illustrate the effects of HFR particularly for stereoscopic 3D content. Once again, while influential in shaping opinions for and against the need for HFR cinema, these evaluations have been qualitative and anecdotal.

The experiments presented here are the first to empirically evaluate the impact of HFR, with synchronized capture and presentation, on preferences for S3D cinema content. Using a paired-comparison design, viewers evaluated video clips on a set of criteria that included motion smoothness and overall quality. The results are the first to provide empirical evidence that typical observers prefer footage captured and presented at 48 or 60 fps over the same footage filmed and displayed at 24 fps.

3. METHODS

3.1 Subjects

Participants were recruited from the Department of Psychology subject pool at York University. They wore their normal spectacle correction and gave their informed consent prior to participating. As part

Bike Shot

Picnic Shot

Warrior Shot

Fig. 2: Stills from each of the three shots. © Bert Dunk

of the test procedure, all participants completed a brief test of their stereopsis prior to participating in the main study and were excluded from the data set if they could not identify letters presented in a random dot pattern with at least 10 arcmin disparity, the largest offset tested here.

3.2 Apparatus

Testing was conducted in a large open studio space (Sheridan Colleges, Screen Industries Research and Training Centre (SIRT) Pinewood studios) with dimmable lighting. Stimuli were projected on to a Dalite silvered screen (22' diagonal) using a Christie Solaria CP4220 projector. Test footage was edited and projected at 24, 48 or 60 fps (per eye) according to the capture frame rate for each clip. The 24 fps content was triple flashed in presentation (72 Hz per eye); 48 fps content was doubled flashed (96 Hz per eye) and 60 fps material was single flashed. Separation of the two eyes views was achieved using a RealD XL circular polarization system that temporally alternated the left and right eye view (frame rate for the combined left and right image sequence was double the frame rate for each eye). Participants wore matching polarized eyewear to view the 3D imagery, and made their responses on pre-prepared response sheets attached to clipboards. Because the polarizing filters attenuate the projector intensity, the screen luminance was calibrated to a standard S3D white-level luminance of 16 cd/m^2 through the filters. The clipboards were illuminated by a white screen projected between presentation pairs.

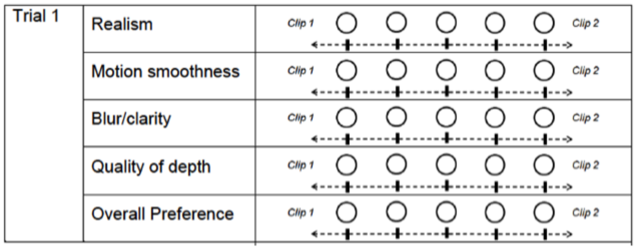

Fig. 3: A sample of the response options for a single trial. All five variables were assessed for each pair of clips using the 5-point scale (1 = prefer first clip, 5 = prefer second clip).

3.3 Stimuli

Footage was shot and edited at SIRT's Pinewood studio facility. Stereoscopic shots were captured using a 3rd Generation Tango 3D Rig with two Alexa Plus cameras equipped with a matched set of Cooke Pancro lenses. Neutral density filters were used to equate exposure across the conditions. Three different scenes were captured for use in this experiment in which i) a woman walks slowly by long grass and sits at a *picnic* table ii) a woman walks alongside a *bike* behind a tall fence and iii) a Wushu *warrior* completes a complex sword routine. Figure 2 depicts a single frame from each of the three sequences. We obtained separate clips for a range of shutter angles (180°, 270°, 358°), and frame rates (24, 48, 60 fps) for the three scenarios. All clips used during testing were edited to 10-s duration and each variant of a given shot was started at the same start point. During testing the pairs of clips were presented in a different pseudorandom order for each test group to ensure there were no consistent order effects. To limit the total duration of the study (and avoid observer fatigue), we did not include the picnic clip in our combined assessment of frame rate and shutter angle.

3.3.1 *Procedure.* Participants were transported by bus to the studio in two groups (26 in session 1, 25 in session 2). At the test facility they were seated in five rows with 1-m separation between rows for viewing distances of 7.3, 8.3, 9.3, 10.3 and 11.3 m from the screen, respectively for each row.

Prior to testing, informed consent and response forms were distributed, and the task was explained. We then asked participants to complete a brief demographic questionnaire followed by an S3D letter identification test to verify that they had stereopsis (letters were presented as random dot stereograms, at disparities ranging from 1-10 pixels, for the 2K projector, which corresponded to approximately 1-10 arc min at the centre row).

During testing, pairs of 10-s clips were presented, separated by a brief dark interval. Following each pair of clips, participants were asked to indicate which clip they preferred, rating them on 5 attributes (Figure 3) using a five-point scale ranging from strongly prefer clip 1, through neutral, to strongly prefer clip 2.

A total of 22 paired comparisons were tested, in pseudorandom order, in each session. During testing the experimenter called out the trial number to help the participants stay in sequence. Each test session lasted approximately 60 minutes. At the end of each session the questionnaires and response sheets were collected, the participants were debriefed, and then returned by bus to campus.

3.3.2 *Comparisons.* For each of the three content types, there were 72 possible ordered pairs of clips for the nine combinations of frame rate and shutter angle. It was impractical to run all 216 comparisons, as each session would last more than 9 hours. Thus, the test pairs were selected to evaluate key variables: frame rate, shutter angle and exposure duration (the product of frame duration and shutter angle/360).

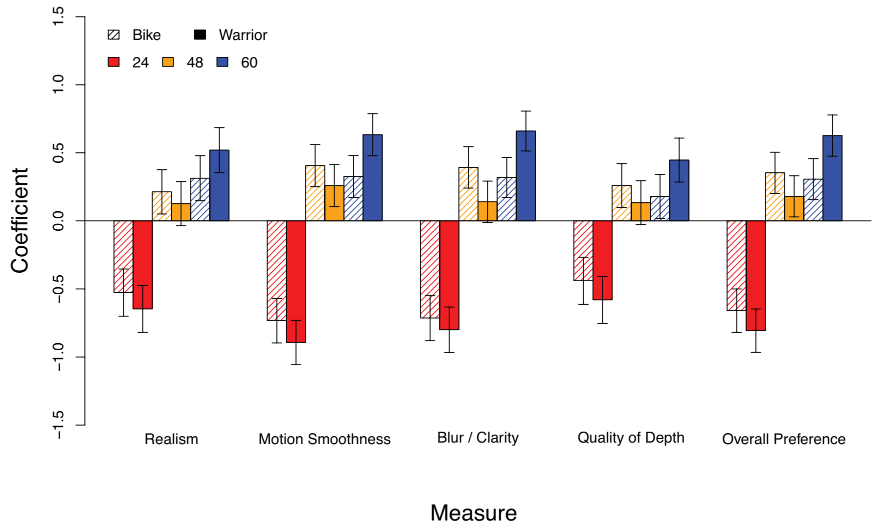

Fig. 4: The likelihood of choosing the clip with a particular frame rate is shown here at a fixed shutter angle (180°) for each of the five measurement attributes. The data obtained using the bike and warrior footage is indicated with lined and solid bars respectively. Each frame rate is indicated by the bar colour (24 = red, 48 = orange, 60 = blue). The measure is indicated below each data set. Error bars represent 95% confidence intervals.

Frame rate. We selected the bike and warrior shots to assess frame rate because these both involved fast motion or potential for strobing and aliasing artifacts. All pairs of comparisons between different frame rates at a fixed shutter angle of 180° were obtained for this analysis. This produced three combinations of 24, 48 and 60 fps for each shot for a total of 6 conditions.

Shutter angle. To assess the effects of shutter angle we used all three shots. The frame rate was fixed at 60 fps and all pairs of comparisons between different shutter angles were tested. This produced three combinations of 180°, 270° and 358° for each shot (bike, picnic and warrior) for an additional 9 conditions.

Exposure. We tested all three pairs of the following combinations for all three shots: 24 fps-180° , 48 fps-180°, and 48 fps-358°. These comparisons allowed us to test whether the effects of frame rate were similar for the picnic shot (since it was not included in the frame rate series) and whether the effect of shutter angle was similar at 48 fps (since the shutter angle series was run at 60 fps). The comparison between 24 fps-180° and 48 fps-358° is important since they have an equivalent exposure time of 20.8 ms (there was less than 1% difference in exposure duration). This produced another 9 pairings but because two were common with the frame rate series above only 7 additional conditions were required.

4. RESULTS

As noted above, all paired comparisons were tested in a single session in random order. Subsequently, the preference data were compiled and analyzed using an additive conjoint analysis. Used commonly in market research, conjoint analysis measures the degree to which each attribute contributes to overall preference as represented by its part-worth utility and coefficient in a regression model [Green and Srinivasan 1990; Luce and Tukey 1964]. The sum of these part-worth utilities is zero and the viewers preference for one attribute (over another) is indicated by the difference of their coefficients. In the

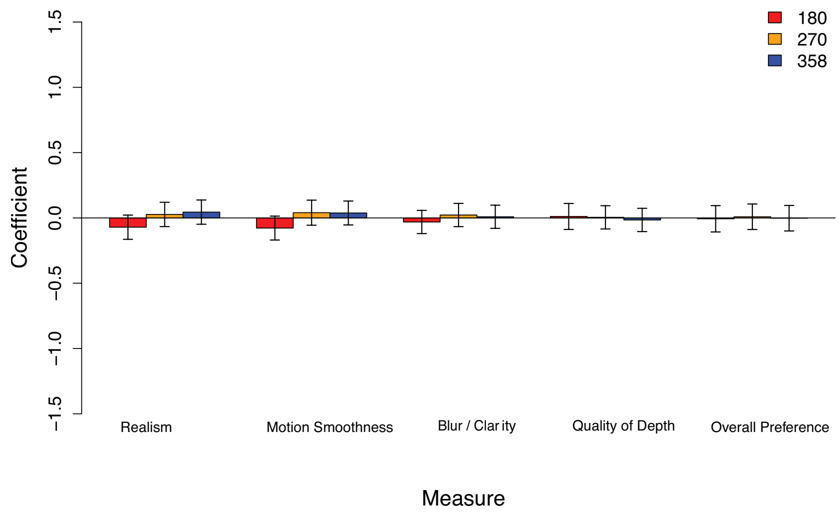

Fig. 5: Coefficients are shown here for clips with variable shutter angle (180° = red, 270° = gold, 358° = blue) and a fixed frame rate (60 fps). The results are collapsed across clip type. Error bars represent 95% confidence intervals.

following sections we examine the coefficients for each of the main groups of comparisons outlined in the Comparisons section above.

4.1 Frame Rate

Figure 4 shows the effect of frame rate, at a fixed shutter angle (180°), for the bike and warrior clips (recall that the picnic clip was not included in this comparison). For both clips, and all measures (realism, motion smoothness blur/clarity, depth quality and overall preference), coefficients are positive for the high frame rate conditions (48 and 60 fps), and consistently negative for the 24 fps footage. There is a tendency (across all measures) to choose the clip with the higher frame rate when 24 fps is paired with 48 or 60 fps. However this graph also shows little or no difference between the preference for frame rates of 48 and 60 except for the warrior clip.

The conjoint analysis confirmed that there was a significant preference for higher frame rates (48 and 60 fps compared to 24 fps), with p values $< .0001$. Also, the interaction between frame rate and clip type was significant for measurements of motion smoothness, blur / clarity, and overall preference, p's $< .01$, but not for realism or quality of depth. Observers preferred the warrior clip when presented at 60 fps compared to 48 fps.

4.2 Shutter angle

The coefficients obtained for the three shutter angles (at 60 fps) collapsed across clip, are shown in Figure 5. There were no significant differences between any of the comparisons, nor was there a significant preference for any shutter angle on any of the individual measures. A histogram of the responses showed no evidence of bimodality as might be expected from a 'film-look' versus 'crisp image' dichotomy.

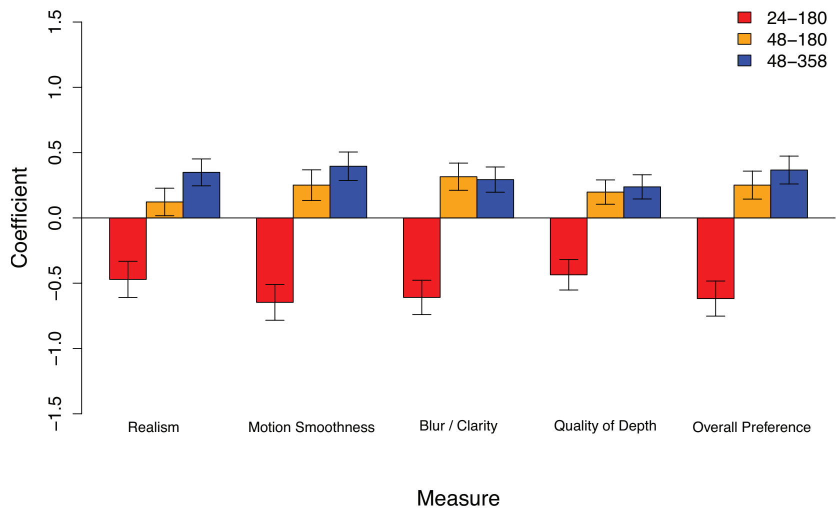

Fig. 6: The coefficients for paired comparisons in which exposure is equated (24 fps with 180° shutter is equivalent to 48 fps with 358° shutter angle) for all measures. Data are averaged across clip-type and show coefficients for conditions with 24 fps at 180°, 48 fps at 180° and 358°. Error bars represent the 95% confidence intervals

4.3 Equivalent Exposure Comparison

To evaluate the effect of exposure on preferences for the five measures and three clip types, we assessed preferences for 24 fps footage with 180 deg shutter angle vs with 48 fps shot with 180° and 358° shutter angles. Note that the exposure duration is equivalent in the 24-180° and the 48-358° conditions, so if exposure drives preferences, coefficients in these two conditions should be equivalent and positive. However, if frame rate is the critical variable, then we should find the pattern of results observed in Figure 3, with large coefficients associated with 48 fps, and small (or negative) coefficients with 24 fps, irrespective of exposure. The data are shown in Figure 6 for all measures, averaged across clip type.

Figure 6 shows that, overall, there is no effect of exposure on preferences. There were significant effects of frame rate ($p < 0.001$), but no effect of clip or shutter angle for all but the motion smoothness measure.

Examination of the coefficients for the motion smoothness attribute, for each clip-type, showed that the coefficients for the 48fps-180° and 48fps-358° cases are similar and positive for the bike and warrior clips. In contrast, for the picnic clip the 48fps-180° coefficient is much smaller and near zero (see Figure 7). The reduced preference for this clip relative to the 48 fps-358° condition suggests that motion artefacts do impact preferences when they are salient, and when viewers are asked to reflect specifically on motion quality. There are a number of reasons why the highest frame rate shutter angle combination is preferred for this measure for this clip. For instance, in the picnic shot there is an initial close-up of a hand passing over tall grasses, which is filmed with a wide depth of field. Given the intimate nature of the composition, perhaps viewers were drawn to the softer appearance provided by the large shutter angle, which matched their 'film-look' expectations. In contrast, there was rapid motion in the warrior clip and the bike clip had periodic structure susceptible to aliasing; thus both these clips were more susceptible to judder.

5. DISCUSSION

In all conditions tested here there was a clear preference for higher frame rates (48 and 60 fps) when contrasted with a standard of 24fps, regardless of content (Figure 3). It is clear from these data that, overall, viewers prefer higher frame rate footage, and that there is a significant impact on preferences of increasing frame rate from 24 to 48 fps. Interestingly, there is little additional benefit afforded by further increasing frame rate from 48 to 60 fps for the bike shot. However, for the warrior shot, viewers preferred 60 fps compared to 48 fps content in terms of motion smoothness, blur / clarity, and overall preference. This suggests that the effect of frame is content dependent. For an action shot like the warrior clip (see Figure 1) the details of the rapid movement are preserved at high frame rates. In contrast, for the bike scene it is likely that, once frame rate was sufficient to prevent objectionable aliasing and judder artifacts, there would be little additional benefit of increasing frame rate. Of course for a perfectly stationary scene there would be no benefit of increased frame rate at all. Overall, our data suggests that the improvement in moving image quality provided by higher frame rates is both perceived and appreciated by viewers. This is consistent with studies in simulation and television [Kuroki et al. 2007], simulation [Winterbottom et al. 2007], video [Banitalebi-Dehkordi et al. 2014] and gaming [Claypool and Claypool 2007]. These results are generally consistent with ours and suggests there is a strong preference for the smoother motion provided by higher frame rates.

Our content was all presented in stereoscopic 3D and there is theoretical and empirical evidence that higher frame rates improve the perception of depth in S3D media [Hoffman et al. 2011; Kuroki 2012]. Our observers did show increasing preference for higher frame rate on the measure of quality of depth consistent with this literature. However, it is worth noting that the preference for higher frame rate was typically weakest for comparisons of quality of depth compared to the other four attributes. This suggests that depth quality was not the principle reason for the overall preference for higher frame rates. It is important to note that our stereoscopic depth budget was set, for aesthetic reasons, within established norms for S3D filmmaking. It might be interesting to explore the tradeoff between depth and frame rate further in future work by systematically varying frame rate and stereoscopic depth to explore their interrelations.

Our viewers preferred higher-frame rate content both in terms of realism and in terms of overall preference. This seems counter to the criticism leveled against recent HFR films that the content was 'too real'. Our participants were predominantly young adults accustomed to higher frame rate experiences from games and HD video and perhaps preferred the more realistic imagery since they were accustomed to it. On the other hand, complaints of hyper-realism often seem to concern the fake nature of props and sets. Our content was filmed on location with minimal set dressing and no elaborate costumes, make-up, or masks. Thus any increased realism in our shots should enhance the experience rather than 'give away' a movie set.

There was no effect of shutter angle on preferences for these clips for any measure (Figure 5). Consistent with these results, we found that when exposure was equated (Figure 6) by comparing 24 fps at 180° with 48 fps at 358°, viewers maintained a preference for the higher frame rate (48 fps). Similarly, in that same comparison, it is evident that there is no specific preference when the frame rate is equivalent (48 fps) but the shutter angle varies (180° vs 358°) except for one specific clip (picnic) measure (motion smoothness) combination (Figure 7).

The absence of an effect of shutter angle is somewhat surprising, given that this variable should have contributed to perceived image blur. One possibility is that this manipulation had no impact because of the high frame rate used (60 fps) for that comparison. However, this explanation does not account for the results shown in Figure 6 where comparisons of preferences for 24 and 48 fps, again show no impact of shutter angle. It is also plausible that, as suggested in the Introduction, audiences

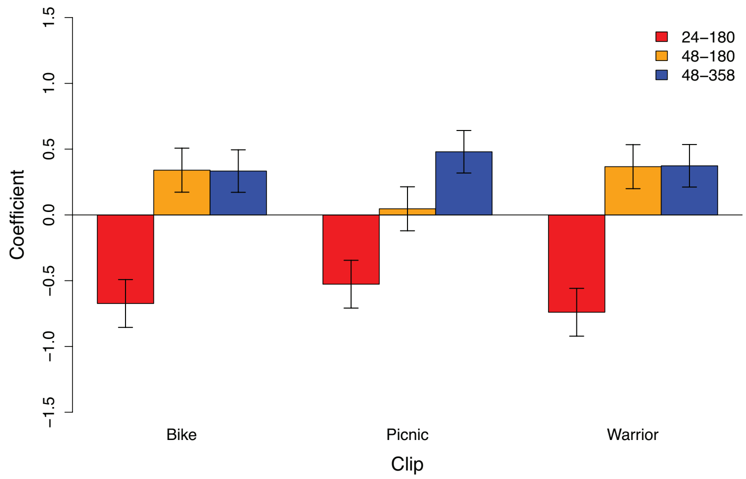

Fig. 7: The choice coefficients are shown here for the motion smoothness measure, for each of the clip types, for three combinations of frame rate and shutter angle. Preferences for the picnic footage show null preferences for the 48 fps condition. Error bars represent 95% confidence intervals.

are accustomed to softer images due to blur, and to the manipulation of depth of field within scenes, so the shutter angle manipulation did not influence their preferences. In ongoing experiments we are evaluating the effect of these variables (both frame rate and shutter angle) on an objective task.

As discussed above, frame rate preferences are modulated by the nature of the content. When viewing a shot with relatively slow motion (walking) there is no preference for 60 vs 48 fps, however there is a preference for 60 fps relative to 48 fps when the shot contains rapid movement. Given that there are reports of dissatisfaction with HFR associated with its hyper-realism (among other factors) it is important that filmmakers consider the costs relative to the potential benefits. This choice is made more complex by the fact that most films contain both slow moving and action shots. Ideally, filmmakers will eventually be able to use a variable frame rate that is tuned to the amount of movement in a scene. Currently this option is not available to filmmakers (or audiences) but is being explored [Quesnel et al. 2013]. Our results show significant preferences for high frame rates in S3D footage among typical audience members, and in all cases viewers preferred content filmed and projected at 48 fps over the standard 24 fps. While the shutter angle had little impact overall, there were conditions where viewers showed preferences for content with more motion blur (60 fps - 358° shutter angle, picnic clip). Given the associated technical and financial costs of implementing variable frame rate, these issues may be addressed by manipulating shutter angle in some situations to achieve a more aesthetically pleasing shot (as in our picnic clip).

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