A Comparison of Active and Passive 3D Television Technology and Their Practicality for Classroom Education Use

Leigh Gongaware

Pacific University, gong9054@pacificu.edu

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A Comparison of Active and Passive 3D Television Technology and Their Practicality for Classroom Education Use

Abstract

Stereoscopic 3D TVs convey depth perception to the viewer by delivering separately-filtered images to each eye that represent two slightly different perspectives. Currently two primary technologies are used in 3D televisions: active shutter systems and passive polarized systems. Active shutter systems use alternate frame sequencing to deliver a full-frame image to one eye at a time at a fast refresh rate. Passive polarized systems superimpose two half-frame left-eye and right-eye images at the same time through different polarizing filters. In this study, sixty subjects were recruited to compare their visual performance and subjective rating of two 3D televisions representing the two technologies.

Image quality for both 2D and 3D images were investigated by objectively measuring participant’s visual acuity and contrast sensitivity on each television. The 3D image was investigated further by objectively measuring stereoacluity, perceived versus intended depth perception, effect of viewing angles and a stepvergence task that measured the participant’s ability to swiftly diverge or converge to a new stimulus. A discomfort questionnaire was used to assess participant’s pre and post movie-viewing comfort. Subjective questionnaires were used to gather participant’s opinions on various image quality components, glasses preference, and overall television preference.

Objectively, the subjects had a lower measured contrast and acuity threshold in 2D on the active television, but they had a lower contrast threshold in 3D, as well as faster vergence reaction times on the passive television. With a single subject investigation, no difference between TVs was found for varying off-axis viewing angles, both horizontally and vertically, when comparing VA thresholds, contrast thresholds and stereoacluity at each angle. The passive television was subjectively preferred in all of the following ways: perceived image clarity, color, motion smoothness, overall immersion, perceived ghosting, less disruption from head tilting and viewing angles, longer predicted viewing time before discomfort, overall glasses preference and overall final television preference.

In conclusion, in this study, passive TV technology was a solid winner when it came to subject’s personal ratings, but only outperformed the active TV objectively with contrast and speed of vergence responses. When considering image quality, viewing comfort and room dimensions, subjects felt the passive TV outperformed the active TV in all three categories. With objective measures, passive statistically excelled at two traits in 3D mode and active statistically excelled at two traits in 2D mode for image quality, while no difference was found between televisions for viewing comfort. In addition, no variables were statistically different between TVs that would change the dimensions of a movie-viewing zone. It should be emphasized that the results are based on a relatively small sample size (57 subjects, most young female adults) and tested on specific display models. Investigation with a larger sample size and reaching to broader populations is required before reaching expansive conclusions. In addition, active and passive projector systems, could be a good option for classrooms that are able to afford the system. Future studies should compare the difference between 3D projector systems as well as any future glasses-free systems developed with a broader viewing range than the current available televisions.

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Master of Science in Vision Science
Committee Chair
Dr. Yu-Chi Tai

Second Advisor
Dr. John Hayes

Third Advisor
Dr. James Kundart

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A Comparison of Active and Passive 3D Television Technology and Their Practicality for Classroom Education Use

by

Leigh Gongaware

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Approved and recommended for acceptance as a thesis in partial fulfillment of the requirements of the degree of Master of Science.

Leigh Gongaware

Accepted Date

Signatures:

Thesis Advisor: Dr. Yu-Chi Tai, PhD.
Pacific University Vision Performance Institute

Thesis Committee: Dr. John Hayes, PhD.
Pacific University College of Optometry

Thesis Committee: Dr. James Kundart, O.D., M.Ed., F.A.A.O.
Pacific University College of Optometry

Thesis Committee: Dr. James Sheedy, O.D., PhD.
Pacific University College of Optometry
ABSTRACT

A Comparison of Active and Passive 3D Television Technology and Their Practicality for Classroom Education Use

by

Leigh Gongaware
Master of Science in Vision Science
College of Optometry
Pacific University Oregon, 2013

Stereoscopic 3D TVs convey depth perception to the viewer by delivering separately-filtered images to each eye that represent two slightly different perspectives. Currently two primary technologies are used in 3D televisions: active shutter systems and passive polarized systems. Active shutter systems use alternate frame sequencing to deliver a full-frame image to one eye at a time at a fast refresh rate. Passive polarized systems superimpose two half-frame left-eye and right-eye images at the same time through different polarizing filters. In this study, sixty subjects were recruited to compare their visual performance and subjective rating of two 3D televisions representing the two technologies.

Image quality for both 2D and 3D images were investigated by objectively measuring participant’s visual acuity and contrast sensitivity on each television. The 3D image was investigated further by objectively measuring stereoacuity, perceived versus intended depth perception, effect of viewing angles and a step-vergence task that measured the participant’s ability to swiftly diverge or converge to a new stimulus. A discomfort questionnaire was used to assess participant’s pre and post movie-viewing comfort. Subjective questionnaires were used to gather participant’s opinions on various image quality components, glasses preference, and overall television preference.

Objectively, the subjects had a lower measured contrast and acuity threshold in 2D on the active television, but they had a lower contrast threshold in 3D, as well as faster vergence reaction times on the passive television. With a single subject investigation, no difference between TVs was found for varying off-axis viewing angles, both horizontally and vertically, when comparing VA thresholds, contrast thresholds and stereoacuity at each angle. The passive television was subjectively preferred in all of the following ways: perceived image clarity, color, motion smoothness, overall immersion, perceived ghosting, less disruption from head tilting and viewing angles, longer predicted viewing time before discomfort, overall glasses preference and overall final television preference.

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INTRODUCTION

3D technology has held a place in Western society since the 1800s when Queen Victoria was taken by Wheatstone’s and Brewster’s newly developed stereoscopes, creating a new fashion craze. Since then, 3D technology has been slowly developed and in 1922 the first commercial 3D feature film was released, “The Power of Love.” In spite of the technological challenge and expense for filmmakers and theaters, 3D movies continue to enchant audiences today, as shown by the 2010 release of “Avatar” in both 2D and 3D, which skyrocketed to the position of the highest grossing movie in history.

In the same year, the American Optometric Association (AOA) worked with the 3D@Home Consortium to create a “Memorandum of Understanding” in order to form common grounds between 3D entertainment and eye health. The two worked together to publish a public health report, “3D in the Classroom: See Well, Learn Well,” to promote the use of 3D in classrooms for educational and eye health benefits (American Optometric, Association, 2010).

Many school systems are currently using 3D education in the classroom and it has been well received by students, teachers and parents (Scrogan, 2012). The use of 3D for education has been linked to improved spatial thinking skills and has been claimed to help students understand complex environments and ideas more readily. Not only are skills apparently improved, but also, 3D lessons have been reported to increase educational immersion and motivation (Delgarno, Hedberg, and Harper, 2002; Newcombe, 2010).

While in real life 3D perception can be achieved through monocular (e.g., relative size, motion parallax, perspective, occlusion, lighting, shading, texture gradient, etc.) as well as binocular cues, the perception of a stereoscopic 3D relies on binocular cues. An image is perceived floating in front or behind the display when the viewer experiences retinal disparity, a binocular depth cue produced by the offset of the left and right eye images. This kind of depth perception is referred to as stereopsis and thresholds vary from person to person. Whether the depth is perceived as concave (towards the viewer) or convex (away from the viewer) depends on the image disparity.

There are two kinds of image disparity, crossed and uncrossed. Crossed disparity results when images fall on the retina temporally to the fovea. This can signal convergence eye movements and the perception that the object is closer to the viewer. Uncrossed disparity results when images fall on the retina nasally to the fovea. This can signal divergence eye movements and the perception that the object is further away from the viewer. The separation of images must be small enough to allow fusion, otherwise double vision will result (Schwartz, 2009).

Currently there are two types of 3D technologies that are popular for at home usage. Each requires the use of 3D glasses to separate images between the two eyes, as required for stereopsis. Passive technology consists of two oppositely oriented circularly polarized filters, one for each eye, which corresponds to a polarized filter on the television screen. Alternating half-frame (alternate rows of pixels) left and right eye images are displayed on the screen, allowing a slightly different image to be presented to each eye, which are then superimposed by the brain, creating 3D perception. Conversely, active technology uses LCD shutter glasses to create a 3D effect. A voltage is alternately applied to the two liquid crystal lenses. This darkens one lens while leaving the other lens transparent. Active glasses
consist of alternating shuttering lenses with a minimum 120 Hz flicker rate, 60 Hz per eye, in order to prevent human awareness of the shuttering. This means that minimum refresh rate of 120 Hz is needed for the television. The lenses are synchronized with the display so that each eye receives a specified image. The left and right eyes are presented with slightly different, full-frame, images to create the 3D perception (Yun, 2010).

For TVs that do not require glasses, currently the number of viewers is limited based on “sweet spots” for the specific technology. A 2013 release has nine “sweet spots” that allow clear 3D viewing (Covert, 2013). The limit to the number of viewers negates this television as a viable option for the classroom and is therefore not included in this study. With future development and broadening of the “sweet spot” zones, perhaps this glasses free technology would be a good classroom option.

Each system, active and passive, has been reviewed in various consumer reports with specific pros and cons. A summary of these reports is discussed here and presented in Table 1. Active shutter glasses must be charged to function while passive glasses do not need any form of electricity. Since electricity is required, active glasses tend to be bulkier and heavier, which may create discomfort for the wearer. Active glasses flicker at a minimum of 60 Hz. This is actually below the average human photopic critical flicker frequency, 70 Hz (Schwartz, 2009). Due to this fact, more flicker sensitive viewers may notice the flickering of the lenses, especially if viewing in lighted conditions. Even if the flicker is not consciously noticed, it may induce visual fatigue after prolonged periods of viewing.

The flickering glasses for active displays allow a full resolution image to be presented to each eye. This full resolution image may allow active displays to have higher quality 3D images compared to passive display, which only show half resolution to each eye. The half resolution of the passive system has also been reported to create jagged line edges. This jaggedness may become more apparent to the viewer with closer viewing distances to the screen. Passive 3D systems may appear brighter than active since the flickering glasses for the active system do fully darken one lens at all times, which makes the image appear dimmer unless the frame rate is much higher.

Active displays are commonly reported as having a more drastic 3D image, more depth is perceived, especially with viewers who tend to suppress one eye. Active systems are also reported to have less image degradation due to off-axis viewing or head tilting. A disadvantage that has been reported for both active and passive technologies is crosstalk, a leaking of one eye’s image to the other eye, leading to a ghost-image (Greenwald, 2012; Morrison, 2012; Woligroski, 2012).
Table 1: Summary of consumer reported pros and cons for active and passive 3D TV technology.

<table>
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<th>Consumer Reported Pros</th>
<th>Active Technology</th>
<th>Passive Technology</th>
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<tr>
<td></td>
<td>• Full resolution image presented to each eye</td>
<td>• Light weight, non-bulky glasses</td>
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<td></td>
<td>• More dramatic 3D image</td>
<td>• Brighter image</td>
</tr>
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<td></td>
<td>• Less effect from off-axis viewing and head tilting</td>
<td></td>
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<tr>
<td>Consumer Reported Cons</td>
<td>• Glasses require charge, making them bulky</td>
<td>• Half resolution image presented to</td>
</tr>
<tr>
<td></td>
<td>• Glasses flicker (may be noticeable or induce fatigue)</td>
<td>each eye</td>
</tr>
<tr>
<td></td>
<td>• Dimmer image</td>
<td>• Jagged image edges</td>
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<tr>
<td></td>
<td>• Crosstalk (ghosting)</td>
<td>• Image degraded with off-axis viewing</td>
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<tr>
<td></td>
<td></td>
<td>and head tilting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Crosstalk (ghosting)</td>
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As can be seen above, many pros and cons exist for each system. When considering the use of 3D technology for educational purposes, many of these factors need to be considered, such as classroom setting, the use of 3D glasses, possible 3D contents, etc. Classrooms come in a wide variety of dimensions and number of students. Large classes will have students horizontally displaced from the central viewing zone and will have students at different viewing distances. Stadium seating classrooms place students at different viewing distances as well as different vertical viewing angles. If the class consists of young children, the students may be more prone to head tilting or laying their heads down sideways on their desks. Will different viewing angles, viewing distances or head tilting affect the visual quality of the 3D image?

When considering glasses, young children are often sensitive to things on their face, especially those who do not wear corrective spectacles. Are either of the 3D glasses less comfortable for the viewer or do they create disruptions in the visual field (i.e. thick borders or temples blocking the visual field)?

A higher quality image is an ideal component of educational material, especially when studying complex spatial structures. A clear image with no ghosting or jagged edges is best. Also, when viewing dark scenes, such as learning about outer space, the display should be bright enough to allow visibility of the scene. Does either 3D television technology have a higher quality image compared to the other?

The purpose of this study is to investigate multiple properties of active and passive 3D home televisions. Considering objective measures of each television’s various display properties on visual discrimination and measures of viewing angles, subjective opinions of image quality and viewing comfort between the televisions, which 3D TV technology, active or passive, is the better choice for use in a classroom setting?

Objective measures were taken using sixty subjects recruited from Pacific University and its surrounding areas. Overall display quality was investigated by measuring visual acuity and contrast sensitivity with both 2D and 3D images on both televisions. The 3D display quality was investigated by measuring subject’s stereoacuity, vergence reaction times and perceived versus intended depth location. Further
display quality was investigated with a single subject by measuring visual acuity, contrast sensitivity and stereoacuity at varying horizontal and vertical viewing angles.

Subjective measures included a pre- and post- movie viewing discomfort questionnaire to measure subjective physical discomfort from either technology. Opinions were also gathered on 2D and 3D image quality (such as color, clarity, and motion smoothness), overall immersion, glasses preference and final overall television preference.

**METHODS**

**Subjects**

Sixty adults (19 males and 41 females, average 24.23 years old) were recruited from Pacific University and the surrounding community. With 60 subjects and correlation of 0.7 we could detect a difference in the average of discomfort symptom scales of 0.37 assuming a SD equal to 1 and alpha = 0.5 with a power of 0.8. Each subject had 20/25 or better far visual acuity for each eye and 60 seconds of arc or better of stereoacuity at near, with habitual correction of contact lens if needed, but not with spectacles since plano 3D glasses were worn for the experiment. Subjects were excluded if they had a previous diagnosis of developmental, neurological or psychiatric disorders, previous diagnosis of strabismus or amblyopia, or if they had a history of experiencing 3D-induced nausea or discomfort.

**Materials**

**Visual discrimination tests**

Experiment Builder program (SR Research, Ontario, CA) was used to operate a set of programs used to test for subject’s visual performance in 2D and 3D on the tested displays. These programs include:

- **Visual Acuity (VA):** The perceived smallest detail, or visual resolution, of the subject was measured with fixed-size, high-contrast images of Landolt C (6.3 mm whole letter height, 1.26 mm opening) with angular size decreased from 20/40 to 20/14 by increasing viewing distance. The subject was tested at 2.73, 3.44, 4.33, 5.45 and 6.12 meters (equivalent to LogMAR: 0.2, 0.1, 0.0, -0.1, -0.15 (due to room size limits)). Individual’s threshold VA value was determined as the smallest angular size for correctly noting at least five out of eight of the Landolt C orientations.

- **Contrast Sensitivity:** Instead of reducing the angular size, the same size (20/32) of Landolt C images were viewed at a constant viewing distance (4.1 meters) while the contrast of the Landolt C was progressively reduced by lightening the letter as trials proceeded, from ranges of 16 to 1.25% black. The contrast threshold for each subject was determined as the lowest contrast level for correctly identifying the orientation of the Landolt C at least five out of eight times.
• **Stereocuacity and step-Vergence**: Wirt circle images (Figure 1) with disparities of the target circle from the rest of the image decreased from 9 pixels by steps of 1. Subjects used a video game controller to note whether the top, bottom, left or right circle was floating, and if it was towards (convex) or away from them (concave). The smallest amount of target disparity for correct responses was registered as a subject’s threshold stereopsis. Then the step-vergence test measured the subject’s ability to quickly fuse images of varying disparities at a working distance of four meters, using a fixed amount of target disparity that is one pixel greater than the measured threshold stereocuity. The entire testing image was presented in steps to induced alternated ocular convergent and divergent responses by interchanging the testing image with a crossed or uncrossed disparity (+20, +40, +60, +80, -20, -40, -60, -80 pixels) and no disparity. Vergence response times were measured in milliseconds.

Figure 1: Wirt circle image

• **Perceived depth location**: A cartoon image with 20, 40, 60 and 80 pixel disparities with convergent and divergent demands. Measures of 3D float localization were obtained through use of a mirror and pulley system (similar to a Howard Dollman apparatus). The TV rested on a height-adjustable stand, with the center of the screen aligned to the subject’s line of sight at a viewing distance of 4 meters. A depth indicator consisted of an upright rod (19 cm high) mounted on a gray wood track that was placed along the viewing path between the subject and the 3D TV. A thin cord and a pulley were used to manipulate the position of the rod. One end of the track was 26.5 cm from the surface of the TV screen. The subject sat next to the other end, centered to the TV. By pulling the cord, the subject moved the rod until its top aligned to the depth of circles perceived through the 3D glasses. Target presentation and data recording were controlled by a custom program developed using the Experiment Builder software (SR Research Ltd., Ontario, Canada). The subject sat at four meters from the center of the screen next to a wooden beam with a vertical glow stick on a pulley. The subject was directed to localize the float of the on screen image by using the pulley system to move the glow stick to the perceived location. Both convergent and divergent tasks were given. A mirror located in front of the subject at the end of the wooden beam allowed divergent float localization behind the television. Perceived depth was measured and recorded by the investigator using centimeter markings on the wooden beam.

• **Viewing Angles**: To measure the display quality from off-line viewing at a wider angle, the first three visual discrimination tests, (visual acuity, contrast sensitivity and stereocuity) were performed by a single subject (the author) from selective visual angles.

**Movie viewing**

Subjects watched a 3D movie on each tested display and then filled out a questionnaire to mark their self-rated viewing discomfort symptoms.
The Blu-Ray format of the movie *Rio* (release on August 2, 2011 by 20th Century Fox Film Corp.) was used to allow subjects to directly compare the active and passive 3D televisions as well to compare 3D and 2D images. A Blu-Ray DVD player (LG Network 3D Blu-Ray Disc Player, Model: BD670) with a channel splitter was used to play the movie on both televisions simultaneously.

A visual and physical discomfort survey (the Visual Symptom Survey) was presented before and after movie viewing to assess any possible changes in subjects comfort (Appendix A).

*Side-by-side display comparison*

A Display Quality Questionnaire was developed using analogue response scales to compare the active and passive 3D images on the tested televisions. The questions were displayed side-by-side on the same laptop screen (see Appendix B). Subjects were allowed to repeatedly change their answers until the page was submitted. Questions were displayed simultaneously while subjects were allowed to freely move between the same scene playing on the active and passive television. Subject’s television preferences were also gathered at the end of all tests.

*Apparatus*

A digital program (Smart System II 20/20 Basic Visual Acuity System, M&S Technologies, IL: Park Ridge) was used to screen subject’s vision condition at 6 meters, including far visual acuity, contrast sensitivity, and stereoacuity. Stereoacuity was also measured with the Wirt Dot Test (Bernell Corporation, Mishawaka, IN).

Two 3D televisions, 55”, LED edge-lit backlight with local dimming effect and equal screen resolution and panel refresh rates (240 Hz in 2D) were used: Samsung Model UN55D7000LFXZA active-shutter 3D television (Active) and LG Model 55LW6500UA passive 3D television (Passive). Each television was placed on a stand at a height of 60cm and had grey cardboard of the same color as the wall lined around the screen to decrease reflections and to remove any brand marks from the subject’s view. The grey cardboard also helped to blend the TV frame into the surroundings and lessened the sense of image cutout on the edges. The 3D glasses all had a piece of black electrical tape placed over the brand mark.

A video game controller (VGC) was used to select answers during testing (left, right, down or up). A spectrometer (Photo Research PR-655 SpectraScan, Chatsworth, California) was used to measure the brightness of each television in 2D and 3D mode.

*Procedures*

All experimental testing occurred in a light-tight room with all aspects (wall, ceiling, carpet and chairs) colored matte grey in order to decrease any possible reflections.
Prior to starting the experiment, subjects were informed of the purpose of the study and all of their questions were answered before giving their written consent on an informed consent form approved by Pacific University Institutional Review Board.

Each subject attended a single two-hour session involving a visual discrimination testing session, a movie viewing section, and a side-by-side display comparison session.

For the first thirty subjects, odd numbered subjects started clinical tests and movie viewing on the active TV while even numbered subjects started on the passive TV. After thirty subjects, this was reversed, having odd numbered subjects start on the passive TV and even numbered subjects on the active TV. This balanced out an effect that may have occurred having the TV on the left or right side of the room. Subject numbers were assigned based upon time of subject arrival (numbers 1-60).

During the visual discrimination session, objective measures of image quality (display resolution, contrast, and depth resolution) were obtained using visual acuity testing, contrast sensitivity testing, stereoacuity testing, step-vergence testing and a perceived depth measurement on each television. These tests were given in a fixed order: 2D visual acuity and contrast sensitivity test, 3D visual acuity and contrast sensitivity test, stereoacuity test, step-vergence test and perceived depth location test. At the end of each test, they were asked to rate the image clarity and the severity of any ghosting image. Subjects were tested on the other TV in the same testing order.

After a brief break, each subject was asked to fill out the pre-movie assessment on the Viewing Symptom Survey to mark their visual and physical comfort status prior to the movie viewing. Then subjects viewed 25 minutes of the movie at a seated viewing distance of four meters, starting at the active or passive television, and then switching to view the next 25 minute segment on the other television. The Viewing Symptom Survey was given again after each movie viewing segment (three times total).

Next, subjective evaluation of display quality was obtained through a side-by-side comparison using the Display Quality Questionnaire. Two different scenes from the movie were played simultaneously on the two televisions in 3D, located approximately a meter apart on the same wall. Subjects were instructed to alternate viewing between the two televisions by freely moving about the room, changing postures (e.g., tilting the head, standing up or sitting down) and switching 3D glasses while answering a direct comparison survey on a small laptop.

Finally, the subject was asked to mark their preference between the two TVs on a two-end scale with the two TVs (labeled as 1 and 2) 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 subject preferred the TV at that end. A score of 50 indicated no preference for either TV display. Again, “TV 1” means active system for the first half of the subjects and passive system for the other half of the subjects. This was accounted for by transforming the data so that marks less that 50 counted for the active system and marks of greater than 50 counted for the passive system.

To compare the range of viewing angles, one subject was tested with the first three visual discrimination tests at different viewing angles (horizontal viewing angles at 10°, 20° and 30° to the right and left of
the center of the screen, and vertical viewing angles at 15° above and below the screen). Visual acuity and contrast sensitivity were measured for three times at each angular position from a viewing distance of 4.3 meters from the screen. Stereoacuity was also tested for 3 times at each viewing angle but at viewing distance of 4 meters.

Luminance was measured in the center of each TV using a Landolt C target, with factory default display settings, in 2D and 3D mode using a spectrometer in the dark movie viewing room. A Landolt C target was used. The opening of the Landolt C was used to measure a white target and the body of the Landolt C was used to measure a black target. Luminance was measured in 3D mode for each TV without glasses and with that TV’s particular glasses held up to the spectrometer aperture to simulate a viewer’s perception. Six measures were taken for each TV and viewing mode.

Data Analysis

Data of three subjects were excluded from analysis, due to incomplete tests caused by software bugs. Data from the remaining fifty-seven subjects (17 males and 40 females, average 24.3 years old, VA average of -0.09 LogMAR, stereo acuity average of 28.1) were analyzed with IBM SPSS Statistics program (Version 19). The equation used to find the expected location for the depth perception test, with all the units in centimeters, was: 

\[
\text{Expected Location} = \frac{(400 \times \text{Disparity})}{\text{PD} + \text{Disparity}},
\]

where PD is the subject’s inter-pupillary distance. The actual measurement of the perceived depth and the perceived depth deviation (i.e., the difference between the perceived depth and the expected depth) was used to analyze the effect of depth perception from the two 3D displays.

Two-way within subjects analysis of variance (ANOVA) (SPSS Proc Mixed) was used to analyze the effects of TV type (Active vs. Passive) and display mode (2D vs. 3D) on the measurements, including various visual discrimination tests, subjectively rated viewing discomfort, and perceived display quality. Statistical significance was defined as having a p-value less than 0.05. In order to test the difference between means, non-overlapping 84% confidence intervals demonstrated statistical significance at an unadjusted p < 0.05 (Payton, Greenstone, and Schneker, 2003).

RESULTS

Visual Discrimination Tests

Visual Acuity. The interaction of TV x display mode on VA thresholds was significant (F(1, 157.2) = 15.3, p < 0.001). There was no significant main effect from either TV type or display mode. Simple-main-effect pairwise comparisons show significant difference between the two TVs in 2D mode but not in 3D mode. There is also significant difference between display modes with the active TV, but not with the passive TV. Figure 2 shows that, overall, VA was smaller (better) with the active system than with the passive system when presented in 2D mode. It was also smaller in 2D mode than in 3D mode when presented on the active system. No difference in VA threshold was found between 2D and 3D for the passive system.
Contrast sensitivity. A significant interaction between TVs (F (1, 50.5) = 518.2, p < 0.001) and TV type x display mode (F (1, 157.7) = 46.4, p < 0.001), was observed on threshold contrast sensitivity (Figure 3). Lower (better) threshold of contrast was measured with the active system than with the passive system when presented in 2D mode, but no difference between the measurements on the two TVs in 3D mode. For the active system, contrast threshold was lower in 2D mode than in 3D but the opposite pattern was observed for the passive system, with lower threshold in 3D than in 2D.

Threshold stereopsis. No statistical difference was found between TVs for measured stereoacuity thresholds (F (1, 58.2) = 0.001, p = 0.97). Pixel size and resolution of the display systems limited the minimum disparity tested in stereo testing at four meters to 32 arcseconds, which was reached by all
subjects. In the pre-screening exam, the average of the subject’s stereo was approximately 23 arcseconds. In order to identify if any difference in stereoacuity exists between TVs, a smaller angle of separation must be used to determine the subject’s actual stereo threshold. This could be done by increasing the viewing distance during the test.

**Step Vergence.** This task evaluated the efficiency of the subject’s visual system response to changes in vergence demands. Using a within-subject design, the response time of the vergence reaction can be used to compare the efficiency of disparity presentation between the two TVs. It was assumed that the subjects were responding with the proper vergence action, although no eye position monitoring was performed.

A two-way mixed ANOVA was used to analyze the effects of TV type and vergence response (convergent vs. divergent) on response time in the step-vergence test. Significant main effects were shown for TV type \((F(1, 836.7) = 20, p < 0.0001)\) and vergence response \((F(1, 53) = 6.6, p = 0.013)\). Figure 4 shows faster response time for divergent trials (uncrossed disparity) in comparison to convergent trials (crossed disparity) for both TVs.

![Figure 4: Average response time (in milliseconds) for trials with crossed disparity (convergent response) and uncrossed disparity (divergent response) in the step-vergence test. Response was faster with uncrossed trials (i.e., divergent response) than trials with crossed disparity (i.e., convergent response).](image)

**Perceived depth.** On the perceived depth task, a significant main effect was found when comparing image disparity levels \((F(6, 713.7 = 802.3, p < 0.001)\), but not between televisions \((p = 0.571)\) or for the interaction of television x disparity \((p = 0.722)\), using a within subjects ANOVA. Pairwise comparisons showed significant differences between all crossed (convergent) disparity levels, but not for the two divergent (uncrossed) disparity levels. As crossed disparity increased, subjects perceived the image as closer to them (increased perceived depth). As illustrated in Figure 5, the amount of perceived depth amount increased with increasing levels of crossed disparity. For no disparity, all but five subjects correctly identified the target as flat on the screen as a 2D image. A much wider range in perceived depth responses was found with the uncrossed disparity levels, although subjects were able to correctly
identify the direction of the target as behind the television instead of floating towards them in front of the screen. The ability to correctly pinpoint the floating target may have been more difficult due to the use of the mirror to localize the uncrossed targets.

![Graph showing perceived depth compared to image disparity for each television.](image)

Figure 5: Perceived depth compared to image disparity for each television. Negative perceived depth and disparity correlate to divergent, uncrossed disparity, demands and responses. Positive perceived depth and disparity correlate to convergent, crossed disparity, demands and responses.

**Viewing Symptom Survey**

There was no statistical difference found between pre and post movie viewing for either TV and only one statistical difference found between TVs. Blurry vision was rated higher on the active TV (F (1, 52) = 4.145, p = 0.47). This result is not considered a clinically relevant difference due to the small effect size (0.26) and overall relatively low blur ratings (average 19.1 out of 100 for active and 13.5 out of 100 for passive with 100 being a strong blur experience). Table 2 shows data for each question. The corresponding questions can be found in Appendix A. Some of the questions did not have data for all 57 subjects; the lowest number of subjects a question had was 53. This was either due to subjects improperly submitting answers for questions or due to a transferring of data error.
Table 2: Visual symptom survey results.

<table>
<thead>
<tr>
<th>Question</th>
<th>Active Mean ± SD</th>
<th>Passive Mean ± SD</th>
<th>F value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes felt tired</td>
<td>12.2 ± 2.8</td>
<td>12.7 ± 2.1</td>
<td>0.468</td>
<td>0.497</td>
</tr>
<tr>
<td>Irritated or burning eyes</td>
<td>12.4 ± 3.3</td>
<td>11 ± 1.7</td>
<td>0.688</td>
<td>0.411</td>
</tr>
<tr>
<td>Strained feeling or pulling sensation around eyes</td>
<td>17.8 ± 3.7</td>
<td>17 ± 2.7</td>
<td>1.107</td>
<td>0.298</td>
</tr>
<tr>
<td>Ache or pain inside of eye</td>
<td>15.8 ± 2.9</td>
<td>14.3 ± 3</td>
<td>0.078</td>
<td>0.782</td>
</tr>
<tr>
<td>Dry or watery eyes</td>
<td>42.6 ± 5</td>
<td>42.2 ± 5</td>
<td>0.362</td>
<td>0.550</td>
</tr>
<tr>
<td>Blurry vision experienced</td>
<td>19.1 ± 2.5</td>
<td>13.5 ± 2.5</td>
<td>4.145</td>
<td>0.047</td>
</tr>
<tr>
<td>Multiple images seen (double vision)</td>
<td>27.9 ± 5</td>
<td>29.4 ± 4.2</td>
<td>2.165</td>
<td>0.147</td>
</tr>
<tr>
<td>Images moved, jumped or swam across the screen</td>
<td>23 ± 2</td>
<td>25 ± 4</td>
<td>0.000</td>
<td>0.986</td>
</tr>
<tr>
<td>Fatigue or sleepiness felt</td>
<td>27.4 ± 5</td>
<td>30.5 ± 4.9</td>
<td>0.255</td>
<td>0.616</td>
</tr>
<tr>
<td>Difficulty switching between near and far</td>
<td>19 ± 4.4</td>
<td>15.7 ± 3.4</td>
<td>1.611</td>
<td>0.210</td>
</tr>
<tr>
<td>Experienced a headache</td>
<td>14.7 ± 3.2</td>
<td>12.7 ± 2.8</td>
<td>3.204</td>
<td>0.079</td>
</tr>
<tr>
<td>Experienced dizziness</td>
<td>41.2 ± 6.4</td>
<td>37.6 ± 6.3</td>
<td>0.057</td>
<td>0.812</td>
</tr>
<tr>
<td>Felt disoriented or had a sense of vertigo</td>
<td>37.1 ± 4.9</td>
<td>43 ± 5.5</td>
<td>0.212</td>
<td>0.647</td>
</tr>
<tr>
<td>Experienced nausea</td>
<td>20.2 ± 3.6</td>
<td>17.8 ± 3.9</td>
<td>0.392</td>
<td>0.534</td>
</tr>
<tr>
<td>Neck discomfort</td>
<td>24.1 ± 3.4</td>
<td>18.7 ± 3.4</td>
<td>0.001</td>
<td>0.975</td>
</tr>
<tr>
<td>General physical discomfort</td>
<td>14.1 ± 3.4</td>
<td>14.1 ± 2.9</td>
<td>1.088</td>
<td>0.302</td>
</tr>
<tr>
<td>Objects looked real as they moved through space</td>
<td>73.5 ± 15.5</td>
<td>74.7 ± 20.4</td>
<td>0.205</td>
<td>0.654</td>
</tr>
<tr>
<td>Viewer felt like part of the movie</td>
<td>63.8 ± 21.5</td>
<td>66.6 ± 22.5</td>
<td>0.429</td>
<td>0.515</td>
</tr>
<tr>
<td>Felt engaged in the movie</td>
<td>77.8 ± 13.7</td>
<td>79 ± 17.9</td>
<td>0.161</td>
<td>0.690</td>
</tr>
<tr>
<td>Lost track of time while viewing the movie</td>
<td>72.4 ± 20.2</td>
<td>77 ± 21</td>
<td>2.051</td>
<td>0.158</td>
</tr>
</tbody>
</table>

**Perceived Image Quality**

Subjects compared images presented on each TV in three different viewing condition: a small 2D image, a small 3D image and a large 3D image. The two small images were a Landolt C target while the large 3D target was a Wirt Dot target (as used in other stereoacuity and vergence testing). Subjective rating of overall image quality after each vision test was analyzed with a two-way (TV type x viewing condition) mixed model ANOVA. Significant differences were found for TV type (F (1, 54) = 7.96, p = 0.007), viewing condition (F (2, 53) = 24.44, p < 0.001), and their interaction (F (2, 53) = 18.63, p < 0.001) (Figure 6). For the active system, image clarity was found to be better in 2D mode than either the small or large 3D image. For passive, the 2D image had better clarity than small 3D image, but worse clarity than the large 3D image. There was no significant difference on overall image quality between the two TVs, except for
large 3D images, where passive system was rated much better than active system. Overall, image clarity was better for the passive system than the active system and poorer for small 3D image than either the large 3D image or the 2D image.

![Figure 6: 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 subjectively had better clarity.](image)

Similar analysis was performed for the rating of perceived ghosting images. Significant differences were found for TV type (F (1, 54) = 18.73, p < 0.001), viewing condition (F (2, 53) = 16.06, p < 0.001) and their interaction (F (2, 53) = 21.75, p < 0.001) (Figure 7). For the active system, ghosting was found to be lowest in the 2D setting compared to small 3D and large 3D. For the passive system, ghosting was lower in 2D compared to the small 3D image, but was not statistically different from the large 3D image. The small and large 3D images had less ghosting on passive than active. There was no statistical difference between TVs for the 2D image. In 3D mode with both small and large images, passive system performed better than active system, with much lower ratings of ghosting images.

![Chart showing subjective ratings of image clarity for different conditions.](chart)
Figure 7: Subjective ratings of noticeable ghosting effects with a 2D image, a small 3D image (Landolt C) and a large 3D image (Wirt dot diamond). A larger rating means less noticeable ghosting, or better image quality.

Side-by-side comparisons of 3D display quality

Paired t-tests were used to compare a series of 3D display quality comparisons, rated by the subjects with the two TV systems presenting the same selected scenes side by side. Table 3 reveals several statistically significant subjective preferences for the passive system, but none for the active system.

Table 3: Subjective side-by-side TV comparison. Passive had statistically higher ratings in the listed variables. Active had no statistically significant higher preference ratings.

<table>
<thead>
<tr>
<th>Item</th>
<th>Active (Mean ± SD)</th>
<th>Passive (Mean ± SD)</th>
<th>Paired t-test</th>
<th>p-value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>75.23 ± 17.64</td>
<td>87.62 ± 12.48</td>
<td>4.339</td>
<td>&lt;.001***</td>
<td>0.82</td>
</tr>
<tr>
<td>Clarity</td>
<td>77.83 ± 15.77</td>
<td>85.03 ± 16.20</td>
<td>2.377</td>
<td>0.010*</td>
<td>0.45</td>
</tr>
<tr>
<td>Motion Smoothness</td>
<td>77.82 ± 17.87</td>
<td>84.63 ± 15.14</td>
<td>2.355</td>
<td>0.011*</td>
<td>0.41</td>
</tr>
<tr>
<td>Immersion</td>
<td>75.80 ± 14.81</td>
<td>81.65 ± 17.15</td>
<td>2.046</td>
<td>0.023*</td>
<td>0.37</td>
</tr>
<tr>
<td>Glasses Preference</td>
<td>63.17 ± 22.38</td>
<td>80.97 ± 19.11</td>
<td>5.044</td>
<td>&lt;0.001***</td>
<td>0.94</td>
</tr>
<tr>
<td>Lighter Weight Glasses</td>
<td>65.88 ± 21.89</td>
<td>81.35 ± 16.19</td>
<td>4.557</td>
<td>&lt;0.001***</td>
<td>0.81</td>
</tr>
<tr>
<td>Frame Edge Less Disruptive</td>
<td>64.95 ± 24.56</td>
<td>75.47 ± 21.95</td>
<td>2.762</td>
<td>0.004***</td>
<td>0.45</td>
</tr>
<tr>
<td>Viewing Angles Less Disruptive</td>
<td>73.43 ± 18.53</td>
<td>81.83 ± 17.05</td>
<td>2.870</td>
<td>0.003**</td>
<td>0.47</td>
</tr>
<tr>
<td>Head Tilting Less Disruptive</td>
<td>50.83 ± 28.58</td>
<td>75.70 ± 21.94</td>
<td>5.956</td>
<td>&lt;0.001***</td>
<td>0.98</td>
</tr>
<tr>
<td>Able to Watch Longer</td>
<td>67.25 ± 19.11</td>
<td>79.28 ± 15.89</td>
<td>4.010</td>
<td>&lt;0.001***</td>
<td>0.69</td>
</tr>
</tbody>
</table>

* P < .05; ** p < .01; *** p < .001
**Final TV Preference:** In order to select their final TV preference, subjects made a mark on an analogue response scale where 100 was passive, 0 was active and 50 was no preference. The average subject mark was 75.11 (± 30.14), showing a preference for the passive TV. Using a one sample t-test comparison, the difference in means for the final selection was significant: \( t(59) = 5.5, p < 0.001 \). 75% of subjects marked a spot greater than 50 on the analogue scale, showing preference for the passive TV.

**Individual Investigator Data: Off-axis viewing angles**

No statistically significant difference in VA, contrast sensitivity or stereoacuity at the nine different viewing angles, 10°, 20° and 30° to the right and left of the screen as well as at 15° above and below the center of the screen, was found between TVs. All measures of VA threshold and contrast sensitivity were exactly the same at each viewing angle. Using a general linear model analysis, the non-significant differences for stereo-acuity, which did have differing values at each location, were: between TVs \( (F(1,2) = 4, p = 0.184) \); between angles \( (F(1, 2.5) = 1.3, p = 0.367) \); between angles on each TV \( (F(1, 7.1) = 1.8, p = 0.159) \) with Huynh-Feldt correction. Differences in stereo acuity are shown in Table 4, where mean values are given in pixel disparities. It was predicted that the passive television would be more affected by different viewing angles based upon consumer reports. This was not found in this data sample. Further analyses to these results are in the discussion section.

<table>
<thead>
<tr>
<th>Viewing angles</th>
<th>Active (Mean ± SD)</th>
<th>Passive (Mean ± SD)</th>
<th>t-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.33 ± 0.58</td>
<td>1.67 ± 0.58</td>
<td>0.707</td>
<td>0.519</td>
</tr>
<tr>
<td>15° up</td>
<td>1.67 ± 0.58</td>
<td>2.00 ± 1.00</td>
<td>0.500</td>
<td>0.643</td>
</tr>
<tr>
<td>15° down</td>
<td>1.00 ± 0.00</td>
<td>1.67 ± 0.58</td>
<td>2.000</td>
<td>0.116</td>
</tr>
<tr>
<td>10° right</td>
<td>2.33 ± 0.58</td>
<td>1.67 ± 0.58</td>
<td>1.414</td>
<td>0.230</td>
</tr>
<tr>
<td>20° right</td>
<td>2.67 ± 1.16</td>
<td>1.33 ± 0.58</td>
<td>1.789</td>
<td>0.148</td>
</tr>
<tr>
<td>30° right</td>
<td>1.67 ± 0.58</td>
<td>2.00 ± 0.00</td>
<td>1.000</td>
<td>0.374</td>
</tr>
<tr>
<td>10° left</td>
<td>2.00 ± 0.00</td>
<td>1.33 ± 0.58</td>
<td>2.000</td>
<td>0.116</td>
</tr>
<tr>
<td>20° left</td>
<td>2.00 ± 0.00</td>
<td>1.67 ± 0.58</td>
<td>1.000</td>
<td>0.374</td>
</tr>
<tr>
<td>30° left</td>
<td>2.67 ± 1.16</td>
<td>2.67 ± 2.08</td>
<td>0.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**Luminance.** Luminance of the white and black pixels was measured in the center of each TV in 2D and 3D mode using a spectrometer in the dark movie viewing room. A Landolt C target was used. The opening of the Landolt C was used to measure a white target and the body of the Landolt C was used to measure a black target. Luminance was measured in 3D mode for each TV without glasses and with that TV’s particular glasses held up to the spectrometer aperture to simulate a viewer’s perception. The purpose of these measurements was to see if any clearly apparent differences existed between televisions in a specific mode. The active television was predicted to have lower levels of brightness in 3D mode since one lens of the flicker glasses is completely darkened. Values are displayed in Table 5.
Table 5: Average luminance measurements for each TV with default factory display settings.

<table>
<thead>
<tr>
<th></th>
<th>2D Mode</th>
<th>3D Mode</th>
<th>3D Mode Through Glasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active White</td>
<td>256 cd/m²</td>
<td>106.2 cd/m²</td>
<td>33.13 cd/m²</td>
</tr>
<tr>
<td>Active Black</td>
<td>0.064 cd/m²</td>
<td>0.064 cd/m²</td>
<td>0.026 cd/m²</td>
</tr>
<tr>
<td>Passive White</td>
<td>309 cd/m²</td>
<td>374.5 cd/m²</td>
<td>151.1 cd/m²</td>
</tr>
<tr>
<td>Passive Black</td>
<td>0.264 cd/m²</td>
<td>0.222 cd/m²</td>
<td>0.128 cd/m²</td>
</tr>
</tbody>
</table>

**DISCUSSION**

Table 6 provides a summary of the statistically significant positive attributes found for each television.

Table 6: Summary of statistically significant positive results for each TV.

<table>
<thead>
<tr>
<th>ACTIVE</th>
<th>PASSIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Contrast threshold better than passive in 2D mode</td>
<td>• Contrast threshold better in 3D mode</td>
</tr>
<tr>
<td>• VA threshold better than passive in 2D mode</td>
<td>• Faster vergence reaction time</td>
</tr>
<tr>
<td></td>
<td>• Subjectively rated with better: color, clarity, motion smoothness and overall immersion as well as less apparent ghosting of images</td>
</tr>
<tr>
<td></td>
<td>• Glasses were chosen as final preference as rated as less weight and less disruptive frame edge</td>
</tr>
<tr>
<td></td>
<td>• Subjectively shown to be less disrupted by head tilt and viewing angle</td>
</tr>
<tr>
<td></td>
<td>• Longer viewing time before discomfort subjectively predicted</td>
</tr>
<tr>
<td></td>
<td>• Subjective choice for final TV preference</td>
</tr>
</tbody>
</table>

**Comparisons on Objective Measures on Image Discrimination**

In this study, the average thresholds on the tests of visual acuity, contrast sensitivity, stereoacuity and step vergence served as indicators of image quality. By averaging the threshold performance of multiple subjects, we can compare the afforded image discrimination with each display technology. The following summarize the findings of each test and its meaning for 3D viewing.

**No difference on displaying high contrast details in 3D**

No statistical difference was found between TVs for visual acuity threshold testing in 3D mode. This means that both technologies, active and passive, will have their image affected to the same statistical degree when watching in 3D mode. This was an unexpected result, considering that the passive system
presents an image with half the number of pixels to each eye as compared to the active TV. The active TV did outperform the passive TV in visual acuity threshold in 2D mode. For 2D viewing, the active TV will have a smaller resolvable viewing angle at greater viewing distances or with smaller targets at close distances than the passive TV. One possible reason for the active TV having a lower visual acuity threshold in 2D mode could be that the passive TV has a polarized filter on the screen. This filter may cause a slight degradation of the 2D image. It should be noted that this visual discrimination test determined subject’s abilities to discriminate small details on a small target of fixed size (the Landolt C ring opening) on each technology, but did not determine the actual smallest detail that could be displayed on each technology.

**Better 3D image contrast with passive TVs**

For contrast threshold, the active TV was significantly better than the passive TV in 2D mode, while the passive TV was significantly better than the active TV in 3D mode. A lower contrast threshold allows the TV to have a lower contrast image that will be better resolvable for viewers compared to its counterpart (active better in 2D mode and passive better in 3D mode). This means a wider brightness range can be used for scene display with the TV. This result in 3D mode may be due to the large decrease in luminance that the active TV experiences when switching into 3D mode, as shown in Table 5 at the end of the results section.

**Inconclusive on comparison of measured stereoacuity thresholds**

No statistical difference was found between TVs for stereoacuity levels at the levels tested. As mentioned earlier, the pixel size and resolution of the display systems limited the minimum angle testable at four meters to 32 arcseconds. This threshold was reached by 100% of subjects on both TVs. In the pre-screening exam, the average of subject’s stereo was approximately 23 arcseconds, smaller than the angle tested. Future studies should resolve this ceiling effect by setting the display at a distance where the resolution can reach the threshold of stereoacuity.

**Faster vergence reaction time with passive TVs**

For the step-vergence test, the passive TV was significantly better than the active TV, meaning vergence reaction times were faster on the passive TV. This suggests that the passive TV permits faster paced jumps in the perceived 3D depths than the active system. One possible explanation deals with the difference in luminance between the two systems. The active system is much dimmer than the passive system in 3D. It has been found that dimmer images have slower conduction along the optic nerve, which would slow down any response to that image presentation (Schwartz, 2009).

**No difference on the perceived 3D depth**

On the perceived depth test, the perceived depth seemed to be linearly increased with the image disparity; however, a wide range of perceived depth was found, due to only a single trial tested at each
disparity. Larger levels of disparity, either convergent or divergent, also induced a wider range of depths between subjects. This suggests that, with either technology, the perceived depth seemed to change in relation to the intended disparity. Further testing is needed with more trials at each testing disparity to test the sensitivity of depth perception from each display.

**Effect of viewing angle on image discrimination**

Based on the data of multiple measurements from a single observer, no statistically significant difference was found between TVs, with varying horizontal and vertical viewing angles, for visual acuity, stereoacuity or contrast threshold. However, subjects rated the passive TV as being less disrupted by varying viewing angles during the side-by-side comparison. The dimensions of the testing room also limited the measurable viewing angles. Further research should be done with more subjects in a classroom setting to identify the effects of viewing angles on image quality between active and passive TV technology.

**Subjective Questionnaires**

**Viewing symptom survey**

No statistical difference was found on the visual and physical symptom survey between TVs or between pre- and post-movie viewing on the same TV after 25 minutes of movie viewing on each system. On the side-by-side comparison, however, subjects felt that they would be able to watch the passive TV for a longer period of time before feeling any discomfort. An investigation of visual and physical symptoms with longer continuous movie viewing time for each technology could possibly reveal more differences on viewing symptoms.

**Display quality questionnaire**

For the perceived quality questionnaire comparing a small Landolt C 2D and 3D image as well as a large Wirt Dot 3D image, no statistical difference was found between TVs for image clarity with the 2D and small 3D image. The passive TV was rated with better image clarity than the active TV on the large 3D image. For ratings of ghosting, or crosstalk, there was no statistically significant difference between TVs comparing the 2D image, while the passive TV outperformed the active TV on both the small and large 3D image. In summary, the subjects rated the passive TV as having higher image clarity than the active TV when viewing large 3D images and as having less ghosting than the active system on any 3D image.

On the side-by-side TV comparison questionnaire, several factors were rated higher on the passive TV, while the active TV was not rated superior on any factors. Subjects rated the passive TV as having better image color and clarity, motion smoothness and immersion (feeling more engaged in the film). The passive TV was rated as being less disrupted, less image degradation, by head tilting and variable
viewing angles. For 3D glasses, the passive glasses were rated as lighter weight, as having a less disruptive frame edges and were selected as the final glasses preference. Subjects also felt that they would be able to watch the passive TV for a longer period of time than the active TV before feeling discomfort, although no difference in visual or physical discomfort was found with the symptom survey.

For final TV preference, the average marking of preference was 75.11 on an analogue scale where a mark of 100 meant the passive TV was the final selection, a mark of 50 was neutral, and a mark of zero was a final selection for the active TV. 75% of subjects marked a spot greater than 50 on the analog scale, showing preference for the passive TV.

**Comparison to Consumer Reports**

Table 1, repeated from the introduction section, shows a summary of consumer reported pros and cons for active and passive 3D TV technologies. The reported active technology pros were not revealed in the tested image quality in this study. Although a full resolution image is presented to each eye, allowing twice the pixel resolution per eye than passive technology, no 3D image quality factors, objectively or subjectively, were found to be better on the active TV. In contrast, subjects rated the passive TV as having better image color and clarity, even though passive technology is reported to have jagged image edges due to the division of the screen between eyes in 3D mode. On the side-by-side comparison questionnaire, there was no statistical difference between TVs for level of jagged edges. Objectively, the passive TV was measured to have a lower contrast threshold, though this may be linked with display brightness.

Active technology is reported to have a more drastic 3D image, but no difference in the perceived depth as compared to the intended depth was found between TVs with the limited number of trials tested. In addition, no difference in stereoacuity was measured in this study, but there was a limit to testable disparities, as discussed above. In contrast, subjects detected change of depth faster with the passive TV on the step vergence test, suggesting the changes of depth were observed more efficiently with passive TVs.
Table 1: Summary of consumer reported pros and cons for active and passive 3D TV technology.

<table>
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<tr>
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<th>Active Technology</th>
<th>Passive Technology</th>
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<tbody>
<tr>
<td><strong>Consumer Reported Pros</strong></td>
<td>• Full resolution image presented to each eye</td>
<td>• Light weight, non-bulky glasses</td>
</tr>
<tr>
<td></td>
<td>• More dramatic 3D image</td>
<td>• Brighter image</td>
</tr>
<tr>
<td></td>
<td>• Less effect from off-axis viewing and head tilting</td>
<td>• Half resolution image presented to each eye</td>
</tr>
<tr>
<td></td>
<td>• Glasses require charge, making them bulky</td>
<td>• Jagged image edges</td>
</tr>
<tr>
<td></td>
<td>• Glasses flicker (may be noticeable or induce fatigue)</td>
<td>• Image degraded with off-axis viewing and head tilting</td>
</tr>
<tr>
<td></td>
<td>• Dimmer image</td>
<td>• Crosstalk (ghosting)</td>
</tr>
<tr>
<td><strong>Consumer Reported Cons</strong></td>
<td>• Crosstalk (ghosting)</td>
<td>• Crosstalk (ghosting)</td>
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Active technology is reported to be less affected by off-axis viewing and head tilting, but testing on an individual subject showed no difference between TVs. The passive TV was actually rated as less disrupted by off-axis viewing and head tilting by the subjects. Linearly polarized filters require a specific angle between the lens filters and the screen filter to block images to each eye. If this angle is disrupted, with a head tilt for example, there will be a misalignment between the lenses and TV screen, leading to image degradation. The passive television in this study used circularly polarized filters, instead of linearly polarized. Circularly polarized filters create a clockwise image for one eye and a counterclockwise image for the other eye. This kind of polarization should not be affected by head tilting (Craig, Sherman and Will, 2009), as found in this study.

Both of the consumer reported passive technology pros, lighter weight, less bulky glasses and a brighter 3D image, were supported by this study. Subjectively, the passive glasses were rated as lighter, as having less disrupted frame edges and were selected as the final glasses preference. The passive TV was measured as brighter under both 2D and 3D mode (Table 5).

The flickering of the active technology glasses is a reported con for the active TV. The tested active glasses have a flicking rate of 120 Hz, above the average human photopic critical flicker frequency, 70 Hz (Schwartz, 2009). In the side-by-side comparison, there was no significant difference on display flickering between the two TVs, although there was a slightly higher rating on perception of flickering with active TVs. Even if the flicker is not consciously noticed, it may induce visual fatigue after prolonged periods of viewing. For active systems, higher flicker rate is recommended to prevent flicker detection and induced fatigue.
Crosstalk, or ghosting, has been reported as a negative for both technologies, depending on the source. In this study, ghosting was subjectively rated as lower on the passive TV.

**Relating it to the Classroom**

Image quality, viewing comfort and room dimensions are all variables that should be considered when deciding which 3D television technology to purchase.

For image quality, subjects felt that the passive TV was superior to the active TV, although, only two subjective measurements were statistically different between the TVs for 3D image quality. Based on the fact that active technology has twice the pixel resolution per eye than passive technology, this outcome seems contradictory to what many technology review articles predict. The passive TV can allow lower contrast images with faster changes in 3D depths. The active TV performed better in 2D mode with a lower contrast and VA threshold. When deciding between TVs, the buyer must consider if they intend to use the TV for both 3D and 2D or mainly 3D. In addition, a strong subject preference for passive technology should not be ignored. Although the basis behind this preference can be inferred from the side-by-side display comparison and the image quality surveys, future studies may want to identify the source of preference directly.

Subjects predicted that they would be able to watch the passive TV longer before experiencing discomfort. Analysis of the pre- and post- movie viewing discomfort questionnaires revealed no difference in symptoms for either TV or when comparing TVs. As stated earlier, more differences may become apparent with a longer movie viewing time for symptoms to arise. Subjects also preferred the passive glasses over the active glasses. Passive glasses have lighter weight, thinner frame edges, no flicker, meaning they do not require charging, and are less expensive. The lighter weight and thinner edges may be a better option for viewers with prescription spectacles, since the 3D glasses would have to be worn on top of any distance spectacles.

Based on data gathered from a single subject in this study, viewing angle does not affect the perceived image quality between the 2 technologies. Therefore, room dimension is not a critical factor when deciding between technologies on 3D viewing. Still, there are differences on the threshold image quality tested at straight-viewing angles. For 2D mode, the active technology was measured to have a lower VA threshold, which would allow a larger viewing distance when watching in 2D. However, passive technology was measured to have lower contrast threshold in 3D. Subjects also rated the passive technology as offering better 3D image quality, being less disrupted by viewing angles and head tilting. In addition, the age of the audience could be a factor since younger children may tilt their heads more or rest their heads on desks in the classroom, and more likely to be affected by the weight of the glasses.

A final factor to consider would be price. The prices of different 3D televisions and their glasses are a constantly moving target, and should be researched by the buyer before purchase.
CONCLUSION

In conclusion, in this study, passive TV technology was a solid winner when it came to subject’s personal ratings, but only outperformed the active TV objectively with contrast and speed of vergence responses. When considering image quality, viewing comfort and room dimensions, subjects felt the passive TV outperformed the active TV in all three categories. With objective measures, passive statistically excelled at two traits in 3D mode and active statistically excelled at two traits in 2D mode for image quality, while no difference was found between televisions for viewing comfort. In addition, no variables were statistically different between TVs that would change the dimensions of a movie-viewing zone. It should be emphasized that the results are based on a relative small sample size (57 subjects, most young female adults) and tested on specific display models. Investigation with a larger sample size and reaching to broader populations is required before reaching expansive conclusions. In addition, active and passive projector systems, could be a good option for classrooms that are able to afford the system. Future studies should compare the difference between 3D projector systems as well as any future glasses-free systems developed with a broader viewing range than the current available televisions.
REFERENCES


APPENDIX A:

Visual Symptom Survey Questions

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<tr>
<td></td>
<td>Strongly Disagree</td>
<td>Disagree</td>
<td>Neutral</td>
<td>Agree</td>
<td>Strongly Agree</td>
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Scale used for marking selection on each question.

1. My eyes felt tired
2. My eyes felt irritated or had a burning sensation
3. My eyes felt strained or it felt like there was a pulling sensation around my eyes
4. I felt eye ache or pain inside of my pain
5. My eyes were dry or watery
6. I experienced blurry vision
7. I saw multiple images (double vision)
8. I saw images move, jump or swim on the screen
9. I felt fatigue or sleepiness
10. I had difficulty switching focus between near and far
11. I experienced a headache
12. I experienced dizziness
13. I felt disoriented or had a sense of vertigo
14. I experienced nausea
15. I had neck discomfort
16. I experienced general physical discomfort
17. The objects look real as they move through space
18. I felt like I was part of the movie
19. I felt engaged in the movie I viewed
20. I lost track of time while viewing the movie
Appendix B:
Side-by-side comparison questions

Image 1: Comparison questions 1-5

The colors displayed were:
TV 1 Very Poor Poor Average Good Excellent
TV 2 Very Poor Poor Average Good Excellent

How was your perception of jagged edges?
TV 1 Disturbing Distracting Noticeable Faint Imperceptible
TV 2 Disturbing Distracting Noticeable Faint Imperceptible

How was the cross-talk (ghosty images around objects)?
TV 1 Disturbing Distracting Noticeable Faint Imperceptible
TV 2 Disturbing Distracting Noticeable Faint Imperceptible

The display flickering was:
TV 1 Disturbing Distracting Noticeable Faint Imperceptible
TV 2 Disturbing Distracting Noticeable Faint Imperceptible

The overall clarity of the 3D was:
TV 1 Very Poor Poor Average Good Excellent
TV 2 Very Poor Poor Average Good Excellent

Submit

Image 2: Comparison questions 6-8

The perception of depth was:
TV 1 Very Poor Poor Average Good Excellent
TV 2 Very Poor Poor Average Good Excellent

The perception of motion smoothness was:
TV 1 Very Poor Poor Average Good Excellent
TV 2 Very Poor Poor Average Good Excellent

What was your sense of immersion?
TV 1 Very Poor Poor Average Good Excellent
TV 2 Very Poor Poor Average Good Excellent

Submit
Image 3: Comparison questions 9-13

The viewing angle was:

TV 1: [Ratings]
TV 2: [Ratings]

Satisfaction with a tilted head position?

TV 1: [Ratings]
TV 2: [Ratings]

The weight of the glasses were:

TV 1: [Ratings]
TV 2: [Ratings]

The edges of the glasses frames were:

TV 1: [Ratings]
TV 2: [Ratings]

Your overall satisfaction of the glasses:

TV 1: [Ratings]
TV 2: [Ratings]

Submit

---

Image 4: Comparison question 14

How long do you think you can watch this TV without feeling discomfort?

TV 1: [Ratings]
TV 2: [Ratings]

Submit
Final television preference: