Effects of Vergence and Accommodative Responses on Viewer’s Comfort in Viewing 3D Stimuli

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ABSTRACT
Vergence and accommodative responses in viewing near objects in the real world are behaviorally coupled to maintain clarity and singularity for the object of regard. However virtual stereoscopic stimuli, such as in 3D displays, create non-normal coupling that may cause improper vergence and accommodative responses, possibly resulting in visual discomfort. The present study examined whether the dynamic aspect of current 3D displays is the underlying cause of visual and physical discomfort. To this end, subjects’ vergence and accommodative responses were measured while they tracked an approaching 2D or 3D target, and while watching a 2D or 3D movie. The tracking target either moved in steps or continuously, and it was either clear or intentionally blurred. Results show that convergence insufficiency and improper accommodation were greater when a 3D target was moving continuously toward the near position compared to a 2D target and a 3D stimulus moving in steps. Clear targets also resulted in greater vergence and accommodative responses than blurred targets. Viewing 3D movie resulted in greater vergence and accommodation, as well as more severe vision- and motion-related discomfort than 2D movie. These findings suggest that with 3D displays, disparity-induced vision difficulty and internal conflicts cause perceived visual and motion-related discomfort. Characteristics of 3D stimuli, such as the frequency and amplitude of target motion, likely critically affect the severity of reported discomfort symptoms.

Keywords: Vergence, accommodation, motion in depth, 3D, stereoscopic display, visual discomfort, motion sickness, binocular disparity

1. INTRODUCTION

1.1 Vergence, Accommodation, and Visual Discomfort
To maintain clear vision of a visual object, the shape and power of the human crystalline lens is changed by ciliary muscle contraction to focus the image onto the retina, a process referred to as accommodation. To fuse the object image formed in the fovea of the two eyes, often referred to as fusional vergence, the two eyes are rotated inward (convergence) or outward (divergence) dependent on the disparity of retinal images. Failure to execute such adjustments can lead to visual difficulties such as blurred vision, due to improper accommodation, and double vision associated with vergence insufficiency. In sustained viewing tasks, such visual difficulties are often linked to perceived visual discomfort. Viewing a stimulus moving in depth requires constant accommodative and vergence adjustments that minimize the blur and disparity of retinal images, likely increasing the difficulty in optimally maintaining such adjustments.

Research has demonstrated that the vergence and accommodative systems are coupled, as changes in visual stimulation to one of the systems results in concerted adjustments in both systems. This neural coupling occurs in the nucleus of Edinger-Westfall near the third cranial nerve nucleus. Neurophysiological findings show that the same neural substrates encode signals for both systems, even when the visual input stimulates only one of these two systems. Such coordination is especially critical in viewing stimuli moving in depth, where binocular disparity registered on the retina helps determine the depth of the stimulus and proper accommodation can be made to focus at the stimulus with adequate clarity.
1.2 3D Display and Visual Discomfort

Three-dimensional (3D), or stereoscopic, displays are increasingly being used for movie viewing and gaming. With 3D displays rendered on a 2D surface, stereovision is achieved by projecting separate images to the two eyes, for which differential disparities are generated based on the intended distance of objects in the image in relation to the eyes \(^{17,18,19}\). When attending to a stereoscopically displayed object moving in depth, vergence responses are expected in order to minimize such disparity for the attended object. However, the required amount of accommodation is expected to remain constant, as determined by the distance of the display surface. When a viewer attempts to focus on an object at a location separated from the display surface in depth, the stimulation ratio for accommodation and vergence is different than encountered in real visual space \(^{9,20,21}\). Since the visual stimulation for the vergence response also drives the accommodative response, the overall accommodation could deviate from the display depth; similarly, the visual input intended to drive accommodative response also contributes to guide the vergence away from the position specified by binocular disparity. As a result, over-accommodation and under-vergence can take place when the stereoscopic target is rendered at a distance significantly different from that of screen surface. Such a compromise could lead to visual discomfort, such as eyestrain, blurred vision, and double vision \(^{8,20}\).

In 3D viewing, visual stimuli can either remain stationary (static) or move in depth (dynamic). In the latter case, viewers are compelled to visually track the object of regard in depth by changing their vergence position. The continuous change in vergence demand likely leads to a constant adjustment in both vergence and accommodation, exacerbating the difficulty in maintaining clear vision. In line with this, it has been shown that viewing dynamic 3D stimuli for an extended period of time results in greater visual discomfort than viewing static 3D stimuli \(^{21}\). In addition, since the adjustment of accommodative and vergence responses depends on visually registering the change in image clarity and binocular disparity, degraded visual images can impede accommodative and vergence responses.

1.3 Research Goals and Hypotheses

The present study aimed to investigate the amount of accommodative and vergence responses elicited by 3D viewing, and the consequent visual and physical discomfort. Specifically, the effects of dynamic and static 3D stimuli on vergence and accommodative responses were compared. To this end, subjects were recruited to participate in two experiments. In the first one, subjects visually tracked a 3D or 2D target that moved in depth, for which its specific depth at any given moment was certain. Their accommodative and vergence responses were recorded and related to the change in target depth. The target moved either in a stepwise (static) or continuously (dynamic) manner, with the displayed image being either clear or intentionally blurred. It is predicted that tracking a 2D target should result in less vergence and accommodative response than a 3D target, and a static 3D stimulus should result in less response than a dynamic 3D stimulus. When the target is blurred, accommodative and vergence responses should be attenuated compared to when it is clear.

To correlate the vergence and accommodative responses with subjective visual discomfort, in the second experiment participants viewed either a 2D or 3D movie on separate days, their vergence and accommodative responses were recorded for the entire duration of viewing, and their visual/physical discomfort before and after movie viewing were also measured. We expected that viewing 3D movies should result in a greater amount of change in vergence and accommodative responses, and greater visual and physical discomfort than viewing a 2D movie; 3D movies should also enable a better viewing experience.

2. METHODS

2.1 Participants

Twenty-one adult subjects (42% male, 24.6 average age) were recruited from Pacific University, in the city of Forest Grove, and surrounding areas. They had stereo acuity better than 60 sec of arc, far visual acuity of 20/16 to 20/30 in each eye (at least 20/25 for the better eye) without optical correction or with spherical contact lens correction. They were excluded from the study if they had significant ocular pathology, abnormality, or oculomotor limitation. Other exclusions were history of photosensitive epilepsy or the use of a cardiac pacemaker. Participants involved in Experiment 1 also participated in Experiment 2.

2.2 Materials

A freeware program, Blender, was used to generate 3D images of a visual target. Separate images were generated for
left and right eyes and then combined using the Synth script program. An encoding free software, Xvid, was used to generate the image for real time playback. Below are the four types of animation:

2.2.1 **Clear Static 3D (CS3D).** A fixation point was displayed on the screen (extending .5 degree of visual angle) at the baseline position (200cm distance) for 1 sec. After this fixation period, a 3D cross target (extending .57 degree of visual angle) was displayed at the far position (267cm distance) for 2.5 sec. The target then returned to the baseline position (200cm distance and 1.15 degree) for 2.5 sec, and was displaced to the near position (132cm distance and 3.47 degree) for additional 2.5 sec. The target was removed after displayed at near position, and additional 1.5 second of blank screen followed. (See Figure 1A.) The image size was scaled to the distance so that angular size did not change, and a 6cm inter-ocular distance was assumed. The entire duration of the trial took 10 sec. Also displayed along with the cross target was a black 3-D circle of 40cm (11.3 degree of visual angle) width rendered at near position. This was displayed to provide a near reference for the depth of the target, as typically found in 3D viewing of a natural scene. The expected vergence demand of the rendered 3D image at far and near positions are 1.5 cm (-.75 Δ in divergence) and 3cm (+1.52 Δ in convergence) in relation to the baseline position. The expected accommodation demands for the far, baseline, and near vergence positions are .75D, .5D, and .37D respectively, whereas the actual accommodative stimulus dictated by the viewing distance of the display was .5D.

2.2.2 **Blurred Static 3D (BS3D).** The stimulus is the same as above, except that a blurred target and reference circle was displayed, as shown in Figure 1B. The blur effect is created by adding a Gaussian blur filter over the image, with a blurring parameter of 15 pixels both horizontally and vertically.

2.2.3 **Clear Dynamic 3D (CD3D).** A clear 3D target moved gradually from the baseline position to the far position, back to the screen position, to the near point, and then back to the baseline position. The movement from the baseline position to the near and far position took 2.5 sec, as well as the return from the near/far position to the baseline.

2.2.4 **Blurred Dynamic 3D (BD3D).** The same stimulus as CD3D was used, but with the target blurred in the manner described in BS3D.

![Figure 1](image-url)  
*Figure 1.* Testing stimuli for 2D and 3D target and reference stimuli. The target either moves in steps (200cm – 267cm – 200cm – 132cm) or in continuous motion in the same depth range. A) Clear stimulus. B) The same stimulus blurred with 15-pixel Gaussian.

To determine the unique effect of 3D stimuli, half of the four types of trials shown above were presented in 2D instead. They are coded as CS2D (clear, static 2D), BS2D (blurred, static 2D), CD2D (clear, dynamic 2D), and BD2D (blurred,
dynamic 2D) respectively. This was achieved by presenting the same image to both eyes, resulting in no binocular disparity in image presentation.

Two commercially available movies (“Spy Kids” and “Lava Girl and Shark Boy”) were chosen to be closely matched in their theme (action- and/or scifi-related) and duration (90 minutes). They were displayed in 2D and 3D format using conversion software, Tridef Experience (DDD Corp.).

A visual and physical discomfort questionnaire developed in our laboratory was used to assess visual and physical discomfort (see Table 1). The questionnaire was displayed on a computer screen one question at a time and was accompanied by an analogue response scale. A computer mouse was used to indicate the chosen response on the scale and the response was stored in the computer for later analysis.

Table 1. Visual and physical discomfort questionnaire. Subjects used a computer mouse to mark the degree of visual/physical symptoms on the analogy scale displayed on screen.

<table>
<thead>
<tr>
<th>Not at all</th>
<th>Mildly</th>
<th>Moderately</th>
<th>Severely</th>
<th>Extremely</th>
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<tr>
<td>1. Did you feel physically more uncomfortable in general?</td>
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<td>2. Did your eyes feel more tired?</td>
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<td>3. Did your eyes feel more strain or pulling sensation?</td>
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<td>4. Did your feel your head is fuller or have greater headache?</td>
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<td>5. Did your feel greater disorientation or vertigo?</td>
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<td>6. Did you notice greater blur from the scene you were viewing?</td>
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<td>7. Did you have greater trouble visually focusing on the scene?</td>
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<td>8. Did you feel more severe dizziness?</td>
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<td>9. Did you see multiple images of the scene more?</td>
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<td>10. Did you see the words move, jump, swim or appear to float on the page more?</td>
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<td>11. Did you feel greater neck ache?</td>
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<td>12. Did you feel more tired or sleepy?</td>
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<td>13. Did you have greater difficulty concentrating in the task?</td>
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<td>14. Did you feel like you have greater difficulty thinking clearly?</td>
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<td>15. Did you have greater trouble remembering what you have seen?</td>
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2.3 Apparatus

The participant’s far (20 feet) visual acuity was measured with a digital Snellen eye chart (Smart System II 20/20 Basic Visual Acuity System, M&S Technologies, IL: Park Ridge). The participant’s stereoacuity was measured with the WIRT dot test (Bernell Corporation, Mishawaka, IN). Accommodation was recorded monocularly (right eye) with an infra-red light-based autorefractor (Grand Seiko WAM-5500). This device samples the accommodation level at 5Hz. Vergence responses were measured by monitoring the eye movements binocularly with a SR Research Eyelink eyetracker. It uses infrared light camera and was mounted on the autorefractor to acquire pupil image and corneal reflection at a 500Hz sampling rate. The spatial resolution is .005° and its accuracy is .5°.

A Samsung 50” DLP 3D TV was used to display stereoscopic stimuli. A pair of wireless LCD goggles with synchronized eye shutters displayed the left and right images at 120Hz (60Hz for each eye). The TV rests on a height-adjustable stand with the center of the screen aligned to the subject’s eye height.
2.4 Procedure

Participants were asked to participate in two separate testing sessions scheduled on different days, each two hours in duration. In both sessions, half of trials in Experiments 1 and 2 were conducted. This allowed the measurement of visual discomfort for 3D and 2D movies to be done on separate days and unaffected by each other. There were at least 48 hours between the two testing sessions.

In the first session, participants were briefed about the general goal of the study and the procedure of the experiments before the experiment was conducted. They were given an opportunity to ask questions about the study and were informed of their rights to refuse or terminate their participation before and during the experiment. The informed consent was obtained with a consent form approved by the Institutional Review Board at Pacific University.

In each of the two experimental sessions, the participant was seated in front of the autorefractor and the 3D TV. Eye cameras were mounted to the autorefractor to monitor eye movements. A chin/head rest attached to the autorefractor was used to keep the head stable, to align the line of eyesight perpendicularly to the screen, and to maintain a constant eye-screen distance of 200cm.

In Experiment 1, the participant viewed the eight types of stimuli for 30 times respectively in the two sessions. Animation type was randomized across trials, and each trial was presented in 2D or 3D in a randomly determined manner. Each trial began with the display of a 3D target at the baseline distance along with the 3D circle. The target then moved in step or continuously for 8.5 seconds and then both the circle and the target were removed for 1.5 seconds. The subjects pressed a button to initiate the next trial. They also pressed a button to report a change in the direction of target motion, which encouraged them to attend to the display stimulus. There were 240 trials, with 120 trials in each testing session. Trials with missing button responses were removed from analysis.

In Experiment 2, a movie was played on the screen for 90 minutes in 2D or 3D mode for each testing session. Each participant saw one movie in 2D in one session and the other movie in 3D in the other session. The movie and the display method (2D vs. 3D) for each session were selected based on Latin Square design. Before and after watching the movie, the participant responded to the same questionnaire to evaluate the effect of movie viewing on visual discomfort. They also were asked to watch the movie as attentively as possible, and answered questions about the movies after the viewing. This encouraged them to be visually engaged during movie viewing.

2.5 Data Analysis

Binocular eye movement data were extracted from recordings to compute the horizontal shift in eye position. Prism Diopters of vergence amplitude (Δ) were calculated by dividing the difference in binocular eye positions with display distance. Accommodative amplitude was extracted from the autorefractor recordings. Both vergence and accommodation data were then subjected to three-way (2D vs. 3D, motion vs. step, clear vs. blur) repeated measures ANOVA, and the estimated means for all eight display conditions calculated. Bonferroni pair-wise comparison was conducted with a family-wise alpha value of .05.

3. RESULTS

3.1 3D animation stimuli

Figure 2 shows the averaged vergence amplitude in relation to the expected vergence demand recorded from a participant. In the figure, positive values on Y axis indicate the proportion gain of normalized amplitude in divergence in relation to the baseline, whereas negative values the normalized amplitude in convergence. It was calculated based on the difference between actual amplitude and expected amplitude, divided by the expected vergence amplitude. Each curve is based on the mean vergence value for 30 trials, with each 50ms time bin containing maximally 750 eye samples (25 sample from each trial). The Dotted line indicates expected vergence amplitude for a stepwise target, whereas the dashed line a dynamic target. The actual vergence amplitude was derived from the change in the positions of the two eyes relative to the mean positions for the first 500ms seconds of a trial, when the subject was fixating a target displayed at a depth of 200cm, namely the distance of screen surface.

The different effect of target display conditions on vergence response can be visually examined here by comparing the curves in the three 500ms time periods, as marked by the black bars (far, baseline, and near) at the top of Figure 2. In Figure 2A, the curve for CD3D trials (clear, dynamic 3D) systematically separated from that for CD2D trials (clear,
dynamic 2D) only when the target was approaching the near position, with CD3D inducing greater convergence. When
the target position was approaching the far and baseline positions, little consistent difference in vergence response was
observed among the four display conditions. Also in Figure 2A, no consistent difference was found between CS3D
(clear, stepwise 3D) and CS2D (clear, stepwise 2D) trials when the target was approaching the near position.

**Figure 2.** Mean vergence amplitude for trials with clear (panel A) and blurred (panel B) target image. Negative disparity
represents convergence associated with a nearer target. The amount of expected vergence amplitude for the target is
indicated by the dotted (stepwise) and dashed (dynamic) line. The actual measured change in vergence amplitude is
expressed in the proportion of gain in relation to the baseline vergence. The three bars at the top of the figures indicate the
500ms before the target reached the far, baseline, and near positions. The baseline vergence amplitude was established
based on in the first 500ms of fixating on a 2D fixation point presented 1 second before target presentation. Error bars
indicate the 95% confidence intervals for each time bin.
Note the initial convergence after the onset of the target and reference circle. This probably reflected the response toward the reference circle, which was rendered at the near position (132 cm). The similar initial convergence response to 3D and 2D targets could have resulted from learned stimulus depth in 3D trials, due to interleaved 3D and 2D trials.

Figure 2B shows the mean proportion gain of vergence amplitude for blurred targets. All four display conditions resulted in similar vergence amplitudes for the 500 ms intervals for far, baseline, and near positions, regardless of whether the stimulus was 3D or 2D, and whether it moved in steps or continuously. Note that there were still initial vergence responses to the onset of reference circle, which again could have resulted from learned target position (depth) in 3D trials.

Three-way repeated measures ANOVA were conducted to determine the effect of 3D rendering, motion type, and image blur on vergence amplitude for targets approaching the three positions. For far position, there was main effect of 3D rendering, $F(1, 19) = 4.342, p = .050$, but not motion type, $F(1, 19) = 1.013, p = .327$, nor image blur, $F(1, 19) = 2.212, p = .153$. There was no interaction among them.

Figure 3A shows the estimated mean vergence amplitude normalized in relation to the expected amplitude for the 500 ms before the target reached the far position. This is based on data from all subjects. It can be seen here that the amount of vergence in relation to the baseline position was greater for conditions with 3D targets, regardless of whether the target moved continuously or stepwise and whether it was blurred or not.

For baseline position, there was no main effect of 3D rendering, $F(1, 19) = 1.672, p = .211$, motion type, $F(1, 19) = 2.079, p = .166$, nor image blur, $F(1, 19) = 2.114, p = .162$. There was no interaction among them. Figure 3B shows the estimated mean vergence amplitude for targets moving toward the viewer and immediately before reaching the baseline position. It indicates that clear 3D images induced significantly greater convergence than blurred 3D images and all conditions with 2D images.

For near position, there was no main effect of image blur, $F(1, 19) = 2.114, p = .246$, motion, $F(1, 19) = 2.042, p = .276$, or 3D rendering, $F(1, 19) = 1.672, p = .415$. There was interaction between 3D rendering and motion type, $F(1, 19) = 4.464, p = .048$. Figure 3C shows the vergence amplitude when the target moved from the baseline position to the near position. It indicates that clear, dynamic 3D images induced greater convergence than blurred 3D images, and greater convergence than clear 2D images. There was no convergence response with 2D targets, regardless of motion type and image blur.

Repeated measures ANOVA were also conducted to determine the effect of 3D rendering, motion type, and image blur on mean accommodation amplitude. For far position, there was main effect of 3D rendering, $F(1, 19) = 4.672, p = .043$, but not motion type, $F(1, 19) = 2.042, p = .169$, nor image blur, $F(1, 19) = 3.016, p = .098$. There was no interaction among them. Figure 4A shows the mean accommodation amplitude for different display conditions 500 ms before the target reached the far position. The focus distance was generally closer for 3D targets than for 2D targets. Clear, dynamic 3D targets resulted in closer focus distance than blurred dynamic 3D and blurred 2D targets. There was no significant difference among conditions with 3D targets.

For baseline position, there was no main effect of 3D rendering, $F(1, 19) = 3.338, p = .084$, motion type, $F(1, 19) = 1.136, p = .300$, nor image blur, $F(1, 19) = 0.956, p = .340$. There was interaction among them. Figure 4B shows the estimated mean accommodation amplitude before the target reached the baseline position. There was no clear difference among all conditions, although there was slightly greater accommodation for clear, dynamic 3D than for blurred 2D conditions.

For near position, there was main effect of 3D rendering, $F(1, 19) = 5.346, p = .032$, image blur, $F(1, 19) = 4.653, p = .044$, but not motion type, $F(1, 19) = 0.972, p = .337$. There was interaction between 3D rendering and image blur, $F(1, 19) = 4.751, p = .042$. Figure 4C shows the mean accommodation before the target reached the near position. Clear 3D targets resulted in greater accommodation than blurred 3D targets. Clear, dynamic 3D targets caused greater accommodation than clear, static 3D. There was no significant increase of accommodation in blurred conditions in relation to the baseline, although the variance of accommodation appeared much greater for blurred conditions.
Figure 3. Measured vergence amplitude in relation to the expected amplitude for targets presented at far, baseline, and near positions. Expected vergence amplitude for the far and near positions was expressed as delta (\(\Delta\)). On Y axis, negative proportions indicate convergence in relation to the baseline vergence at screen distance and positive proportions divergence. Error bars indicate 95% confidence intervals.
Figure 4. Measured accommodation amplitude in relation to the expected accommodation demand for targets presented at far, baseline, and near positions. The accommodation amplitude for different positions is expressed as Diopters (D). On Y axis, negative proportions indicate less accommodation in relation to the accommodation demand of the baseline distance, and positive values greater accommodation. Error bars indicate 95% confidence intervals.
3.2 3D Movie Viewing

To examine whether greater changes in vergence response were induced by movies rendered in 3D in relation to the same movies rendered in 2D, the variance in vergent distance was computed for 3D and 2D viewing of the same movie. Since there was no precise way to link the presently attended object in depth to the amount of vergence response, the standard deviation of vergence amplitude was computed instead. In addition, to determine whether the amount of change in vergence response varies in relation to time, the standard deviation of vergence response were computed for five 18-minute periods of movie viewing. Figure 5 shows the standard deviations of vergence amplitude for all 21 subjects in 3D and 2D viewing. It reveals that 3D movies resulted in greater change in vergence amplitude in all 5 time periods, significantly so in three of five time periods; the time interval in relation to the beginning of viewing did not appear to affect the change in vergence response.

Figure 5. Variance in vergence amplitude for in 3D (blue) and 2D (red) movie viewing. The Y axis represents the standard deviation of vergence amplitude, as expressed in prism diopters (Δ).

Figure 6 shows the variance in accommodative response in the five time intervals of 3D and 2D viewing. Greater change in accommodative response was observed during 3D viewing in all time intervals, significantly so in two of the five time intervals. Again, there was no evidence of consistently increasing or decreasing changes in accommodation at later stages of viewing.

To determine when and how soon participants perceived visual/physical discomfort during movie viewing, immediately after movie viewing they were asked to report the timing when they began to perceive any overall discomfort (instead of any specific symptoms). This was achieved by asking them to click on an analogue scale displayed on the screen. The resultant mean estimated time of perceiving discomfort was significantly earlier during 3D movie than 2D movie (21 vs. 29 minutes, t = 2.415, p = .025).

In addition, we evaluated the changes in visual/physical symptoms before and after viewing 2D or 3D movies. Results of paired t-test show slightly greater symptoms of defocused (blurred) vision (t = 2.012, p = .058), double vision (t = 2.381, p = .027), and floating/drifting image (t = 2.125, p = .046).

There were also significant differences in symptoms related to motion sickness. 3D viewing resulting in greater perceived dizziness (t = 2.387, p = .027) and nausea (t = 2.232, p = .037) than 2D viewing.
We also examined changes in cognitive performance by asking if the subjects had any difficulties with concentration, thinking, or memory. Results show that 3D viewing led to better concentration ($t = 5.425$, $p < .001$), thinking ($t = 2.775$, $p = .012$), and memory retention ($t = 4.877$, $p < .001$).

![Figure 6](image_url)

**Figure 6.** Variance in accommodative response in 3D (blue) and 2D (red) movie viewing. The Y axis represents the standard deviation of accommodation amplitude, as expressed in Diopters.

### 4. DISCUSSIONS

The present study has demonstrated greater deviation of accommodation from the display surface and greater convergence in viewing an approaching 3D stimulus than a 2D stimulus. In viewing 3D movies, greater variance in vergence and accommodative responses were also found compared to viewing 2D movies. Conversely, in viewing 3D movies a higher degree of blurred vision and double vision were also reported.

Reacting to an approaching object appears to hold an evolutionary importance. It is not surprisingly that neural substrates involved in motion detection and encoding are much more sensitive in responding to objects close to the viewer, and are more sensitive to moving stimuli than static ones in near positions. In line with these, binocular disparity cues have been shown to play a more important role in detecting and determining the speed of motion in depth. The greater convergence and accommodative responses to near 3D stimuli likely reflect the enhanced neural signals in encoding visual inputs related to motion in depth. Further studies should examine whether such physiological response is critical in affording viewers with greater presence and immersion in the visual display, and is critical in ensuring more timely and accurate visuo-motor responses.

We observed two main types of symptoms, those related to degraded visual perception (blurred and double vision) and those related to motion sickness. The perceived visual discomfort most likely is associated with the observed convergence insufficiency and excessive accommodation. As the binocular disparity for near objects demands great convergence, and the farther screen surface requires less accommodation than the binocular disparity would suggest, the neurophysiological influence from these two mechanisms causes under-convergence and excessive accommodation. Blurred vision and double retinal images were perceived as a result.

Binocular disparity is also critical for the perception of motion in depth. Individuals judge how fast an object moves in depth by comparing the position and velocity of the two retinal images of the same object. Such
information is then integrated with other signals (e.g., vestibular) to determine the motion direction and speed of an object in relation to the viewer. 3D movies afford such binocular disparity cues while the viewers sit stationary, thus providing incongruent visual and vestibular inputs. Research on visually induced motion sickness has suggested that such incongruency is one of the main causes for inducing motion sickness 25,26.

Our findings suggest a physiological limit in 3D viewing, above which visual discomfort and motion sickness might be induced. The degree of visual and physical stress may be determined by mismatch of the vergence and accommodative demands created by the 3D stimuli. Future research should investigate whether proper attenuation of such mismatches could result in improved comfort while still maintaining the presence and immersion provided by 3D viewing. Research should also be done to identify factors mediating the effect of vergence demand on viewing discomfort, such as the quality (i.e., spatial resolution) of 3D display 27, viewer’s visual capacity (e.g., binocular acuity and stereoacuity), the distance of display screen in relation to image size, and the frequency and velocity of stimulus motion.

5. CONCLUSIONS

The present findings suggest that viewing 3D images causes increased vergence and accommodative responses compared to viewing 2D images. 3D stimuli that are clear and perceived as moving toward the participants are more effective in stimulating accommodation and convergence. This enhanced effect is significantly attenuated if 3D stimuli are blurry, move in a stepped fashion, and move away from the viewer.

In addition, viewing 3D movies also incurs greater accommodative and vergence responses. Comparisons of visual/physical symptoms before and after viewing 2D and 3D movies suggest that 3D movies induced greater motion sickness symptoms, and visual symptoms related to vergence or accommodation, such as blurred and double vision.

In summary, 3D viewing effects greater vergence and accommodative responses, especially when the stimulus appears to move toward the viewer. This places a greater amount of vergence and accommodative stress on the visuo-ocular system, and likely accounts for the increased visual symptoms by causing compromised vision such as blurred and double vision.

6. ACKNOWLEDGEMENT

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REFERENCES


