Article ▸

Comparison of S3D Display Technology on Image Quality and Viewing Experiences: Active-Shutter 3D TV vs. Passive-Polarized 3D TV

Yu-Chi Tai, PhD, Pacific University College of Optometry, Forest Grove, Oregon

Leigh Gongaware, BS, Pacific University College of Optometry, Forest Grove, Oregon

Andrew Reder, BS, Pacific University College of Optometry, Forest Grove, Oregon

John Hayes, PhD, Pacific University College of Optometry, Forest Grove, Oregon

James Sheedy, OD, PhD, Pacific University College of Optometry, Forest Grove, Oregon

ABSTRACT

Background: Stereoscopic 3D TV systems convey depth perception to the viewer by delivering to each eye separately filtered images that represent two slightly different perspectives. Currently two primary technologies are used in S3D televisions: Active shutter systems, which use alternate frame sequencing to deliver a full-frame image to one eye at a time at a fast refresh rate, and Passive polarized systems, which superimpose the two half-frame left-eye and right-eye images at the same time through different polarizing filters.

Methods: We compare visual performance in discerning details and perceiving depth, as well as the comfort and perceived display quality in viewing an S3D movie.

Results: Our results show that, in presenting details of small targets and in showing low-contrast stimuli, the Active system was significantly better than the Passive in 2D mode, but there was no significant difference between them in 3D mode. Subjects performed better on Passive than Active in 3D mode on a task requiring small vergence changes and quick re-acquisition of stereopsis – a skill related to vergence efficiency while viewing S3D displays. When viewing movies in 3D mode, there was no difference in symptoms of discomfort between Active and Passive systems. When the two systems were put side by side with selected 3D-movie scenes, all of the subjective measures of perceived display quality in 3D mode favored the Passive system, and 10 of 14 comparisons were statistically significant. The Passive system was rated significantly better for sense of immersion, motion smoothness, clarity, color, and 5 categories related to the glasses.

Conclusion: Overall, participants felt that it was easier to look at the Passive system for a longer period than the Active system, and the Passive display was selected as the preferred display by 75% ($p = 0.0000211$) of the subjects.

Keywords: Active 3D shutter display, display quality, Passive polarized 3D display, stereoscopic 3D, viewing comfort, visual discomfort symptom

Introduction

Presently most stereoscopic 3-dimensional (S3D) display systems deliver separate images to the two eyes using one of two methods: with Active-shutter glasses or with Passive polarization.[1] The Active shutter 3D TVs present S3D images to one eye at a time while blocking the other eye and repeat this process to the other eye, alternating rapidly to yield perceived fusion of the two images into a single 3D image. A key element is the Active shutter glasses. Each lens of an Active shutter pair of glasses is an independent liquid crystal panel, which incorporates two states of operation. When a voltage is applied, the liquid crystal stays in place, which is 90 degrees relative to the polarizing filter, to prevent the input light from being transmitted, and the lens is opaque. When no voltage is applied, the liquid crystal rotates to be aligned with the polarizing filter, and the lens is transparent. The glasses are controlled by a precise timing signal to enable alternate change of the opaque and transparent state for each lens. By synchronizing the shuttering effect of the lens to the refresh rate of the display, a full spatial resolution image is displayed to one eye at a time according to an alternating right and left sequence of images. Because of the way these displays work, the resulting display frame rate to each eye is half of the TV refresh rate (half temporal resolution). An S3D-ready TV with a refresh rate of 120 Hz is required in order to give 60 frames per second for each eye to minimize perceived flicker. The technology of Active-shutter glasses allows full picture information; however, the technical challenge is to set precise timing for lens shuttering to coordinate with the refreshment of TV frame and avoid cross-talk or ghosting, which can result in decreased effectiveness of S3D and possible visual discomfort. Also, to lessen the effect of ghosting from image

cross-talk, extra time is needed to allow full replacement of the display from one eye to another. Therefore, an image is displayed to each eye less than 50% of the time. As a result, the actual amount of light reaching each eye is less than 50% in 3D mode compared to 2D mode and can decrease perceived brightness.

Passive-polarization S3D TVs utilize glasses with circular polarized lenses (opposite rotation to each eye) with a film-patterned-retarder (FPR) technology on the display to split the screen view into two sets of interleaved images, one for each eye. Each polarized image is delivered only to one eye with alternate rows of pixels oppositely polarized by strips of thin polarized films. For a high definition screen with 1080 rows of pixels, each eye receives information from only 540 horizontal lines. In contrast to the Active system, the Passive system permits a full temporal resolution (complete frame rate) but half spatial resolution (half of the vertical display information) to each eye. Unlike the Active shutter glasses, the Passive polarized glasses do not have any Active (i.e., powered) components. The assumption is that the brain of the viewer will combine the separate images perceived from each eye simultaneously and generate the final visual perception of a full-resolution image.

This study aims objectively to measure the performance of both an Active-shutter and a Passive-polarized S3D display system in relation to critical parameters of display quality in both 2D and 3D modes and to compare the viewer's visual performance and visual comfort. Two high-end S3D TVs, each using one of the above two methods, with comparable screen size and screen pixel density, were acquired and tested in the default settings specified by the manufacturers. In addition, naïve volunteer human research participants were recruited to view the displays. The participants were tested with specially designed 3D vision tests and regular S3D movie-viewing. Performance and viewing comfort in 2D and 3D modes for both TV types were compared. It is expected that the results derived from the study will provide useful feedback for S3D TV manufacturers and consumers regarding the image quality and viewing experiences between the two technologies and enhance the advancement of S3D display technology.

Methods

Participants

Sixty young adults (19 males & 41 females; age 18-40 yrs, average = 24.23) were recruited from the Pacific University campus and the surrounding communities. All were screened to have distance (at 4 meters) visual acuity of 20/25 or better for each eye and stereopsis of 60 seconds of arc or better with near stereo fly chart (20-40 seconds of arc, average = 23.21). Habitual-wear contact lenses were allowed if needed but not glasses to avoid interference with S3D glasses. None was previously diagnosed with strabismus, amblyopia, or any visual, ocular, or neurological disorders, and none had history of nausea or severe discomfort in viewing S3D stimuli. All participants signed a human subject consent form approved by the Institutional Review Board of Pacific University.

Apparatus

3D TVs and glasses. One Active-shutter 55" (47.7" x 26.9") 3D TV (Samsung Model UN55D7000LFXZA) and one Passive-polarized FPR-based 55" 3D TV (LG Model 55LW6500UA) were used to display both 2D and 3D content. Both TVs had the same pixel count (1920 x 1080, with 1 inter-pixel distance of approximately 0.63 millimeters) and panel refresh rate (240 Hz) in 2D. Each TV was placed on a black rolling cart of the same type, and the edges were covered in gray to hide the brand name. For half of the participants, Active TV was labeled as TV-A and Passive TV as TV-B, and the label was reversed for the other half of the participants. The center of the TV screen was about 4.5' above the floor, and the seats were 3' above the floor, yielding an appropriate viewing position with eyes level with the middle of the screen for most people while sitting.

Home theater setting. The test was performed in a light-tight room with the wall painted in 50% reflectance gray to create the effect of immersive viewing without distraction or reflection from surrounding lights or objects. All room lights were turned off except the illumination from the TV displays. Up to four participants were tested at the same time with at most two subjects sitting next to each other, and the TV was set at the center of the two subjects. Depending on the tests, the participant was tested from a viewing distance of 4 meters from the front center of the TV (for contrast sensitivity, stereopsis, and step-vergence test), moved backward in a series of designated steps starting at 2.7 meters (for visual acuity test), or seated comfortably at a viewing distance of 2.2 meters (in the movie-viewing condition), as advised by the manufacturers (3.2 times the screen height). From this viewing distance, each inter-pixel distance subtended 0.98' of arc, hereafter rounded to 1' arc per pixel.

Materials

Visual discrimination of fixed size high- and low-contrast small stimuli. A Landolt C (a letter C with opening at 1/5 of the letter height which was presented in one of four orientations) with high-contrast (black text on white background) was employed to evaluate the participant's ability to discern small stimuli on the tested displays. Orientation of the Landolt C was randomly determined by a computer program and occurred equally frequently among the four directions. The actual size of the Landolt C was fixed (10 pixels, or 6.3 mm in height) but the angular size was systematically reduced (from 0.2, 0.1, 0, -0.1, to -0.15 logMAR) by increasing the viewing distance. The fixed size of 10 pixels meant that the Landolt Ring was 20/40 (LogMAR 0.3) at a movie viewing distance of 2.2 meters. The fixed size of 10 pixels also meant that the critical detail (gap-width in the Landolt Ring) was 2

pixels for the 2D conditions for the Active and Passive displays, and also for 3D conditions for the Active display. However, this meant that for the 3D condition for the Passive display, the gap width was 2 pixels when the gap was on the top or bottom, but only 1 pixel to each eye when the gap was on the right or the left. When a participant identified 5 or more trials correctly out of 8 attempts, he/she was moved further back to the next viewing distance. Threshold visual acuity (VA) is the smallest angular size for correctly identifying the orientation of the Landolt C, which represents the smallest detail that a viewer can discern under the specific display condition. The test was first performed in 2D mode (without 3D glasses) and then repeated in 3D mode (with 3D glasses).

Then the test was repeated in low contrast (gray text on white background) format. Instead of reducing the angular size, the same size of the Landolt C (15 pixels of letter height) was presented at a constant viewing distance of 4.1 meters (20/32, or logMAR 0.2) while the contrast of the Landolt C was progressively reduced by lightening the letter as trials proceeded. The contrast was calculated with the formula of Weber Contrast: the luminance of the background minus luminance of the letter, divided by the luminance of the background. As the test proceeded (with at least 5 out of 8 trials answered correctly), the contrast decreased from 16, 12.5, 10.0, 8.0, 6.3, 5.0, 4.0, 3.0, 2.0, to 1.25%, which match the contrast steps in a digital vision testing system (M&S Smart System 20/20 digital eye chart). The lowest contrast level for correctly recognizing the letter orientation (at least 5 out of 8 trials) was recorded as the threshold contrast sensitivity. The test was administered in both 2D and 3D mode.

Step-vergence stereo-reacquisition test of large objects. This test was only appropriate for 3D and hence conducted only in 3D. Using simulated 3D presentations, an image of 4 circles within a diamond frame was presented, with one circle (the target) presented with convergent disparity (hence perceived as 3 dimensional or floating in front of the diamond and other circles). Locations of the 4 circles within the diamond were changed with each presentation to remove symmetry clues. From a distance of 4 meters, the participant identified the circle that was disparate in each image with a controller. The test was separated into two steps. First, the subject's stereoacuity threshold was measured. The disparity in the target circle was decreased from 9 pixels by steps of 1, and the smallest amount of disparity for correct responses was registered as a person's threshold stereopsis. While a well-trained observer may discern disparity as small as 4 or 5 seconds of arc, as confined by the display resolution limitation of these TVs, the smallest disparity presented was 32 seconds of arc, which was reached by most subjects. Then we measured each subject's ability to change the vergence position of their eyes quickly and re-acquire stereopsis. The same testing stimulus used to measure stereopsis threshold was used in this experiment, and the disparity was set to 1 pixel greater than their previously-measured threshold. The entire target (diamond and circles) was presented in steps of required ocular convergence and divergence. Each time the vergence changed, the circle with disparity likewise changed, and the subject pointed out as quickly as possible the circle seen in depth compared to the others. After each step of convergence (+) or divergence (-), the target returned to zero vergence. At zero vergence, the subject likewise had to identify the correct circle seen in depth, but the reaction time back to zero was not used in the analysis. Vergence steps were (in pixels): +20, +40, +60, +80, -20, -40, -60, -80. The sequence was tested 4 times. The average response time for each pair was used to indicate the efficiency of the subject's vergence system to fuse quickly and reacquire stereopsis.

Image Clarity Questionnaire (ICQ). Participants rated image clarity and their perception of image cross-talk (i.e., ghosting image) immediately after the visual discrimination test in 2D and 3D mode separately, as well as after the threshold stereopsis test and the step-vergence test. The questions were presented on a laptop, and participants responded by marking their ratings on a 5 point analog scale with labels (disturbing, distracting, noticeable, faint, imperceptible) marked at each quartile position from left to right.

Viewing Symptom Survey (VSS). Participants' subjective visual and physical discomfort were measured with the Viewing Symptom Survey (VSS), modified from the Viewing Discomfort Questionnaire (VDQ) which has been shown effectively to measure eyestrain and other visual discomfort symptoms.[2,3] There are 17 questions in the VSS displayed on a laptop screen one question per page. These questions include sensation of blurred vision, double image, unstable image, dizzy, nausea, disoriented or vertigo, difficulty in switching focus between far and near, tired eyes, irritated or burning eyes, strained or pulling eyes, ache inside the eye, dry eye, watery eye, fatigue, headache, neck discomfort, general physical discomfort. Before and after watching the S3D movie from each TV display, participants rated their sensation by clicking on a 5 point analog scale with labels (Strongly disagree, Disagree, Neutral, Agree, Strongly agree) marked at each quartile position from left to right.

S3D movie. An animated S3D movie (*Rio*, http://www.rio-themovie.com/) was viewed on one TV for 25 minutes and, after filling out the VSS questionnaire, continued to be viewed on the other TV for another 25 minutes. The viewing order of the TV displays was based on a predetermined order balanced between participants.

Display Quality Questionnaire (DQQ). At the end of the study, participants were asked to assess the quality of tested TVs and their preference. This was achieved by playing a series of still movie clips simultaneously on the two side-by-side TV displays while assessing the display quality on 15 questions (Appendix A). These questions were categorized into 4 groups, each presented on separate display screens: General display quality (color quality, perception of jagged edges, perception of cross-talk/ghost images, perception of flickering, overall display quality), 3D presentation display quality (3D depth,

motion smoothness, immersion), Viewing comfort (viewing angle, tolerance of tilted head position, weight of glasses, edges of glasses frame, overall satisfaction of glasses), Tolerance in watching 3D.

Participants alternated their glasses between the two TV displays while examining each clip and answering the questions. Two separate analog scales on a laptop display were used to register their response, one for each TV. Participants were encouraged to compare the quality of the two TVs before marking their responses. Finally, they were asked to indicate their S3D TV preference by marking on a two-end sliding scale with the two TVs (labeled as A and B) on either side and the center marked as "Neutral, no preference." The response was graded on a 100 point scale. The closer the slider was marked to one end (0 or 100), the stronger the participant preferred the TV at that end. A score of 50 indicated no preference for either TV display.

Procedures

As participants arrived at the lab, they were given a description and explanation of the experimental procedures and an explanation of the experimental setup. They were encouraged to ask any questions about the study. Formal consent of the participant was obtained in writing using a consent form approved by the Pacific University Institutional Review Board. Participants who met the recruitment criteria and signed the consent form were then entered into the experiment.

The experimental session lasted approximately two hours, including three parts in fixed order: threshold vision test, followed by 3D movie viewing, and ending with side-by-side TV quality evaluation. For vision testing and movie viewing, the participant was tested with each TV sequentially in a pre-designated order balanced between participants. Up to four participants were tested at a time. Participants were compensated for their time and effort at the end of the experiment.

For threshold vision testing, the participant first performed the visual discrimination task with threshold high-contrast stimuli and the low-contrast stimuli in 2D. Immediately after the test, they were asked to recall the quality of the tested image (image clarity and sense of ghosting) on the Image Clarity Questionnaire (ICQ). The same test was repeated in 3D followed by filling out the ICQ. Then the threshold stereopsis test and the step-vergence stereo re-acquisition test were presented followed by filling out the ICQ. After completing all the vision tests on one TV, the same procedures were repeated with the other TV.

After a break, the participant filled out the VSS to rate their viewing discomfort symptoms before viewing a movie, then watched a 3D movie on one TV for 25 minutes and switched to the other TV for another 25 minutes. Post-viewing symptoms were measured after viewing from each TV. Sense of immersion and motion sickness were also rated after viewing from each TV.

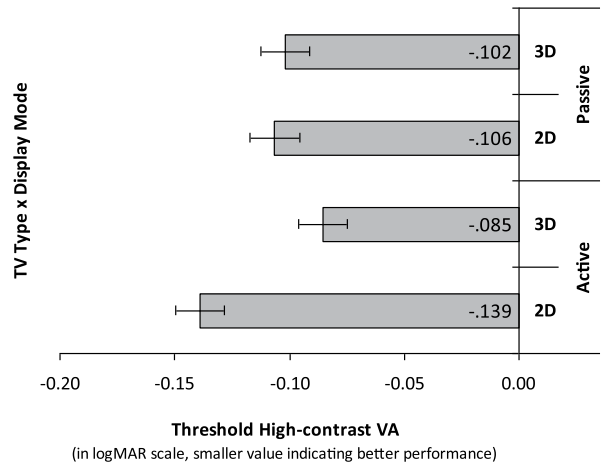

Figure 1: *Minimal angular size for high-contrast visual discrimination. At logMAR unit (log scale of the Minimum Angle of Resolution), smaller (or more negative) values denote better performance (smaller angular size that can be perceived). 2D had better threshold on Active TV ($p < 0.001$). There was no statistical difference in thresholds between TVs for 3D mode. (Error bars indicate 95% confidence interval; non-overlapping bars indicate statistically significant difference at $p < 0.05$. The same rule applies to the rest of the bar charts.)*

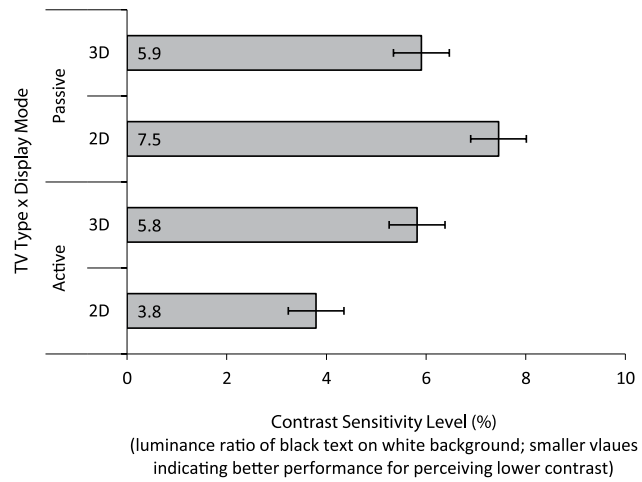

Figure 2: *Threshold contrast sensitivity in discriminating low-contrast stimulus. The X axis represents the lowest contrast level that can be perceived (0 to 100). Smaller values indicate better performance.*

At the end of the study, the participant viewed the same images of selected video clips simultaneously on both TVs displayed in 3D and indicated their evaluation/preference of the TVs with the Display Quality Questionnaire (DQQ).

Data Analysis

Descriptive statistics were conducted to characterize demographics including age, gender, and visual abilities (visual acuity, stereoacuity). Performance data were pre-processed separately for each individual with each TV display, including objective measures (i.e., threshold visual acuity, contrast sensitivity, and average response time for stereopsis re-acquisition) and subjective measures (i.e., ratings of image clarity, display quality, and viewing symptoms). Subjective

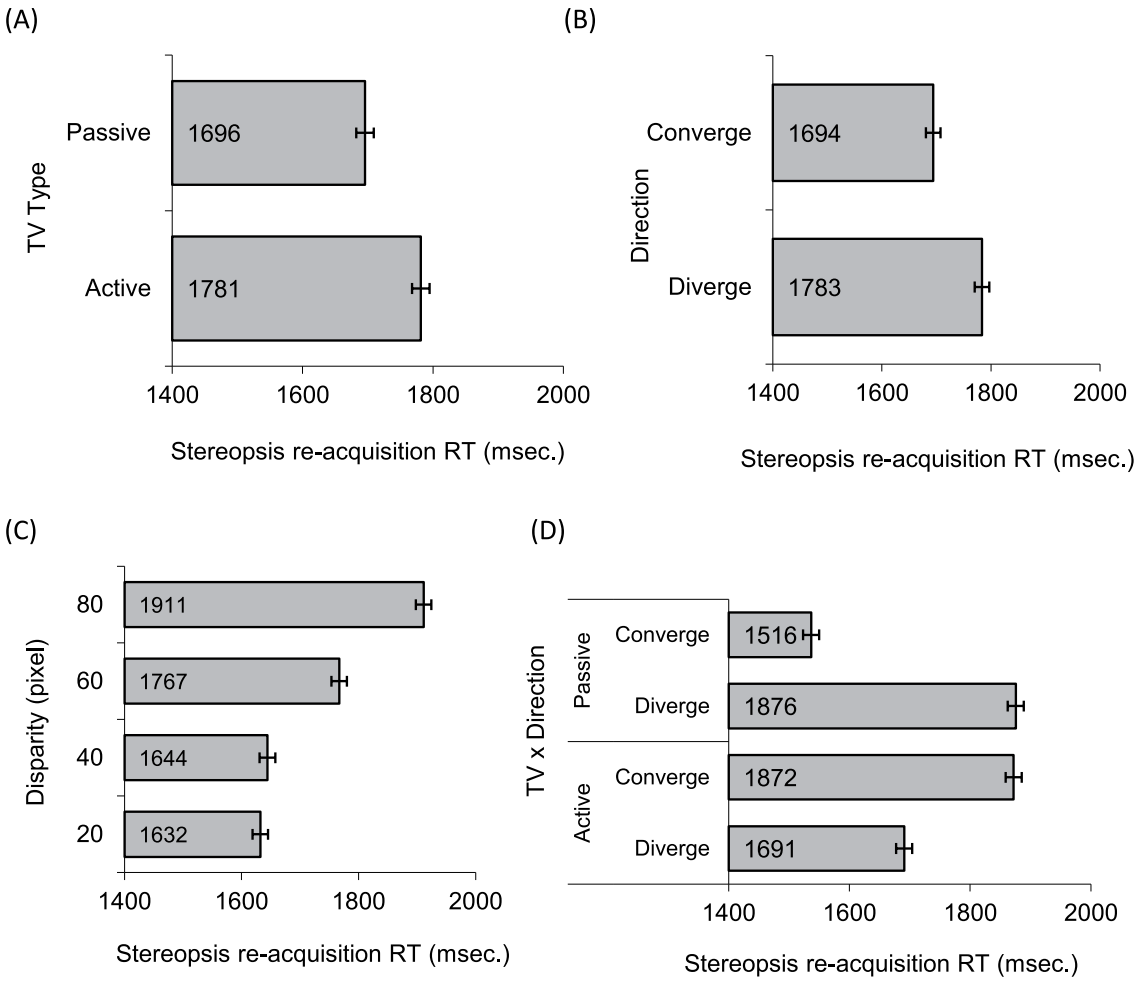

Figure 3: *Mean RT (msec) for step vergence stereo-reacquisition test. Smaller values indicate faster response for changes in ocular vergence. There was faster response with Passive TV (3A), with change to divergent eye movement behind the TV (3B), and with smaller disparity (3C). While faster response was observed for divergent response than for convergent response for Active TV, the opposite (convergent faster than divergent) was seen with Passive TV (3D).*

measurements were transformed to a 0-100 scale. These outcome measures were analyzed by TV type (Active vs. Passive) and TV Mode (2D vs. 3D) using within-subject Mixed Model ANOVA.

Results

Visual Discrimination of High-Contrast Small Stimuli (High-Contrast Visual Acuity)

With a single, high-contrast viewing stimulus (Landolt C), there was a significant main effect of TV Mode ($F[1, 157.244] = 13.571$, $p < .0005$) and interaction of TV Mode x TV Type ($F[1, 157.244] = 9.6$, $p = .002$). No significant effect of TV Type was observed ($F[1, 162.547] = 0.983$, $p=.323$). Figure 1 shows that the difference primarily resulted from a smaller (better) measured VA with Active TV in 2D. Participants discerned a high-contrast fixed-size small Landolt Ring at a smaller angular size in 2D mode than in 3D mode, but the difference was significant only for the Active TV. No significant difference between 2D and 3D mode was observed with Passive TV. The performance in 2D mode was significantly better with Active TV than with Passive TV (Figure 1).

Threshold Contrast Level for Visual Discrimination of Small Stimuli (Contrast Sensitivity)

With low-contrast Landolt C, there was a significant main effect of TV Type ($F[1,160.282] = 20.560$, $p < .0005$) and interaction of TV Type x TV Mode ($F[1, 55.819] = 18.602$, $p < .0005$), but not the main effect of TV Mode ($F[1, 154.292] = .332$, $p = .565$). Overall, participants perceived the orientation of the Landolt C at a lower contrast level with Active TV than with Passive TV, but the difference mainly occurred when presented in 2D; there was no difference in 3D. For Active TV, the performance was better (lower contrast level perceived) in 2D than in 3D. For Passive TV, performance was better in 3D mode than in 2D. There was no difference in 3D mode between Active and Passive TVs (Figure 2).

Response Time for Step-Vergence Stereopsis Re-acquisition Test

Prior to the test of stereo re-acquisition, a stereopsis test was used to acquire individual threshold stereoacuity to be used in the step-vergence test. Limited by the resolution of the 3D displays, the smallest disparity tested was 32 arc seconds

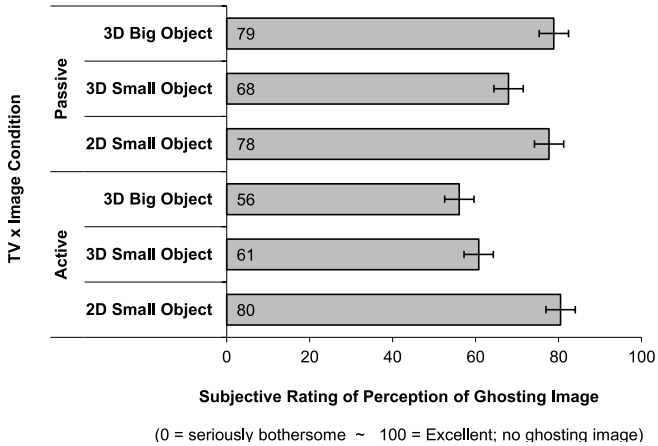

Figure 4: *Subjective ratings on perception of ghosting images with a small 2D image or 3D image (Landolt C) and a large 3D image (Wirt dot-diamond set). Smaller values indicate more bothersome ghosting images.*

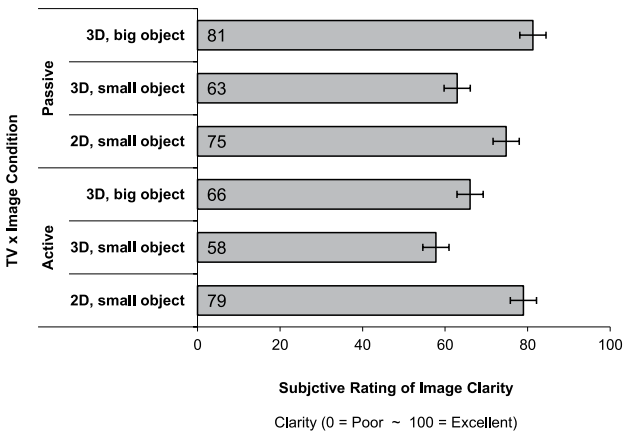

Figure 5: *Subjective ratings of image clarity for a 2D image, a small 3D image (Landolt C) and a large 3D image (Wirt dot diamond). A larger rating means the image had better perceived clarity. For the large 3D image, Passive TV had better perceived clarity than Active TV (p < 0.001). There was no statistical difference between televisions for 2D or the small 3D image.*

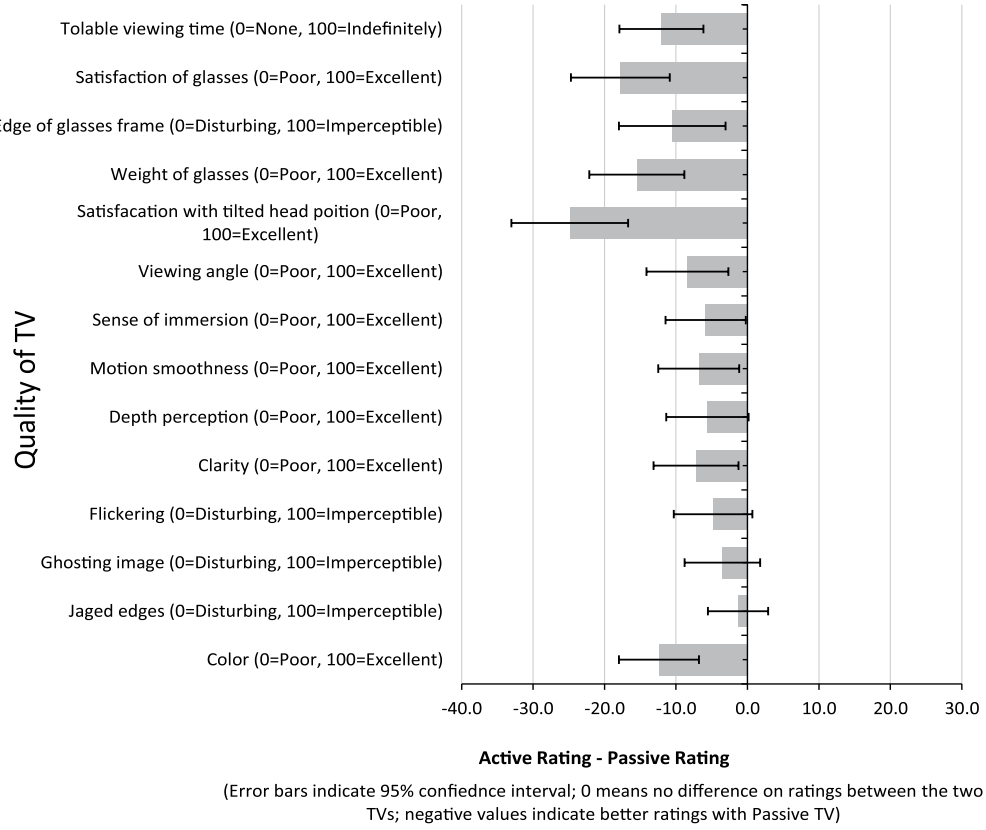

Figure 6: *Subjective side-by-side comparison of display quality. Values were calculated by mean rating with Active TV – mean rating with Passive TV. Negative values indicate Passive TV was rated better than Active TV. Comparisons in which the error bar does not include zero (and the bar is filled gray) are statistically different. The results show that Passive TV was rated better statistically in 10 of the 14 tested attributes on the Display Quality Questionnaire.*

(disparity of 1 pixel from a 4-m viewing distance), larger than the threshold stereoacuity of most participants (avg. = 23.21 arc seconds). Almost all participants reached the limit, with a few having threshold stereoacuity of 2 to 4 pixels of retinal disparity. There was no difference in threshold stereopsis between the two TVs (p = 0.712).

For the stereopsis re-acquisition test, faster response indicates better performance. Individuals' threshold stereopsis was used as covariate in the Mixed Model ANOVA. Faster response time was found with Passive TV than with Active TV (F [1, 836.680] = 19.989, p < .0001), with divergent stimulus than with convergent stimulus (F [1, 825.648] = 54.844, p

Table 1: Mean ratings of Active and Passive TVs in 3D mode

Display attributes	Active Display Mean	Active Display SE	Passive Display Mean	Passive Display SE
	General display quality			
Satisfaction of the displayed color	75.23	2.278	87.62	1.612
Perception of jagged edges around objects	77.77	2.095	79.08	2.252
Perception of ghost image	80.08	1.999	83.58	2.517
Satisfaction of display flickering	79.47	2.691	84.27	2.634
Overall 3D image clarity	77.83	2.036	85.03	2.091
	3D entertainment effect			
Perception of depth	77	2.325	82.6	2.095
Perception of motion smoothness	77.82	2.307	84.63	1.955
Sense of immersion	75.8	1.911	81.65	2.214
	3D-glasses viewing comfort			
Range of acceptable viewing angle	73.43	2.393	81.83	2.201
Satisfaction with tilted head position	50.83	3.69	75.7	2.832
Weight of the glasses	65.88	2.826	81.35	2.09
Is the edge of glass frame bothersome?	64.95	3.171	75.47	2.833
Overall satisfaction of the glasses	63.17	2.889	80.97	1.995
	Tolerable viewing time			
Tolerable viewing time (0: none; 100: infinite)	67.25	2.468	79.28	2.051

Notes:
1. N = 60
2. Participants marked their ratings on a scale from 0 - 100, with 5 markers at point 0, 25, 50, 75, and 100. For all questions, smaller values mean lower display quality and higher values mean better quality. Depending on the questions, the five markers can be: "Bad, Poor, Fair, Good, Excellent" or "Very disturbing, Distracting, Noticeable, Faint, Imperceptible".

< .0001), and with smaller disparity change than with larger disparity change (F [3, 825.648] = 25.139, p < .0001). Significant two-way interaction (TV Type x Direction) was observed (F [1, 825.648] = 6.037, p = .014), with faster RT for divergence trials than convergence trials on both TVs and a larger difference between convergence and divergence with Active TV than with Passive TV. Other two-way interactions and the three-way interaction were not significant (Figure 3).

Evaluation of Ghosting Images (Perception of Ghosting Images During Vision Tests)

After each set of vision tests, the participant rated the severity of their perception of ghosting images and the clarity of the image quality. Comparison of rating of ghosting severity was made between TV Type and Viewing Condition (i.e., TV Mode and Object Size, including 2D small object, 3D small object, and 3D large object). Significant effects were found with TV Type (F [1, 270] = 18.417, p < .0005), Viewing Condition (F [2, 270] = 18.064, p <.0005), and their interaction (F [2, 270] = 12.429, p < .0005). In Figure 4, lower values mean perception of bothersome ghosting images and higher values represent faint or insignificant appearance of ghosting images. Participants rated more bothersome ghosting with Active TV than with Passive TV and in 3D mode than in 2D mode. There was no significant difference between Active and Passive TVs in 2D, but there was in 3D, especially with large objects. Overall, ghosting was more bothersome for Active TV in 3D mode than for passive TV in 3D mode (Figure 4).

Evaluation of Image Clarity (Rating of Display Clarity During Vision Tests)

For rating of image clarity, there were significant main effects of TV Type (F [1, 270] = 8.021, p = .005), Viewing Condition (F [2, 270] = 28.416, p <.0005), and their interaction (F (2, 270) = 8.686, p < .0005). In Figure 5, larger values mean better perceived image clarity. Overall, participants rated better image clarity with Passive TV than with Active TV and with 2D mode than with 3D mode. There was no statistical difference between the two TVs in 2D mode or for small objects in 3D mode, but Passive TV was rated for better image clarity than Active TV in 3D for large objects (e.g., Worth-dot pattern) (Figure 5).

Viewing Symptom Survey (VSS)

Using pre-viewing VSS rating as covariate, ratings for individual questions on VSS with each TV were entered into SPSS Mixed Model ANOVA for analysis. For all 20 questions, there was no significant difference between TV Type, except for the rating of blurred vision, where ratings were higher with Active TV (mean = 19.12) than with Passive TV (mean = 13.52) (F [1, 51.842] = 4.154, p = .047). Then with explorative Factor Analysis, the 20 questions on pre-viewing VSS ratings were

categorized into 5 factors (External visual discomfort, Internal visual discomfort, Motion sickness, Movie immersion, Visual function difficulty) and the same factor coefficients were applied to post-viewing with TV1 and TV2. Then General Linear Model Repeated Measure Module was used to compare individual factor scores between the two TV types, with Pre-viewing factor as covariate. None of the factors reached statistical significance, suggesting no significant difference on viewing symptoms after viewing the selected animated S3D movie for 25 minutes on each TV.

Side-by-Side Comparison on Display Quality Questionnaire (DQQ)

For S3D viewing quality, participants were asked to rate specific display attributes between the two S3D systems in 3D mode with proper glasses. They were reminded to examine the attributes on a display, mark their rating, repeat the procedure with the other system, and then look at each system again to confirm their ratings before submitting their results.

Subjectively, the film-patterned-retarder technology for Passive TV received higher ratings for S3D image quality and glasses preference than Active TV, as shown in Table 1. Figure 6 shows the differences (Active rating – Passive rating) of subjective ratings on various attributes of display quality. All of the mean values are negative, indicating better ratings for Passive TV. The mean values across all participants were significantly below 0 for all items except perception of jagged edges ($p = .543$), ghosting images ($p = .200$), screen flicker ($p = .092$), and depth perception ($p = .062$). This result suggests that Passive TV was rated better in most tested attributes (Table 1, Figure 6).

Final Preference

Among the 60 participants tested, 45 preferred Passive TV. Binomial distribution test shows significant preference for Passive TV (75%) over Active TV (25%) ($p = .0000211$). There is also a gender difference on the TV preference (Chi-Square (1) = 4.339, $p = .037$); more females preferred Passive TV than Active TV, but no significant difference was found among male participants (Figure 7).

Discussion

From the end user's perspective, the present study compared the display quality and viewing experiences offered by two types of S3D TV displays: Active frame-sequential displays with shutter glasses and Passive circular-polarized film-pattern-retarder displays with polarizing glasses. The two S3D systems (one Active and one Passive display) were of identical screen size, pixel count, and refresh rate. Young adults with good binocular vision and depth perception were recruited. To assess the display quality, aspects of human visual performance were measured. After watching an animated S3D movie, participants were asked to rate their visual and physical discomfort. They also closely inspected and compared the perceived quality of the two S3D systems along each of several specific attributes.

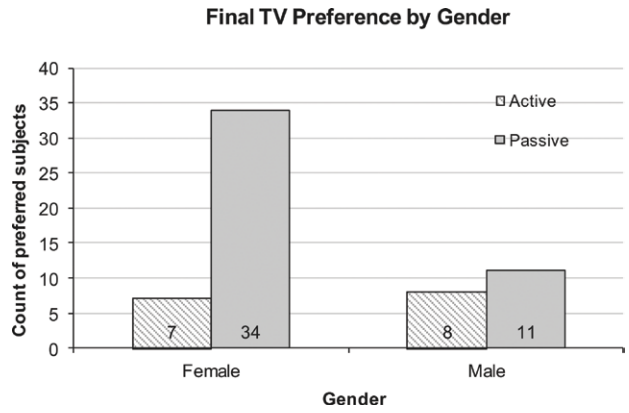

Figure 7. *Participants' preference of S3D TV for viewing S3D movies. 75% preferred Passive TV and 25% preferred Active TV. There is a significant difference between males and females on their choice of S3D TV.*

Discrimination of a Small Fixed-Size Stimulus

Comparing the two TV systems, discrimination ability in 2D was better (smaller threshold angular size) in Active 2D (LogMAR -0.139) as compared to Active 3D, Passive 2D, or Passive 3D. The difference was small (0.03 logMAR, or 30% of one acuity line) but statistically significant. The reason that Active 2D had the best discrimination is not clear. Certainly 2D has a brighter image than 3D, but this applies to both the Active and Passive displays. The measured difference in discrimination is likely related to other display parameters. It is of particular interest to note that the ability to discriminate small Landolt Rings was not different between Active 3D and Passive 3D. This is somewhat surprising because the number of pixels in the vertical direction is halved to each eye with the Passive 3D display. The Landolt ring was 10 pixels in height, and therefore the gap width was 2 pixels. With inter-leaved images in 3D Passive TV the resulting image presented to each eye is degraded, with only 50% information to each eye. This differentially affects the vertical (top and bottom gap locations) compared to the horizontal (right and left gap locations) of the 2 pixel gap in Landolt Rings. Further analysis comparing accuracy by the orientation of Landolt C in 3D mode shows no significant difference between horizontal and vertical gap location ($F [1, 53] = .721$, $p = .400$), suggesting that the halved vertical resolution for each eye in 3D mode of the Passive display did not affect the viewer in this task. This indicates that the opening was perceived equally well, even though each retina received only half of the details in 3D. However, it is important to remember that the Landolt Ring was sized to be small (20/40 in size at 2.2 meters) and larger than the pixel resolution limit of the Passive 3D display. By design, this experiment tested the ability to discriminate detail in a small target of fixed size; it did not determine the smallest physical size that could be shown in the display.

Low Contrast Discrimination

Contrast sensitivity is a measure of the ability to discern the luminance of the target from the luminance of its background. In this study, contrast sensitivity was measured as the lowest luminance contrast of a suprathreshold-sized Landolt C that could be identified. The luminance value of the target and its background was predetermined and saved as an image file from a separate system (a desktop PC and an LCD monitor). Any difference perceived between the two S3D TVs should be attributed to the differences in the display attributes (e.g., gamma, brightness, contrast, etc.) and the filtering effect of the glasses, if any.

Testing results for contrast sensitivity were similar to those with high contrast target resolution above: 2D on Active TV was better than the other 3 conditions, and there was no difference between the Active and Passive 3D displays. Surprisingly, contrast threshold was smaller (better) with Passive 3D than Passive 2D. The measured differences appear to be related to differences in the display attributes (e.g., gamma, brightness, contrast, etc.) and possible filtering effects of the glasses.

Efficiency in Adjusting for Depth Direction (Rt In Step-Vergence Test)

The main goal of S3D display systems is to provide a quality experience in terms of immersion through depth rendering. As an object changes in depth, the vergence position of the eyes must change in order that the image is applied to each fovea. Such bi-foveal fixation will optimize the stereoscopic perception of depth. The step-vergence test was designed to measure the efficiency of a viewer's vergence system when switching between converging and diverging positions. When comparing a viewer's performance with different displays, longer response time could then reflect increased difficulty in accomplishing the task. Therefore, with within-subject comparison of RT in different displays, the test examined whether the display type influenced the ability properly to perceive stereoscopic depth and quickly to converge or diverge the eyes to the next stimulus requirement, with faster response time reflecting better performance.

Faster response was found with Passive display than Active display, with uncrossed disparity (divergent movements) than crossed disparity (convergent movements), and with smaller disparity than larger disparity. The reason for slower response with Active display is not clear.

The interaction of TV with disparity direction (convergence or divergence) shows the same pattern with both TV systems, but response was significantly longer in the convergence trials with Active display. In the test, the initial eye vergence position was to the surface of the screen and served as control of no baseline disparity. This control vergence position also was used prior to each presentation in the testing. Although having the same amount of disparity, an uncrossed trial would induce divergent eye movements achieved by relaxation from the convergent position in the control trial, possibly closer to the resting position of the eye; a crossed trial would require further convergence of the eyes. Similar findings of faster divergent than convergent responses at a far viewing distance were also observed in earlier studies.[4] Some reported that with the same amount of disparity subjects preferred uncrossed disparity over crossed disparity, even though crossed disparity resulted in a larger stereoscopic depth, possibly also for the more comfortable eye positions at far.[5] Further studies are required to confirm the explanation.

Response time was also exacerbated by the increase of disparity for both directions. This is expected as greater image disparity drives the eyes to an off-axis angle further away from the initial position. Similar to other motor control functions, when the amplitude of the motor response is larger, the response time increases.

Image Clarity and Perception of Ghosting Image

After each threshold vision test, the participant was asked to rate their perception of image clarity and the severity of ghosting images, if any. The reduced vertical resolution has been a concern for Passive displays, as image clarity in 3D can be affected by the halved vertical resolution, especially when it comes to fine details and tiny text. However, the image clarity was rated higher on Passive 3D than on Active 3D. This difference was significant for larger objects but not significant for smaller objects. Any decreased threshold resolution that may exist in the Passive 3D appears to be overcome by the strength of other factors that cause better perceived clarity. There was no difference between perceived clarity between Active 2D and Passive 2D.

The Active display, on the other hand, would be expected to result in greater perception of cross-talk (ghosting) because of the shutter timing mechanisms. The results confirm that cross-talk was judged more bothersome with the Active 3D than the Passive 3D. This difference was greatest with larger objects.

These cross-talk evaluations were made after viewing the threshold testing stimuli – most of which were high contrast (black-on-white) targets. Black-on-white targets are those that are most likely to cause the perception of ghosting.

Viewing Comfort

There were no significant differences in symptoms of discomfort between Active 3D and Passive 3D. While it is possible that discomfort symptoms may surface with longer viewing time, at the end of the 50 minutes, our participants still seemed to enjoy the movie well without any sign of viewing discomfort from either system. These results seem to indicate that symptoms caused by viewing S3D may be primarily related to factors such as the vergence-accommodation dissociation and that any differential effects of the TV type are relatively small.

Table 2: Summary of Active display and Passive display measurements

Comparison		Active vs. Passive	Note
I. Threshold visibility	High contrast acuity: 2D High contrast acuity: 3D Contrast sensitivity: 2D Contrast sensitivity: 3D Minimal stereopsis Vergence efficiency	Active better no difference Active better no difference no difference Passive faster	
II. Movie viewing discomfort		no difference	
III. Ghosting with single object on positive display polarity	Small object in 2D Small object in 3D Big object in 3D	no difference Passive better than Active Passive better than Active	Less visible ghosting with Passive
IV. Image clarity with single object on positive display polarity	Small object in 2D Small object in 3D Big object in 3D	no difference no difference Passive better than Active	
V. Display quality side-by-side comparison with movie clips	General display quality 3D entertainment effect 3D glasses related viewing comfort Tolerable viewing time Overall preference	Passive better than Active Passive better than Active Passive better than Active Passive longer than Active Passive over Active	Passive glasses were lighter, less disruptive by frame edge, head tilt, and viewing angle

Side by Side Comparison of Display Quality

When directly compared with the selected movie clips, subjects rated all attributes to be better on the Passive 3D than Active 3D display – for 10 of the 14 measured attributes the differences were significant. The Passive 3D display was rated to have significantly better image clarity and better color quality. This may be related to higher luminance with Passive 3D display compared to Active 3D display.

In terms of the entertainment quality for 3D presentation, the Passive 3D display was also rated significantly better than Active 3D display in perception of motion smoothness and viewer's sense of immersion. Passive 3D was also rated better on depth perception, but the difference was not significant ($p = .062$).

It should be noted that there were small, non-significant, better ratings on Passive 3D for flicker, jagged edges, and ghosting. Ghosting is likely less noticeable for movie viewing where high contrast borders, such as were used for ghost observations in threshold testing, are not as frequently encountered.

The largest differences between the two systems were found on the ratings of viewing comfort with 3D glasses. Participants were more satisfied with Passive 3D glasses, as shown with significantly better ratings on glasses satisfaction, tolerable viewing time, viewing angle (it allowed tilted head positions), weight (the polarized glasses were lighter) and less constraint from the edge of the glasses frame. Overall, subjects felt more satisfied with the Passive glasses and rated that they would watch the TV longer with Passive display.

Overall Preference

Overall, when asked about their final choice of S3D display for viewing S3D content without consideration of cost, 45 out of 60 participants chose Passive display, a preference that was statistically significant. Table 2 summarizes the comparison between Active and Passive displays performed in this study. Although the Active 2D display performed better than Passive 2D display in high contrast discrimination and low contrast threshold measurements, there were no differences in these measurements between Passive 3D and Active 3D. Moreover, participants seemed to be more satisfied with the display quality of Passive TV than Active TV, especially when it came to the comparison of cross-talk/ghosting, image clarity, display color, viewing angle, the weight of glasses, and perception of comfort with 3D glasses, even though both TVs provided an equally good sense of 3D depth.

Interestingly, there is a gender difference on participants' TV preference: While there was no significant difference (8 for Active and 11 for Passive) with male subjects between the two TVs, female participants preferred Passive TV ($n = 34$) over Active ($n = 7$) display. This might be a topic of further investigation (Table 2).

Conclusions

The purpose of the study was to compare Passive polarized FPR-based displays and Active alternate frame sequencing-based displays on visibility thresholds, viewing comfort, and rating of specific display attributes during S3D viewing. In 2D and 3D modes of both TVs, participants were tested to determine threshold legibility of small targets, ability to discern low levels of contrast, minimum perceptible disparity for 3D depth, quickness in switching vergence positions and re-acquiring stereopsis, and they were asked to evaluate image clarity and cross-talk at the end of those tasks. They also viewed movies on Passive 3D and Active 3D and rated their viewing comfort with various perceived display qualities. They also were requested to compare the general display quality and other attributes with the two TVs standing side by side and to select the preferred one.

Our results show that in 2D mode, the Active TV was better than Passive in recognition of details in small targets and seeing low contrast stimuli. There was no difference in those tests when the Active and Passive TVs were in 3D mode. The Passive display enabled better performance in the vergence-stereopsis re-acquisition test.

When viewing movies in 3D mode, there was no difference in symptoms of discomfort between the Active and Passive displays. All of the subjective measures of display quality favored the Passive display in 3D mode compared to the Active TV in 3D mode; 10 of 14 comparisons were statistically significant. In 3D movie viewing the Passive display was rated significantly better for sense of immersion, motion smoothness, clarity, color, and 5 categories related to the glasses. Overall, participants felt that it was easier to look at Passive display for longer periods than Active display, and the subject population significantly preferred the Passive TV in 3D mode compared to the Active TV in 3D mode. The Passive display was selected as the preferred display by 75% of the subjects.

References

1. May S. Active Shutter vs. Passive 3D TV: which is best? In Depth Pros and cons of Active Shutter and Passive 3D TV [Internet]. 2011 May 24th [cited 2012 Oct 11] http://bit.ly/1lzY3EG.
2. Tai Y, Sheedy JE, Hayes J, Kundart J, Laukkanen H. Viewing distance and visual discomfort while using handheld displays. Proceedings of the American Academy of Optometry (AAO) Annual Conference in Anaheim, California, October 22-25, 2008. http://bit.ly/1svGCqb
3. Hayes JR, Sheedy JE, Stelmack JA, Heaney CA. Computer use, symptoms, and quality of life. Optom Vis Sci 2007;84:738-44. http://bit.ly/1jLujWq
4. Kumar AN, Han Y, Garbutt S, Leigh RJ. Properties of anticipatory vergence responses. Inves Ophthalmol Vis Sci 2002;43:2626-32. http://bit.ly/1sRsr0z
5. Van Eijk, RLJ. Beyond the flat screen: Minimal and optimal camera-base distances for viewing 3-D images [internet]. 2003 [cited 2012 October 11] http://bit.ly/1kyS29P. Last accessed on September 11, 2012.

Appendix

General Display Quality in 3D

- The colors displayed were… (Very poor, Poor, Average, Good, Excellent)
- How was your perception of jagged edges? (Disturbing, Distracting, Noticeable, Faint, Imperceptible)
- How was the cross-talk (ghost images around objects)? (Disturbing, Distracting, Noticeable, Faint, Imperceptible)
- The display flickering was… (Disturbing, Distracting, Noticeable, Faint, Imperceptible)
- The overall clarity of the 3D was… (Very poor, Poor, Average, Good, Excellent)

3D Presentation Display Quality

- The perception of depth was… (Very poor, Poor, Average, Good, Excellent)
- The perception of motion smoothness was… (Very poor, Poor, Average, Good, Excellent)
- What was your sense of immersion? (Very poor, Poor, Average, Good, Excellent)

Viewing Comfort (in 3D Mode):

- The viewing angle was… (Very poor, Poor, Average, Good, Excellent)
- Satisfaction with a tilted head position? (Very poor, Poor, Average, Good, Excellent)
- The weight of the glasses was… (Very poor, Poor, Average, Good, Excellent)
- The edges of the glasses frames were… (Disturbing, Distracting, Noticeable, Faint, Imperceptible)
- Your overall satisfaction with the glasses is… (Very poor, Poor, Average, Good, Excellent)

Tolerance (in 3D mode):

- How long do you think you can watch this TV without feeling discomfort? (None, A little, Some, A lot, Infinite)

Preference:

- Final television preference: (TV1 vs. Neutral vs. TV2)

Correspondence regarding this article should be emailed to Yu-Chi Tai, PhD, at ytai@pacificu.edu All statements are the authors' personal opinions and may not reflect the opinions of the the representative organizations, ACBO or OEPF, Optometry & Visual Performance, or any institution or organization with which the author may be affiliated.

Tai YC, Gongaware L, Reder A, Hayes J, Sheedy J. Comparison of S3D Display Technology on Image Quality and Viewing Experiences: Active-Shutter 3D TV vs. Passive-Polarized 3D TV. Optom Vis Perf 2014;2(3):130-40.

The online version of this article contains digital enhancements.