Preference for motion and depth in 3D film

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ABSTRACT

While heuristics have evolved over decades for the capture and display of conventional 2D film, it is not clear these always apply well to stereoscopic 3D (S3D) film. Further, while there has been considerable recent research on viewer comfort in S3D media, little attention has been paid to audience preferences for filming parameters in S3D. Here we evaluate viewers' preferences for moving S3D film content in a theatre setting. Specifically we examine preferences for combinations of camera motion (speed and direction) and stereoscopic depth (IA). The amount of IA had no impact on clip preferences regardless of the direction or speed of camera movement. However, preferences were influenced by camera speed, but only in the in-depth condition where viewers preferred faster motion. Given that previous research shows that slower speeds are more comfortable for viewing S3D content, our results show that viewing preferences cannot be predicted simply from measures of comfort. Instead, it is clear that viewer response to S3D film is complex and that film parameters selected to enhance comfort may in some instances produce less appealing content.
Keywords: 3D film, preference, stereoscopic depth perception, motion perception

INTRODUCTION

The accessibility and variety of stereoscopic three-dimensional (S3D) media available has rapidly increased in recent years. Two-dimensional (2D) film has a well-established set of guidelines or language that is widely used to produce aesthetically pleasing content and to guide viewers' attention. These film-language conventions help viewers make sense of a moving image with dynamically changing viewpoint and cuts between scenes in time and space, all determined by the film director rather than the viewer's own actions. Filmmakers have traditionally used parameters like the angle of view and depth of field to build a coherent sense of space in a 2D display. For instance, adjustments of focal length can shift the perspective of images by exaggerating or flattening distances within a scene. Together with control of camera focus and lens aperture (and hence depth of field) these adjustments help direct the viewer's attention to the point of focus in a scene. Adding camera motion, such as dollying (i.e. moving the camera rig in depth) and tracking (i.e. moving the camera rig laterally) can introduce motion artifacts if film practices are not optimized [1]. Thus, the ideal camera speed for a given sequence depends (among other variables) on the focal length, shutter angle, and frame rate. In general, longer focal lengths require slower camera movements, larger shutter angles produce more motion blur, and higher frame rates reduce the appearance of motion artifacts. In most situations, moving the camera too quickly can create uncomfortable motion artifacts, such as motion judder (i.e. shaky, inconsistent movements) or blur (i.e. streaking of rapidly moving objects).

While the 2D film heuristics described above have evolved over decades, it remains unclear how these apply to S3D film. The addition of binocular parallax (depth) has the potential to enrich film with a vivid sense of depth, volume, and solidity. However, by providing an additional, highly salient cue to depth, S3D content risks alerting the viewer to visual errors that might have otherwise been forgiven in 2D content. These visual errors are commonly due to the mismatch in depth cues provided by binocular parallax and monocular depth information (i.e. shading, blur, linear perspective, texture gradient, occlusion etc.). Multiple sources of depth information may lead to incomplete, ambiguous, or contradictory depth percepts [2]. Given this, S3D content will likely demand its own unique conventions that are separate, but still derived from the existing 2D language.

Framing is a good example of how violating filming heuristics can have dramatically different consequences in S3D versus 2D. Typically, cutting off objects at the edge of the screen in 2D film has little aesthetic or visual impact, apart from appearing awkward. However in S3D film, three-dimensional objects that extend beyond the edges of the screen can produce stereoscopic window violations. Conflicting depth cues between the 3D object and the zero disparity edge of the screen can lead to flattening of 3D objects. In addition, depending on the size of the region and depth ordering (positive or negative parallax) it may appear pinned to the edge of the screen, or produce rivalry [3]. This and other parallax violations in S3D can severely distort the final 3D representations of objects. Thus—unlike 2D film—the allocation of binocular parallax in S3D film must be scrupulously regulated, and is typically controlled by the stereographer who manipulates the interaxial distance or IA (i.e. separation between optical axes of the cameras) to control the range of binocular parallax or depth budget. The relative absence of heuristics for the optimal creation and presentation of S3D media has lead to great debate regarding which parameters are crucial to attaining an optimal viewing experience. Further, the vast majority of previous research focuses on subjective measures of viewing experience, and typically evaluate factors that influence viewer comfort.

Studies of viewer comfort have concentrated on the effects of excessive binocular parallax and motion on subjective reports of comfort and associated physiological changes in accommodation [4]. In general, low subjective reports of comfort correlate with rapid motion in combination with large binocular parallax in stereoscopic images [5]. The direction of motion can also significantly affect subjective ratings of comfort. For instance, movements in-depth tend to elicit larger discomfort ratings than lateral movements, most likely due to the shifts in convergence that are required to track moving objects in-depth compared to the relatively stable convergence needed to track laterally moving objects [6]. However, there is currently no consensus on the relationship between the amount of binocular parallax, object motion, and visual comfort, possibly due to a lack of standardized subjective assessment methods for visual comfort [4].

A factor that makes it difficult to relate the literature on viewer comfort to S3D film is the fact that the majority of studies have been performed under restricted experimental conditions, using simple (often static) stimuli presented at short viewing distances [6][7]. At short viewing distances (less than one meter) the vergence-accommodation conflict is exacerbated, and under such conditions this conflict has been linked to headaches, visual fatigue, and eyestrain [8]. In a standard theatre environment, viewers will typically be seated much further from the screen (at least 4m), where vergence-accommodation conflicts are rare (except for fixated objects portrayed well in front of the screen plane). It is possible then, that the experience and appreciation of S3D film will be related to factors other than the vergence-accommodation relationship or even the degree of visual comfort.

In a novel approach to understanding the impact of S3D film parameters, we evaluated viewers' aesthetic preference for camera motion in moving S3D dance sequences presented in a theatre setting. We recorded preferences for combinations of camera motion (both direction and speed) and interaxial distance (IA). If we assume that viewer preference of S3D content is defined by the same criteria as viewer comfort, we would expect viewers to prefer slower camera speeds, filmed with smaller IA separations.

METHODS

Subjects

A total of 80 participants were recruited through the York University Undergraduate Research Participant Pool for course credit. In separate sessions, approximately half (39) of the observers viewed in-depth motion while the remaining viewed lateral motion (41). All observers had normal or corrected-to-normal vision and wore their corrective lenses during testing. Observers were excluded if they could not reliably perform a random dot stereoacuity task for elements with at least 0.05 degrees of disparity. Five observers did not meet this criterion (4 from the in-depth, 1 from the lateral motion condition). Observers were also excluded based on a measure of attention, repeating the same responses on 15 or more consecutive trials. Only 2 individuals from the in-depth motion condition were eliminated based on this criterion.

Stimuli

The moving stimulus for this experiment was footage of a professional actor performing a six-second dance phrase. A summary of the dance sequence can be seen in Figure 1. The actor was filmed under each combination of IA (zero=0mm, small=10mm, or large=65mm), camera speed (low=0.11 m/s, medium=0.15 m/s, or high=0.45 m/s), and motion direction (in-depth along the z-axis or lateral along the x-axis) at 24 frames per second. Camera speeds were selected to be within the range used in conventional 2D filmmaking. In total, 18 stereoscopic video clips corresponding to each unique combination of IA, camera speed, and motion direction were created. This resulted in 9 clips for each of the in-depth and lateral motion testing sessions. For each testing session, paired comparisons were created by randomly ordering all possible unique clip pairs to produce a procedurally generated playlist in MATLAB. Using the formula for calculating paired combinations with repetition (1), where n = number of video clips and r = number of video clips in each combination, we obtained a total of 45 paired comparisons for each testing session containing all unique combinations of the 9 video clips (including paired comparisons between identical clips) for each motion condition (in-depth and lateral).

$$\frac{(n+r-1)!}{r!(n-1)} \tag{1}$$

Apparatus

S3D film footage was shot in a parallel camera configuration using dual SI-2K Digital Cinema Cameras. The cameras were mounted 1.49 meters from the ground on a rig consisting of a 3.65 m long dolly and track system that was positioned orthogonally (in-depth motion condition) or parallel (lateral motion condition) with respect to the actor. The detailed layout of the filming conditions can be seen in Figure 2. Post-production horizontal image translation was performed using Cineform FirstLight, and the first frame of all images was converged on the leading corner of the left-most chair (See Figure 2 object P). The video clips were edited in Adobe Premiere Pro CS4 and subsequently exported as separate left and right AVI files using a Cineform codec. Separate S3D video clips were filmed for each unique combination of IA, camera speed, and motion direction.

Testing was conducted in a screening room with multiple viewers in a single session. Each motion condition (in-depth and lateral) was completed in 4 testing sessions with 15, 13, 12, and 10 individuals in the in-depth, and 7, 15, 10, and 12 individuals in the lateral motion conditions. Images were projected onto a white-surface cinema screen (2.97x1.65m) using a Christie HD6K-M system (positioned 7.6m from the screen at a resolution of 1920x1080) via Stereoscopic Player [9]. Viewers wore LC shutter glasses (Xpand Active Shutter 3D™) that alternately blocked the left and right eye views in synchronization with the display of the right and left images, respectively. Viewers were positioned in three rows, at viewing distances of 3.4m, 4.6m, and 5.8m from the screen. At the closest distance, the screen subtended 47.2°x27.3° of visual angle and one pixel subtended 0.03°.

Responses for each trial were recorded electronically using Response Card RF electronic remotes from Turning Technologies™. Each viewer was assigned an electronic remote when they entered the theatre and subsequently used them to record their responses by pressing a button (either 1 or 2) to indicate which video clip was preferred (1 or 2). Responses were recorded electronically using TurningPoint Anywhere 2008™ software and subsequently exported as an Excel document.

Figure 1. A series of frames from the six-second dance phrase are shown here to illustrate the movement. The actor started and ended the sequence in the same standing position with his arms at his side. The actor transitioned to first arabesque in Step 2, he then extended his right arm, bringing his left arm through the arabesque to meet his right hand in Step 3. In Step 4, he returned his arms to second position. Lastly in Step 5, he performed a plié with both hands resting on his right hip before finally returning to his original position in Step 6.

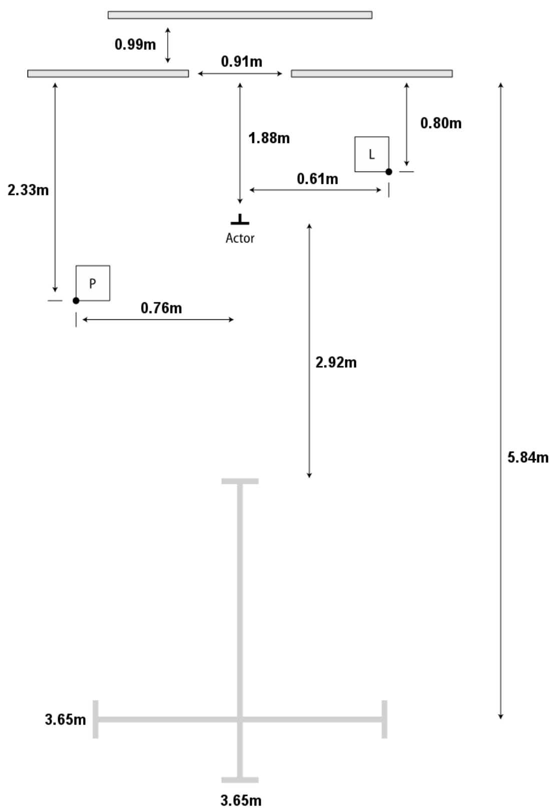

Figure 2. Layout of the film set. The grey inverted cross indicates the position of the parallel and orthogonal dolly and track system used in the lateral and in-depth motion conditions, respectively. The grey rectangles at the top of the diagram indicate the position of three off-white screens. The objects P and L represent the positions of two seated actors.

Procedure

Before each test session, observers filled out a brief demographic questionnaire. On this form they recorded their seat position (front, middle, or back row), the approximate number of S3D films they have attended in their lifetime, their preference for S3D versus 2D films, and how many hours a week they spend watching S3D media. Viewers then completed a set of pre-trials to verify the experimental set-up. First they verified that they could see depth in a S3D image, then they confirmed that the left and right eye were synchronized correctly by identifying text presented to each eye, and finally they completed a stereoacuity test. This test consisted of a series of 6 random dot stereograms each depicting three letters with decreasing positive parallax. From the row of seats closet to the screen, the largest disparity was 0.26° and the smallest 0.03°.

On each trial, a pair of video clips from the combinations described above, was presented with a two second fade to black interval between them. After the pair of video clips, viewers were shown a gray screen containing the text "Please provide your answer" at the screen plane. This screen remained visible until all viewer responses were recorded for that trial, at which point the experimenter initiated the next trial. Two experimenters were present in the screening room, one at the side of the seating area monitoring viewers' electronic responses via a laptop computer, and another at the back of the room coordinating the trial transitions. Viewers indicated which clip they preferred by pressing "1" or "2" to choose the first or second clip, respectively.

Viewers participated in either the in-depth or lateral motion test session. Each of the forty-five test pairs was presented twice in a single session for a total of ninety trials. These trials were divided into two halves (forty-five trials each) separated by a five-minute rest period. A brief break was also given at the midpoint of each half session. In total, each test session lasted one hour.

RESULTS

Figures 3A and 3B show the average probability of preferring a particular test condition in the two motion conditions, as a function of IA and camera speed, respectively. While there is little apparent impact of IA in either of the motion conditions, there is an effect of camera speed on preference, but only in the motion in-depth condition.

The paired-comparison results were analyzed as a 2x3x3 mixed experimental design with two levels of motion direction (motion in-depth and lateral motion) tested between-subjects. Camera speed and IA were within-subject variables each with three levels (0.11m/s, 0.15m/s, 0.45m/s, and 0mm, 10mm, or 65mm, respectively). Excluding comparisons of identical clips, each observers' preferences were evaluated for 36 paired comparisons consisting of 9 unique video clips (3 levels of camera speed by 3 levels of IA). Our dependent variable was the probability of choosing a given video clip, calculated as the number of times a video clip was chosen divided by the total number of times it was presented.

A preliminary evaluation using the Shapiro-Wilk test revealed significant violations of normality across the standardized residuals of multiple experimental conditions [10]. A subsequent evaluation using Levene's test further revealed heteroscedasticity within both between-subject groups across both within-subject variables [11]. Ordinarily, these small departures from normality within residuals would not significantly affect the results of a parametric analysis of variance; however, the addition of heterogeneous variances across multiple experimental conditions could bias the results of a non-robust test. Therefore, we used a robust ANOVA with 20% trimmed means to examine the relationship between our variables and viewer preference. This statistical method has been shown to be effective for mixed designs and is robust to departures from normality, as well as covariance heterogeneity in unbalanced repeated measure designs [12][13].

The robust repeated-measures mixed ANOVA was used to evaluate the effect of motion direction, camera speed, and IA on viewer preferences. Tests of our independent variables revealed a significant effect of motion direction ($Q=4.75$, $p=0.03$), but no main effect of camera speed ($Q=1.29$, $p=0.28$) or IA ($Q=2.65$, $p=0.07$). The average response probabilities for each level of IA for both motion direction conditions can be seen in Figure 3A. The lack of an effect of IA implies that the simple presence or absence of S3D does not impact viewer preference. Viewer preferences appear unchanged whether they are viewing S3D or effectively 2D (IA = 0) content. Two-way tests of interactions revealed a significant effect between motion direction and camera speed ($Q=3.27$, $p=0.04$), and non-significant interactions between motion direction and IA (Q=1.22, p=0.30), and camera speed and IA (Q=0.94, p=0.44). Figure 3B highlights the significant two-way interaction between camera speed and motion direction by plotting the mean probability of choosing a video clip for each level of camera speed in both in-depth and lateral motion conditions. No significant three-way interaction between motion direction, camera motion, and IA was found (Q=1.49, p=0.20).

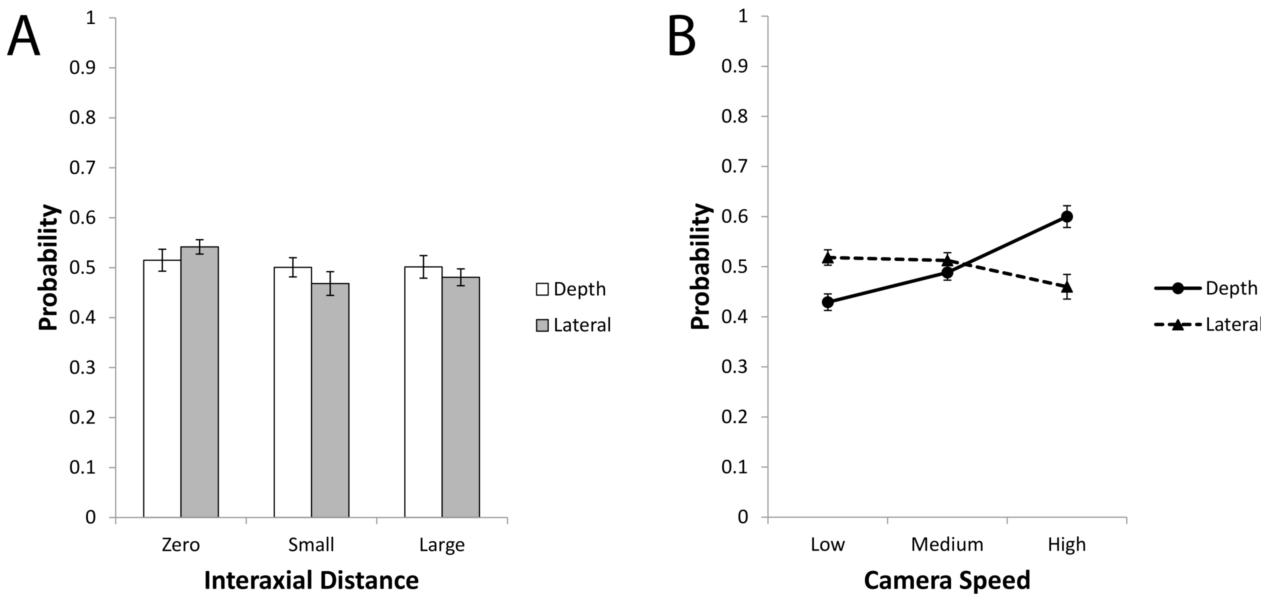

Figure 3. A) Probability of choosing a video clip (i.e. number of times chosen divided by number of presentations) based on zero, small or large IA (0, 10, and 65mm respectively) for each motion direction (in-depth or lateral). B) Probability of choosing a video clip in the low, medium, and high camera speed conditions (0.11, 0.15, and 0.45m/s respectively) as a function of motion direction. Error bars represent ± one standard error of the mean.

To explore the nature of the significant two-way interaction, contrasts were performed using two robust one-way repeated measures ANOVAs for each motion direction condition by camera speed. While a significant effect of camera speed, $F(1.23, 29.49)=6.7$, $p=0.01$, was found for the in-depth motion condition, no such effect was seen in the lateral motion condition, $F(1.26, 30.32)=1.99$, $p=0.17$. These results suggest the root of the interaction between motion direction and camera speed lies in the different effects of camera speed in the two motion direction conditions. In Figure 3B, there is an increase in preference with increasing camera speed in the motion in-depth condition, but a shallow, decreasing trend across camera speed in the lateral motion condition. To evaluate differences between the two motion direction conditions as a function of camera speed, multiple pairwise comparisons were performed evaluating each combination of the two motion directions and the three levels of camera speed. The results can be seen in Table 1. Figure 3B illustrates the results of the pairwise comparisons. Overall, there is a clear difference between motion direction conditions at each level of speed. The motion in-depth condition demonstrates a positive linear trend as camera speed increases, highlighted by the significant differences between the slowest camera speed and the medium/high camera speeds. In contrast, in the lateral motion condition there were no significant effects of camera speed although the data does demonstrate a decreasing trend as camera speed increases (Figure 3B). These results suggest that viewer preference is only dependent on the speed of camera movements when the motion is in-depth.

Table 1: Multiple pairwise comparisons between the two levels of motion direction and three levels of camera speed were performed using Wilcox's (2005) functions bwamcp() and bwbmcp() for between-within designs. Critical p-values reported are designed to control the probability of at least on type 1 error to less than or equal to 0.05

Contrast		**Q**	**SE**	**p-value**	**p-critical**
Motion Direction	**Speed**				
Depth:Lateral	Low	-2.60	0.46	0.013*	0.025
Depth:Lateral	Medium	-2.09	0.35	0.042*	0.05
Depth:Lateral	High	2.96	0.72	0.005**	0.017
Depth	Low:Medium	-2.29	0.31	0.035*	0.05
Depth	Low:High	-2.69	0.94	0.013*	0.017
Depth	Medium:High	-2.29	0.80	0.031	0.025
Lateral	Low:Medium	0.92	0.23	0.369	0.05
Lateral	Low:High	1.12	0.73	0.275	0.025
Lateral	Medium:High	1.49	0.75	0.150	0.017

Statistical Significance: * = 0.05, ** = 0.01

DISCUSSION

We evaluated viewer's aesthetic preferences for moving S3D content for individual shots that varied in camera motion (both direction and speed) and IA. While there was little impact of IA in either motion condition, there did appear to be an effect of camera speed on preference, but only for motion in depth. Our results are the first to demonstrate that viewer preferences for S3D content are not necessarily driven by the same factors that determine subjective ratings of viewer comfort. Importantly, it is clear from our results that camera motion has a strong influence on preference, and this preference is opposite to that predicted from the viewer comfort literature. Thus, the results of the present study highlight the complexities of subjective evaluations of S3D content and draw attention to the fact that decisions made to enhance viewer comfort may not always produce the most appealing content to the viewer.

Effect of Interaxial Distance

The amount of stereoscopic depth (i.e. interaxial separation) in the S3D content had no impact on judgements of viewer preference regardless of the direction of camera movement. Comparison of the 0mm IA results with the 10mm and 65mm data (Figure 3A) show that the presence of parallax had no apparent impact on preferences; the presence of S3D on its own does not make the film sequence more appealing to viewers. It is possible that this result is related to the video content; the actor stayed in position, with only the upper body motion in for all conditions, and the same dance sequence was presented repeatedly. Observers reported their preference, but were not instructed to attend to any aspect of the depth or motion in the scene. The fact that the patterns of preferences found were the same whether there was binocular parallax in the scene or not suggests that the typical conventions for camera motion applied to 2D film may be equally applicable to S3D content.

Effect of Camera Motion

We examined the effect of camera motion by varying both the direction of camera movement, that is, along the z-axis (motion in-depth) or along the x-axis (lateral motion), and the speed of camera movement (i.e. low, medium, and high). Our results show that viewers' preference depended on the speed of camera movements when the motion was in-depth, preferring faster camera movements. In contrast, in the lateral motion condition, viewers' preference did not depend on camera speed.

The difference between the results in the two motion direction conditions may be simply due to differences in the visual information in the two conditions. Objects approaching the viewer, due to object or camera motion in depth, provide the specialized stereoscopic motion-in-depth signals of changing disparity and differential interocular motion [14][15]. However, these are unlikely to explain the difference between the in-depth and lateral cases since there were no differences between the 2D and S3D conditions. That is, in the 10mm and 65mm IA conditions the changing disparity signal increased with increasing IA, yet there was no change in preference, nor was there any difference between preferences in these conditions and the 0mm (2D) condition. Motion in depth toward an object also provides the monocularly available cue of looming. As the object approaches (or is approached), its retinal size increases or looms. This is an important biological signal that warns of an impending collision with the head or body. Many species such as humans [16][17], pigeons [18], monkeys [19] and locusts [20] respond rapidly and automatically to such signals. There is compelling evidence humans can use these signals to precisely estimate the time of a potential collision [21]. Since this highly salient signal would indicate a more imminent collision as velocity increased it might underlie the speed effect found in the motion-in-depth case. Dominance of this monocular cue to motion in depth could also explain why the IA had no effect in this case.

Comparison with Viewer Comfort Literature

The results of the current study are not consistent with predictions based on existing literature on viewer comfort. In general, low subjective ratings of comfort are obtained when scenes contain high amounts of motion, excessive binocular parallax, and/or changes in binocular parallax, either by continuously manipulating the amount of parallax in a scene or by presenting scenes with motion in-depth [4][5][6]. If viewers find changes in binocular parallax uncomfortable, we would expect viewer preferences to decrease in the S3D conditions (i.e. 10 and 65mm IA) compared to the essentially 2D condition (i.e. 0mm IA) in the motion in-depth condition. Instead, in our study viewers' preferences showed no effect of IA in this condition, but did show strong preferences for scenes with stronger motion in-depth (regardless of whether there was also changes in binocular parallax) at fast camera speeds.

Models have been proposed to quantify the level of visual comfort caused solely by the velocity of object motion; this work generally finds that speeds greater than approximately 1.92m/s in-depth produce subjective ratings of discomfort at viewing distances of 1.5m [22]. Related studies, that include binocular parallax as a factor, report uncomfortable ratings for movements in-depth greater than 1.3m/s at viewing distances of 1m [23]. The increase in discomfort as speed in-depth increases is commonly attributed to the increased rate of disparity change in these conditions. The larger viewing distance and slower camera speeds (0.11m/s, 0.15m/s, and 0.45m/s) used in the current study would presumably lead to less discomfort from camera speed alone. Further, the capture parameters used in the current study were selected to encompass a reasonable range of speeds and disparities while remaining within the observer's zone of comfort [24]. It is likely that at even higher speeds resultant motion artifacts would become increasingly salient and reduce the aesthetic appeal of the video clips. However, over the range of conditions tested here (which include conventional camera speeds) it is clear that camera parameters that should maximize viewer comfort do not necessarily produce maximum enjoyment. Instead, it appears that under these conditions, the preference for faster movement in depth is driven by other factors. As outlined above, an alternative explanation for the observed preference for fast movement in the motion in-depth condition is that this manipulation provides more salient looming information from radial optic flow (compared to the lateral condition) through either induced linear vection, object motion (discussed in the previous section), or possibly a greater sense of immersion.

When the entire scene moves in manner consistent with self-motion, compelling illusions of self-motion, known as vection, can be produced in stationary observers. In some instances, looming (i.e. radial expansion simulating motion in depth) optic flow can generate greater vection strength than lateral optic flow (simulating sideways motion) in displays of the same size [25]. It is possible that the in-depth conditions produced more effective vection than the lateral conditions and that subjects were responding to increases in this sensation with increased speed in the former condition [25][26]. Contrary to the notion that vection drives preference, while binocular cues to simulated forward self-motion reportedly increase perceived speed and decrease onset of linear vection we found no difference in preference in the 3D conditions (10mm and 65mm IA) compared to the 2D condition (0mm IA) [27][28]. However, the influence of stereoscopic cues in the previous studies was relatively small and thus it is possible the looming optic flow dominated in our stimuli. Relative depth cues in a display with looming optic flow have previously been implicated as the determining factor in the onset and strength of vection more so than the presence of stereoscopic information alone [25].

We also cannot exclude the possibility that higher-level cognitive effects, such as a greater sense of immersion are responsible for the observed preference for motion in-depth. In the in-depth condition the experience of the footage is that of 'entering' the scene, whereas in the lateral motion case the viewer 'passed by' the scene. As speed increased the extent of the movement into the scene increased and the viewers may have found this more enjoyable, engaging or interesting. It is also possible (but not tested here) that the increased engagement experienced in the motion in-depth condition promoted an increased sense of immersion that was preferred by viewers. In future experiments, it will be important to directly assess these factors.

Conclusion

Our results suggest that viewer preferences for moving S3D content do not necessarily depend on the same factors that influence visual comfort. Unlike earlier studies that reported that slower speeds and smaller disparities are more comfortable to view in S3D, here we found viewers preferred faster over slower camera movements in-depth, and showed no change in preference for different amounts of stereoscopic depth. This interesting inconsistency is likely due to variables that are known to influence visual comfort having a different impact on viewer preference. The results may also reflect temporal characteristics that impact preferences for vection and immersion. Given the apparent disconnect between the visual comfort literature and the preference results reported here, it is clear that appreciation of S3D film is a complex issue; parameters used to enhance comfort may in some instances produce less appealing content. Filmmakers should be aware of this balance between comfortable and preferable viewing in 3D motion to provide an experience that is both comfortable and enjoyable.

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