Redirecting View Rotation in Immersive Movies with Washout Filters

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ABSTRACT

Immersive movies take advantage of virtual reality (VR) to bring new opportunities for storytelling that allow users to naturally turn their heads and bodies to view a 3D virtual world and follow the story in a surrounding space. However, while many designers often assume scenarios where viewers stand and are free to physically turn without constraints, this excludes many commonly desired usage settings where the user may wish to remain seated, such as the use of VR while relaxing on the couch or passing the time during a flight. For such situations, large amounts of physical turning may be uncomfortable due to neck strain or awkward twisting. Our research investigates a technique that automatically rotates the virtual scene to help redirect the viewer's physical rotation while viewing immersive narrative experiences. By slowly rotating the virtual content, viewers are encouraged to gradually turn physically to align their head positions to a more comfortable straight-ahead viewing direction in seated situations where physical turning is not ideal. We present our study of technique design and an evaluation of how the redirection approach affects user comfort, sickness, the amount of physical rotation, and likelihood of viewers noticing the rotational adjustments. Evaluation results show the rotation technique was effective at significantly reducing the amount of physical turning while watching immersive videos, and only 39% of participants noticed the automated rotation when the technique rotated at a speed of 3 degrees per second.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Virtual reality;

1 INTRODUCTION

Virtual reality (VR) systems are often used to promote engaging experiences in simulated 3D environments using features such as stereoscopic imagery and head-tracked viewing to help users feel like they are a part of the virtual world. In recent years, the popularity of commercial head-worn displays and advancements in mobile phones has spurred the development of a growing number of new interactive narratives for entertainment purposes. Many commercial virtual reality experiences have been presented as forms of immersive stories or movies that bring new opportunities for storytelling that allow users to naturally turn their heads and bodies to view more of the virtual world and follow the story within a surrounding graphical space. For such applications, interactive view control is generally assumed as a requirement to be considered a VR experience, and designers look to take advantage of the "immersive" rotational head-tracking capabilities supported through phones and displays such as the Google Daydream, Oculus Go, or HTC Vive.

However, while many designers often assume the use of VR where users stand and are free to physically turn without constraints, this excludes many commonly desired usage settings where the user may wish to remain seated, such as the use of VR while relaxing on the couch or passing the time on a plane during a flight. For such situations, it may be uncomfortable to have the head and body physically turned beyond a certain point, as too much turning could cause neck strain or awkward twisting in a non-rotating seat. This is especially problematic for the use of mobile VR applications that are expected to be used "on the go" and in a wide variety of usage settings that might not match the intended freedom for physical rotation initially planned for by application designers. While one potential solution could be to allow button or joystick-based rotation to override the use of physical interaction, many immersive story experiences are not designed to require additional controller input, and the simplicity of natural view control is often seen as one of the primary appeals of light-weight immersive experiences.

To address this problem, our research investigates the use of a technique that automatically rotates the virtual scene to help redirect the viewer's physical rotation while viewing immersive narrative experiences. By slowly rotating the virtual content, viewers are encouraged to gradually turn physically to align their head positions to a more comfortable straight-ahead viewing direction in seated situations where physical turning is not ideal. The approach is similar to other techniques such as *redirected walking* [26], which gradually rotates the view in VR applications that involve real-world walking, or *washout filters* [4] used with motion platforms to gradually move the platform to its default state so it's ready to simulate future movements. Our work is novel in studying the design of a related technique that can be applied to immersive narrative experiences. Because immersive movies and interactive narratives often have action and character movement unfolding over a period of several minutes, more time is available to account for gradual viewing adjustments that might otherwise feel jarring in other types of immersive applications.

Using the approach of gradually rotating back to the neutral orientation, a VR experience is able to simulate a large range of virtual rotation while limiting the total amount of physical rotation needed to enjoy the narrative. In this paper, we expand on preliminary work on this approach previously presented by an extended poster abstract [34]. We present our advancements in technique design along with an evaluation by controlled user studies focusing on assessing how the redirection approach affects user comfort, sickness, the amount of physical rotation, and likelihood of viewers noticing the rotational adjustments. Our experiment studies the approach across three immersive narrative movies, and it compares multiple parameterizations of the technique along with a control condition without rotational adjustments.

2 RELATED WORK

The presented research builds off of prior research in immersive movies, most notably with regard to techniques that aim to direct attention or manipulate rotation during VR experiences.

2.1 Immersive Movies and 360 Video

Immersive movies can have various meanings. A recent media review of various forms of interactive and immersive applications and videos discusses a variety of fundamental differences in types of interactivity and storytelling strategies among commercially available media [41]. For the purposes of our research, we focus on 360-degree videos and experiences that allow viewers to interactively adjust the view to look around while the video plays. Such

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videos can be captured from the real world using 360-degree cameras (e.g., [9, 18]) or synthetically crafted using computer-rendered imagery and animated characters (e.g., [2, 5]). While traditional video assumes a fixed viewpoint, 360 video consists of visuals in a surrounding field of regard beyond what can be seen at once with a fixed viewpoint and a standard field of view. Such video can be viewed with an interactive 360 video player that allows users to rotate the field of view as the video plays to control which direction the viewer sees at any given time.

These 360 video players commonly support motion-based or head-tracked controls for interactively adjusting the viewpoint, which makes it possible to easily watch such movies from a mobile smart phone by simply turning the entire body while holding the phone. Providing additional viewing options, numerous commercial head-worn VR displays have become available at affordable prices in recent years. For instance, the Oculus Rift and HTC Vive serve as head-worn displays that can be powered from a standard home computer with sufficient rendering capabilities. Many head-worn options are also designed as light-weight mobile VR options. For example, the Google Daydream and Samsung Gear work by providing a viewing frame and additional motion sensors that combine with a smart phone for the display, and the Oculus Go and HTC Vive Focus serve as stand-alone VR headsets that do not require separate phones or computers.

The availability of VR display options has led to great improvements in accessibility that allow consumers to easily experience immersive movies with little setup, and video producers have taken advantage of the immersive medium to create novel narratives with surrounding content. In this paper, we present a technique for view adjustment that could be applied to either 360 video from real-world camera capture or to synthetic 360 experiences, though our demonstration and evaluation focuses on synthetic narrative videos.

2.2 Directing Attention in Immersive Movies

While immersive movies offer engaging experiences that support viewer choice in which part of the video to watch during a movie, such freedom is also accompanied by challenges. In narrative videos, for instance, viewers might miss important parts of the story if they are not looking in a certain direction at the right time [19]. Lin et al. [16] discussed this issue and studied several approaches to direct attention to a focal point using methods that automatically rotate the camera or add arrows to suggest viewing directions. In related work, Rothe et al. [29] studied lighting, motion, and sound cues to direct attention. They found lighting and movement changes to be effective for influencing viewing.

Methods for guiding attention often look to prior VR techniques (e.g., [22, 23]) for encouraging physical turning in cases where the user might reach the bounds of the physical tracking area, and methods such as distractor objects or hard breaks in the experience added at times when physical turning is needed due to practical constraints of the VR setup. For example, Nielson et al. [19] studied rotational adjustment as well as the use of supplemental visual guidance by an animated firefly (i.e., a type of distractor) in the virtual scene. In related work but with a somewhat different goal, Brown et al. [2] discussed the limitation of immersive videos not supporting multiple viewers together due to VR headsets isolating viewers from each other in the real world. They investigated multi-user immersive narratives and methods to help coordinate attention among multiple people in a shared viewing experience, and they also considered distractors and view manipulations as options.

While our work is related to techniques that aim to encourage the viewer's physical turning, our research differs in that it does not try to direct attention or viewing direction within the virtual environment. Instead, we study an approach that assumes viewer freedom to look around normally and freely, but gradually adjusts the view to encourage the user to make a corresponding physical rotation to support comfortable viewing of the content they want to look at.

2.3 Redirection and Washout Filters

Our approach leverages past research in encouraging physical rotation to correct for practical limitations of physical VR setups. For instance, in VR systems that support real physical walking as a means of travel, an obvious problem is the amount of virtual travel possible will be limited by the size of the tracked physical space. One promising technique for overcoming this problem is *redirected walking* [26], which gradually adjusts the virtual orientation of the scene in such a way that encourages the user to physically turn more or less than they normally would for the desired virtual motion. Many researchers have studied redirected walking and various forms of redirection [20]. Some examples of redirection techniques include rotational manipulations (e.g., [17, 26, 35]), translational manipulations (e.g., [36, 40, 42]), or manipulations of the layout of the virtual environment (e.g., [37–39]). In many cases, users might not even notice the changes or adjustments during the virtual experience [20]. However, these techniques often take advantage of the user's linear and angular motion, altering the virtual environment based on these measures. This prevents a disconnect between the user's visual and vestibular senses, which could lead to VR sickness [1]. Without linear or angular motion, however, these techniques cannot be used effectively.

While most applications of redirection techniques are applied as manipulations to virtual movement during physical movement (e.g., physical walking and turning), researchers have also explored applying redirection techniques for stationary experiences. For example, Sargunam et al. [31] presented a *guided rotation* technique for seated VR that is applied as the user virtually travels through the 3D world. Similar to our approach, the gradual view adjustments encouraged users to physically turn back towards the forward direction. This work studied unconstrained interactive navigation through a virtual environment, and the evaluation showed limitations due to sickness effects and a need for slow rotational adjustments due to the large amount of free rotation common in unconstrained travel. In contrast, this paper focuses on immersive narrative experiences in which the user has head-tracked view control but does not have control of translational movement, which requires new design decisions and has the opportunities for more gradual view adjustments in accordance with the narrative flow. And unlike the method in [31], our presented approach does not require pre-specified points of interest within an immersive experience.

Razzaque et al. [27] also studied rotational adjustment during virtual travel. Their approach determined rotation speed as a function of user-controlled translation speed. This work was demonstrated for CAVE systems that do not fully surround users so as to help prevent users from turning towards a gap (i.e., a missing screen wall) in the display area. The approach we investigate similarly adjusts virtual rotation but is independent of user travel and applied by a custom video player to existing 360 videos. Researchers have explored rotation-scaling methods with similar goals of allowing 360-degree virtual viewing with limited physical rotation (e.g., [15, 24]), and numerous researchers have evaluated the effects of such "amplified" head rotations for user tasks as visual search and spatial navigation (e.g., [11, 14, 25, 31]). Our current paper does not study amplified rotations during physical turning, thus allowing users to turn normally to see different parts of the virtual scene while limiting risks of sickness associated with scaled rotation (see [25, 31]).

Our approach is also similar to the use of *washout filters* [8, 21] applied to motion platforms to compensate for the physical limitations of motion simulation. In virtual simulations, the motion platforms can physically move the user just as the user moves in the virtual experience, but the platform cannot continuously move in a single direction (e.g., the platform cannot move up forever due to the physical limits of the mechanism). Washout filters gradually return the platform back to the default position and orientation during periods of non-motion so it is ready for future motions. If the resetting motion is gradual enough, the motion may not be detectable to the user, though the threshold for detection can vary based on the type of motion and the specifics of the simulation [30].

2.4 Detection of Rotational Adjustments

Our method employs rotational adjustments about the vertical axis (i.e., yaw rotations) as a means of resetting head orientation. For additional virtual rotation added along with a corresponding physical rotation, redirection studies suggest users may have difficulty detecting manipulations between approximately 11% and 49% more added yaw rotation [3, 12, 36]. Studies with washout filters are more concerned with motion over time, and studies of detection of yaw motion with motion simulators estimate detection thresholds in a range approximately between 2.2–3.2 degrees per second [10, 28].

Samji et al. [30] found evidence that perceptual thresholds can be affected by whether the user is in control of the rotation with motion platforms. Interestingly, the results showed that users were more sensitive to noticing motion adjustments when *not* controlling the motion. This could have implications of whether the estimations of detection thresholds for rotational gains from studies based on redirected walking could apply to passive viewing experiences. However, immersive narrative experiences often have periods that encourage actively looking around as well as periods where the story requires little change in gaze direction.

Also regarding detection, Schmitz et al. [33] provide evidence that a scene redirection technique for immersive movies may be viable. In their paper, they discuss detection of a break in a user's presence or engagement in an experience [33]. Their research suggests that traditional detection thresholds may often be too conservative for interactive experiences that demand a user's attention. They found that they were able to apply rotation gains significantly greater than traditional detection thresholds without breaking the user's immersion. While their research covers redirected walking techniques and rotational gain, the same concept may apply to immersive movies in VR, which also frequently demand a user's attention and provide a situation that may distract the user from scene rotation.

3 Technique

Our scene rotation technique uses an approach similar to that found in motion simulator washout filters but for VR movies with head-worn displays. This washout technique assumes a default head orientation, which is assumed to be a comfortable viewing position where the user is looking straight ahead. We call this the *neutral* position. The technique is designed to reduce the amount of time spent physically turned away from the neutral position based on the premise that too much time spent turning towards the side can cause physical discomfort in some seated usage scenarios. Thus, our technique is initiated after the user rotates her head to an extreme enough angle and remains for a given amount of time. After turning to the side, the technique will slowly rotate the virtual scene such that the viewer can maintain focus on the same point of interest while that focal point is brought back to align with the neutral physical position. The technique accomplishes this by slowly rotating the entire scene of the immersive movie, causing the user's virtual viewing direction to be shifted directly in front of her. This allows the focal point (i.e., wherever the viewer was looking) of the immersive movie to come towards the front of the user so it can be viewed in a comfortable position.

If the focal point again moves to one side of the user, the same process can be repeated. Figure 1 shows an example of how the process works and how the scene is rotated to shift the focal point. While we use the term *focal point* to refer to any region of interest where the viewer wants to maintain attention, note that the technique

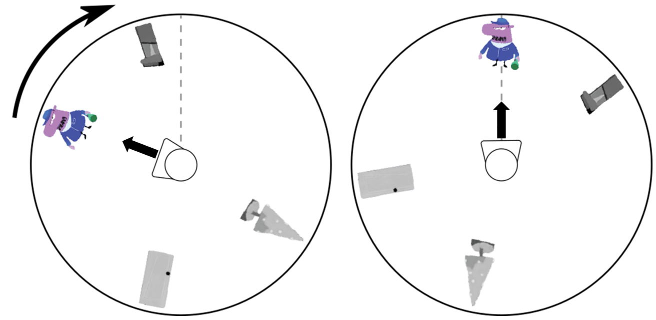

Figure 1: Example Scene Rotation. The redirected scene rotation adjusts the virtual viewing orientation so the user can maintain attention in the virtual direction of interest (in this case, towards the colorful purple and blue character). Not that rotation is triggered based on physical rotation and does require known or specified points of interest from the video.

does not require any predetermined or user-defined focal points in the video. The technique is activated entirely based on physical head orientation and a timer. This provides flexibility to allow the rotational correction to work regardless of what portion of the video the user is interested in.

Our implementation of the technique uses an easing function to reduce any visual-vestibular discrepancies of the rotation. We used a Bézier curve with flat tangents at the endpoints to interpolate the rotation of the scene and ensure smooth acceleration. Given the angle of the user's gaze, a corresponding washout rotation angle is calculated that will rotate the scene to such a direction that the user's head returns to a neutral orientation. In our implementation, the magnitude of this rotation angle determines the duration of time over which the scene will rotate. Thus, there is a direct relationship between rotation angle magnitude and rotation duration, which ensures that the scene always rotates with the same average *rotation speed* (which can be parameterized according to preference or requirements for a specific video). It would also be possible to implement a dynamic rotation speed based on the magnitude of the physical head rotation away from the neutral direction, so a greater head rotation would cause faster rotation speed. This could be useful in cases where a video's focal point moves quickly, so the scene would need to rotate quickly for the user to be able to follow the focal point.

The curve used is a cubic Bézier curve defined by the equation:

$$r(t) = (1-t)^3 P_0 + 3(1-t)^2 t P_1 + 3(1-t)t^2 P_2 + t^3 P_3$$

with control points:

$$P_0 = (s_0,\ \alpha_0)$$
$$P_1 = ((s_f - s_0)/2,\ \alpha_0)$$
$$P_2 = ((s_f - s_0)/2,\ \alpha_f)$$
$$P_3 = (s_f,\ \alpha_f)$$

The duration between the *start time* s_0 and *end time* s_f is determined by the *rotation speed* parameter so that the speed is constant. The *starting angle* α_0 is the video's current rotation, and the *final angle* α_f is the angle that will return the user's head to the neutral physical direction.

The washout approach can be implemented as a wrapper for existing 360 video players or as a custom video player that can control the video rotation using both head tracking data and the technique's automated rotation. The player needs to track where a user has been looking and for how long. If the user has looked at an extreme enough angle (we call this angle the *angle threshold*) for

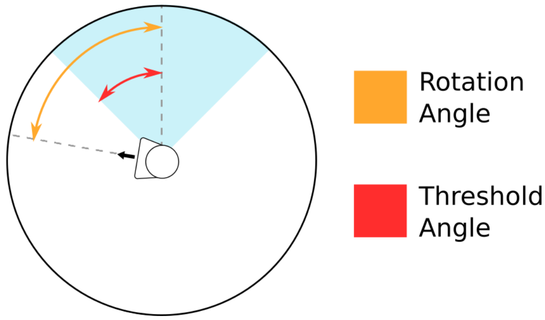

Figure 2: Example showing how *rotation angle* is determined based on *angle threshold*. The blue region is the physical forward direction with a size of twice the *angle threshold*. If the user's physical rotation extends beyond the threshold for a time longer than the *rotation delay*, the *rotation angle* is calculated as the angle between the user's direction and physical forward.

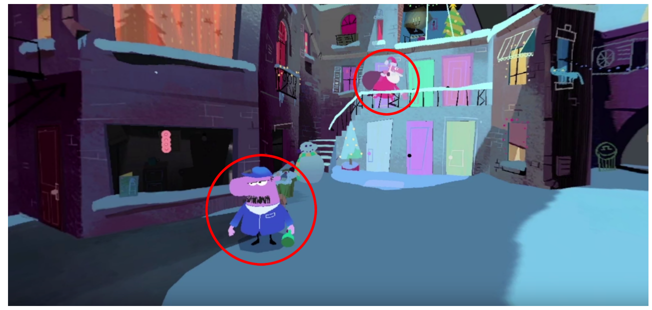

Figure 3: Example image from *Special Delivery*, a 360 movie from Google Spotlight Stories (single frame used under fair use for research and demonstration purposes). The focal point of the story follows two main characters (circled in red—the circles are not a part of the video). Since the viewer is expected to turn to follow these two characters together in 360-degree rotation, the redirection technique can assist in rotation to neutralize the need for physical turning.

a long enough time (we call this time the *rotation delay*), then the scene rotation is triggered. The appropriate scene rotation angle can be calculated as the difference between the current direction and the neutral direction, and the scene then begins rotating at the specified *rotation speed*. Figure 2 shows an example of the scene rotation angle.

The following sections describe an evaluation with different variations of the washout settings, which helped us to determine recommendations for implementation settings. While preferences may vary by user and video, we recommend an *angle threshold* of approximately 45 degrees, a *rotation delay* of approximately 2–4 seconds, and a *rotation speed* of approximately 3 degrees per second.

Lastly, the washout technique includes a *rotation override* feature such that if the user rotates his or her head faster than a specified speed while the scene is rotating, the technique's automated rotational adjustment is temporarily stopped. We discovered the need for this override from preliminary user testing, in which some users complained that the scene would continue to rotate after they had stopped moving their head or while they were trying to shift their gaze to look at another point in the scene. By using this scene rotation override, we reduce the likelihood of any unnecessary or undesirable scene rotation from occurring. Thus, the rotation override feature is automatically triggered by the user making a fast physical rotation. While different approaches for implementation would work for the override check, we wanted the user to be able to immediately regain full control of rotation as quickly as possible. Therefore, in our implementation, the override check was conducted each frame with an activation minimum of 1 degree of change between frames to trigger an override. When triggered, the override feature temporarily interrupts the rotational adjustment by resetting the timer for the rotation delay. After a fast head movement that triggers the override, the technique will be reset and can again activate based on the rotation delay period and angle threshold.

4 Evaluation

To evaluate the technique, we conducted a controlled experiment to: (1) gauge overall feasibility and effectiveness of the washout technique for scene rotation and (2) determine the effects of rotation speed and delay-angle threshold settings on user experience.

4.1 Research Goals

The goal of this research is to evaluate the effectiveness of a rotation washout technique for viewing immersive video while limiting the amount of physical rotation. We also sought to contribute evidence of the most relevant factors for implementing this approach and to determine the implications of such factors on user comfort, sickness, and distraction.

The presented research aims to assess whether the approach is feasible at a coarse level before attempting to precisely optimize settings for parameters such as activation delay, activation angle, and rotation speed. Our goal is not to determine detection threshold for noticing rotational manipulations applied to immersive cinema, but instead to determine the factors that are likely the most important for optimizing a rotation washout technique for immersive movies. Due to the variation in movies as well as in the different contexts used to evaluate estimation thresholds for different types of rotational adjustments, it is difficult to accurately estimate a rotational speed that would not be noticeable for all cases. Further, the amount of rotational adjustment needed for immersive movies would depend on the amount of physical rotation needed to follow the story. Movies involving large amounts of rotation or movement of content/characters all around the user would benefit from more aggressive algorithms with faster rotational updating to keep the focal point in front of the user, but faster rotations may be distracting or induce sickness or disorientation. Thus, due to the complexity of relevant factors, our evaluation chooses to test variations of the washout technique with settings derived from the results of prior studies as well as our own pilot studies with participants [34].

Following a previous review of immersive stories and videos [41], we found that yaw rotations are the most common type of rotation needed to follow changes in commercially-available immersive applications. Yaw rotation is also most notably restricted in seated VR, which is one of the primary motivating scenarios for study the washout technique. For these reasons, our evaluation only studies the technique applied to yaw rotations.

4.2 Experimental Design

The experiment evaluated the effects of two *rotation speeds* and two parameterizations of the rotation delay and angle threshold settings, which we call the *delay-angle threshold*. The decision to combine the delay and angle threshold parameters is based on the fact that their required settings are closely linked for use cases that aim to limit physical rotation from the neutral direction. This is because the farther the user must turn his or her head to activate the scene rotation (i.e., angle threshold), the less time the user would want to maintain that physical rotation before the adjustment starts (i.e., delay threshold). Similarly, since a small physical turn away from the forward direction is expected to be more comfortable than larger turns, a lower angle threshold should require a longer delay before activating the scene rotation.

Figure 4: Example image from *Rain or Shine*, a 360 movie from Google Spotlight Stories (single frame used under fair use for research and demonstration purposes). Here, a girl is seen under an isolated rain storm.

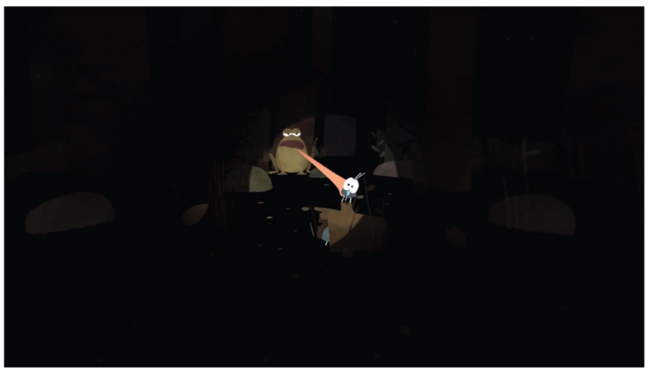

Figure 5: Still frame from *Buggy Night*, a 360 movie from Google Spotlight Stories (single frame used under fair use for research and demonstration purposes). This video was mostly dark with the exception of characters eyes and areas illuminated by a spotlight moving over the environment.

For the rotation speed factor, the *slow* variation used an average speed of 3 degrees per second, and the *fast* variation used an average speed of 13 degrees per second. These speeds were chosen as two extremes, where the lower speed approximates the threshold for detection of yaw motion from prior studies with washout filters [10, 28], and the higher speed was determined from pilot studies as a speed that would almost certainly be noticeable in all cases but would also quickly return the head orientation back to the neutral direction.

These pilot studies were conducted to collect feedback on various technique settings using a combination of interviews and questionnaires similar to those used in the full experiment. The pilot study was conducted with five university students using the same videos as the experiment. The pilot study included speeds of 5, 20, and 40 degrees per second in the tests. User feedback indicated that the 20 and 40 degrees per second settings were too distracting and felt uncomfortable, and the slowest speed was strongly preferred. Given the strong negative feedback for 20 degrees per second, we concluded that 20 degrees was too high to be practical, but we still wanted to study a faster speed for the experiment. We decided to take an approximate halfway point between the 5 and 20 speeds, and therefore chose a speed of 13 degrees per second as the fast speed for the study.

For the delay-angle setting, one variation had a delay of 2 seconds with an angle threshold of 45 degrees to each side, and the other had a delay of 4 seconds with an angle threshold of 25 degrees to each side. We derived the angle thresholds from feedback during our pilot studies about approximate thresholds for comfort without neck strain during movie viewing, where we informally asked participants indicate viewing angles they would feel uncomfortable holding for extended time. We chose 45 degree threshold as the maximum to test since turning beyond 45 degrees can be uncomfortable if held, and we chose 25 degrees for a tighter threshold that might keep participants closer to the neutral viewing direction at the cost of greater rotational interference.

The delay values were similarly chosen based on observations of viewing behaviors such that the 2 second delay window would allow enough time to look around without accidentally triggering the auto rotation, and the 4 second delay was chosen for the smaller angle threshold based on the reasoning that users would not mind staying at a smaller angle for a longer amount of time.

The experiment followed a mixed design in which *rotation speed* was tested within subjects and *delay-angle threshold* was tested between subjects. We chose to test rotation speed within subjects because we believed it would be the most influential parameter, and thus it would be best for users to be able to directly compare the different speeds. As a control condition, all participants also viewed a video without the washout technique. Thus, the experiment followed a 2x2+1 mixed design.

According to this design, each participant viewed three different videos: one in the control condition, one with the washout technique with fast rotation, and one with the washout technique with slow rotation. Each participant experienced both variations of the washout technique with the same assigned version of the delay-angle threshold. We used a Latin square design to balance the order in which the techniques and videos were presented to the users. This helped to reduce any bias that the order of the videos or techniques might have on the experimental results.

The immersive movies used in the study were taken from Google Spotlight Stories, which focuses on production of 360-degree storytelling for mobile platforms. The three movies were selected to provide variability in our evaluation: *Special Delivery*, *Rain or Shine*, and *Buggy Night*. These are all short, good-natured, digitally animated narrative 360 videos lasting between approximately 3 and 5.5 minutes. The movies are freely available online [1]. *Special Delivery* is about a grumpy animated character attempting to catch Santa Claus (see Figure 3). *Rain or Shine* is about an unlucky girl whose sunglasses cause a rain cloud to form above her, bringing a constant downpour (see Figure 4). *Buggy Night* is about a group of small bugs in the dark attempting to escape being eaten by a frog (see Figure 5). The washout approach is designed to assist with viewing 360 movies where content moves around the user in the horizontal direction; therefore, the selected videos did have animation that would require turning to see different focal areas, but of course the movies were different in the types and amount of movement.

4.3 Apparatus

Our washout technique was implemented in a custom 360 video player in the Unity game engine. The evaluation used an HTC Vive headset (with approximately 110 degrees of diagonal field of view) with rotational head-tracking enabled. Positional tracking was not used, as the test 360 videos did not support positional updates. The VR experiences were run from a desktop computer running Windows 10 with an Intel Core i7 processor and Nvidia GeForce GTX 970. Because we were interested in seated situations where physical rotation is not ideal, participants sat in a non-rotating chair during the study. Though our research is also largely motivated by the use of mobile VR, the dedicated VR headset and desktop computer setup was used so the experimenter could easily monitor and guide the study procedure. To do this, the view from the Vive

[1] https://atap.google.com/spotlight-stories/

was also displayed on a separate computer monitor to allow the experimenter to follow the study procedure.

4.4 Procedure

The study was approved by our organization's institutional review board (IRB) for ethical research. All participants provided written consent prior to beginning the study procedure. Then, each participant filled out a background questionnaire, which included questions about the participant's age, gender, occupation, education, and experience with VR.

The experimenter then explained that the user would be watching a series of three VR videos and providing feedback. Participants were not told about the rotation techniques or given any special instructions to pay attention to anything abnormal during the experience. We chose to do this because we were interested in whether participants would notice the scene rotation at all. Before watching any of the videos, participants were first familiarized with the headset and VR by briefly viewing a sample 3D environment. Each participant was given as long as he or she desired to view the environment and to get used to the system and using head-tracked viewing.

Next, participants watched the three movies in the order and with the corresponding techniques based on the experimental design. Before starting each video, the experimenter asked each participant to relax and face forward in the chair to establish that each viewing started from a similar posture. After each video, the participants completed a questionnaire that asked about comfort, preferences, and various symptoms related to simulator sickness. The experimenter then conducted a short interview with the following questions:

1. How was the experience?
2. Did you notice anything interesting about the experience?
3. Did you feel distracted at all during the experience?
4. Did you feel nauseous during the experience?

The questions were intentionally vague to avoid informing the user about the scene rotation technique if they did not notice it themselves. After watching all three videos, participants completed an experience survey, which asked them to rate various aspects of each of the videos they watched. Finally, another informal interview was conducted in which the following questions were asked of the participants:

1. Were you able to follow the focal points easily during the videos?
2. Did you notice anything strange with how the videos moved?

After these questions, the experimenter explained to the participants the technique being tested and gathered feedback on how participants felt about the different variations (if they noticed any differences).

4.5 Participants

The study included 18 participants (11 female and 7 male). Ages ranged from 18 to 46 years, with a median age of 21. All participants were well-experienced with computers, with a median self-reported weekly computer usage of 50 hours and a mean of 49 hours. All participants reported having at least some experience with 360 videos, whether in VR displays or simply viewed on a phone or tablet. When asked to rate their experience with VR on a scale from 1 to 10, five participants rated themselves 1–3, eight participants rated themselves 4–7, and five participants rated themselves 8–10.

5 Results

We report results based on the amount of physical rotation measured with the system's head tracking data, the perceived comfort and sickness based on questionnaires, and whether participants reported noticing the rotational adjustments.

5.0.1 Analysis Methodology

We employed multiple types of statistical tests to analyze the results in accordance with the mixed experimental design. For each outcome, we first tested for effects due to the variations of the techniques with (i) the two levels of angle-delay threshold and (ii) the two rotation speeds, and we also included (iii) video order in all tests to account for possible interactions of the technique variations with the different videos themselves. Thus, we used three-way mixed ANOVA tests. However, none of the tests for any of the outcomes detected evidence of significant effects of delay-angle threshold or video ordering. For this reason, we do not include reports of these three-way tests in this paper for the sake of simplification and readability.

We instead only report the tests comparing the control conditions to those using the washout technique. For these tests, we had to collapse the delay-angle factor since it was varied between participants while the control and speeds were experienced in a repeated-measures fashion. Since the previous tests found no effects of delay-angle threshold for any of the outcomes, collapsing this factor should have little bearing on the results. Thus, we report two-way mixed ANOVA tests that account for the different repeated-measure variations (*control*, *slow*, and *fast*) along with video order again included as a between-subjects factor.

All ANOVAs were conducted with type III sum of squares, and the assumptions for parametric testing were met for all measures with one exception for sickness ratings, which we explain in the corresponding subsection.

5.0.2 Physical Rotation Results

We analyzed physical head orientation to assess whether the washout technique was effective for reducing the amount of physical rotation during video viewing. Throughout the user studies, our implementation recorded the user's head orientation over time. We are primarily concerned with rotation about the vertical axis (i.e., yaw), as this is the metric affected by the scene rotation, and yaw rotation was the primary type of rotation needed to follow the activity in the videos (we observed little pitch and roll rotation by participants). Therefore, our analysis of physical rotation only considers yaw.

For analysis, we calculated the average unsigned rotation angle of the participant's physical heading away from the forward physical direction indicated by the default original orientation at the start of each video. To calculate this, our technique recorded the current time in the video and the participant's head rotation at that time for every frame. We then normalized the rotation values by multiplying the absolute value of each recorded rotation value by the time delta for that frame. These normalized values were summed and divided by the total video duration to produce the mean rotation amount. So, for example, if the participant spent 1 minute looking at 0 degrees (i.e., straight ahead) and 1 minute looking at 90 degrees to either side, then the average rotation angle away from the physical forward direction would be 45 degrees.

In addition, we calculated the percentage of time per video that participants maintained a large rotation away from the forward direction. For this measure, we consider rotations beyond 45 degrees from the straight-ahead direction (to either the left or right) to be a large rotation. The 45-degree threshold was chosen on the basis that maintaining a total 90-degree angular range of forward viewing would allow fairly comfortable viewing while still accommodating some head movement to look around.

The results show strong evidence that the technique was effective for its intended purpose of reducing the amount of physical turning while watching the immersive videos. Figure 6 shows the physical rotation results for amount of rotation and time beyond the forward threshold. The figure shows average values to aid comparison of the slow and fast speeds of the washout technique along with the control condition without any additional rotational manipulation.

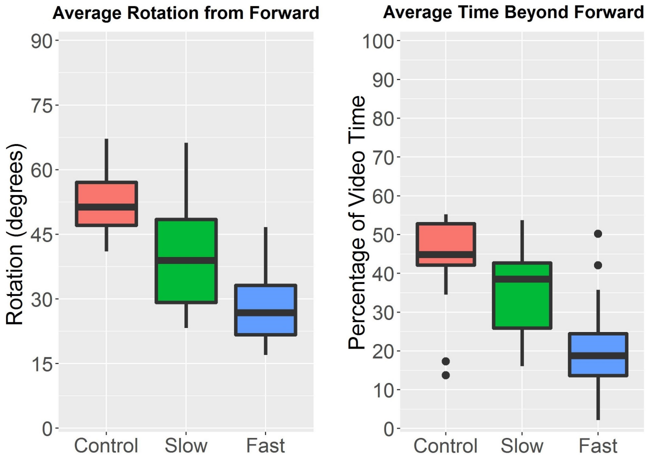

Figure 6: Results for physical rotation for the control condition without the washout filter compared to the videos using the slow and fast variations of the washout filter. The left plot shows the average amount of unsigned physical rotation away from the forward direction. The right plot shows the percentage of video time the participants were turned at least 45 degrees to either direction from the physical forward direction.

For simplicity, these averages collapse the delay-angle threshold variations as well as the different videos themselves.

The two-way ANOVA found a significant effect of technique on physical rotation amount with $F(2,30) = 27.34$ and $p < 0.001$, and posthoc Bonferroni-corrected t-test found the *control*, *slow*, and *fast* variations were all significantly different from each other. In other words, both variations of the washout technique led to significantly less physical rotation than the *control*, and the *fast* version had significantly less rotation than the *slow* version. Pairwise effects were large with Cohen's d ranging from 1.05 to 2.85. No effect was detected due to video order, and no interaction was detected.

As seen in Figure 6, the results for rotation time away from the forward direction followed a similar pattern, and a two-way ANOVA found a significant effect of technique with $F(2,30) = 17.73$ and $p < 0.001$. A posthoc Bonferroni t-test found the *fast* washout technique to have significantly less high-rotation time as compared to the *control*. However, note the four outlier points shown in Figure 6 (right) for the *control* and *fast* conditions. These outliers were identified following the 1.5 IQR rule (i.e., outliers are flagged if they are at least 1.5 of the interquartile range beyond the lower or upper quartiles). With these outliers removed, the test yielded $F(2,22) = 33.94$ with $p < 0.001$, and all posthoc Bonferroni comparisions were significantly different with large effect sizes (Cohen's d ranging from 1.19 to 3.45). For both analysis cases, no effect was detected for video order, and no interaction effect was found for rotation time.

5.1 Comfort and Sickness

For preferences based on comfort and sickness, we were most interested in participants' direct comparisons of experiences with and without the washout technique. For this reason, measures for comfort, sickness, and preference were based on a questionnaire asking for relative ratings of the three video experiences rather than from standardized questionnaires (e.g., SSQ [13]) that are often more challenging for repeated-measures comparisons due to compounding sickness effects from continued use of VR over time. The questionnaire consisted of questions asking for side-by-side ratings of the three experiences with the control, fast, and slow variations on a scale from 1 (lowest) to 10 (highest) for each factor. This method provides an approximation but lacks standards to aid direct comparison with other standardized scales. While we acknowledge that our use of custom questions are not a full validated method allowing detailed breakdown of different sub-components, this approach provides a fast and simple assessment on meaningful measures.

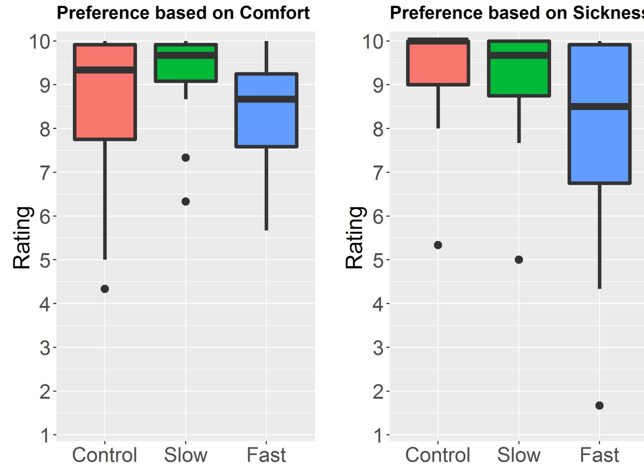

Figure 7: Results for preference ratings based on questions for comfort (left) and sickness (right). Higher ratings indicate more preferred variations.

A measure for comfort was calculated by averaging responses for three questions that asked about preference with respect to comfort, fatigue, and neck strain. The results are shown in Figure 7 (left). A two-way mixed ANOVA failed to detect differences in comfort preferences due to either the three variations or the video order.

A measure for sickness was calculated by averaging responses for three questions that asked about preference with respect to nausea, dizziness, and headache. See Figure 7 (right) for the sickness results, where higher values indicate greater preference (i.e., higher is better with regard for sickness). We note that the data for the sickness results was skewed due to a ceiling effect for positive ratings and a small number of low and middle ratings, and transformations were unable to correct the problem for parametric testing. However, due to the mixed experimental design, we were not able to identify an appropriate non-parametric alternative for data on this scale. For this reason, and because ANOVA tests are often robust to violation of the normality assumption [32], we report the results of the parametric approach to aid in assessing differences. The two-way mixed ANOVA found a significant effect of technique on sickness rating with $F(2,30) = 8.29$ and $p = 0.001$. A posthoc Bonferroni t-test found the *fast* version of the washout technique to be significantly worse than both *slow* and *control* conditions (medium effect sizes with Cohen's $d = 0.67$ and $d = 0.78$, respectively). No effect was detected for video order, and no interaction was detected.

Thus, although the comfort results varied greatly by participant, the sickness results demonstrate risks of employing the washout technique with fast speeds for rotational adjustment. In comparison to the control condition without the washout technique, the slower variation of the washout filter was not found to be significantly different in terms of either comfort or sickness.

5.2 Detection of Rotational Adjustments

Based on participant responses to the sequence of questions described in Section 4.4, we determined whether or not participants noticed the rotational adjustments during trials with the washout technique applied. We analyzed the likelihood of detecting the added rotation based on the number of positive and negative detection occurrences. These analyses only considered trials with the washout filter applied.

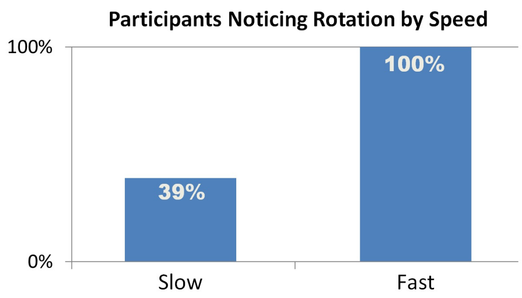

Figure 8: Percentage of participants detecting technique rotation.

Due to the mixed experimental design, we conducted separate tests for the between-subjects and repeated-measures factors of technique configuration. To test for differences in detection likelihood for the two variations of the *delay-angle threshold*, we conducted a Fisher's exact test because this was a between-subjects factor. The test yielded $\chi^2(1) = 0.13$, finding no evidence of a difference due to *delay-angle threshold*.

To test for differences due to *rotation speed*, we conducted a McNemar test since speed was varied within subjects. The test found a significant effect with $\chi^2(1) = 9.09$ and $p = 0.002$. As expected, all participants noticed the rotational adjustment with the *fast* variation; however, only 39% of participants (7 of 18) noted the rotational adjustment in the slow condition (see Figure 8). This result suggests that, for many viewers, the use of the washout technique with a low speed parameterization may not be noticeable. With a gradual adjustment and the distraction of the video's narrative and visual animation, the washout approach could have minimal effects on distraction.

6 Discussion

Our research explores the use of a scene rotation technique that uses a washout filter to redirect a viewer's gaze over time while watching immersive videos from a seated position where turning is not ideal. We tested the feasibility of the technique using different *rotation speed* and *delay-angle threshold* settings, and we compared the technique to a control condition without the technique. From the physical rotation data collected from the user study, we found strong evidence that the rotation technique was effective at significantly reducing the amount of physical turning away from the forward direction (see Figure 6). While the purpose of the technique was to reduce awkward rotation or neck strain for the purpose of aiding comfort for use of seated VR, the results did not show significant differences in comfort ratings (see Figure 7, left). However, the similarity in ratings might be due to the relatively short period of time watching the videos in the study. And while not significantly better, the slow version of the washout technique did have high comfort ratings compared to the fast version.

On the other hand, the fast version of the technique had noticeable drawbacks. While faster rotation speeds led to significantly less physical rotation (see Figure 6), it also resulted in significantly worse sickness ratings (see Figure 7, right). It is not surprising to see negative effects of added rotational adjustment, as prior studies with automated rotation have found similar results (e.g., [31]), but one of our goals was to empirically assess potential limitations for variations of the washout technique.

We did not find significant differences between the two delay-angle threshold settings tested, though we sometimes observed that the lower *angle threshold* (25 degrees) tended to activate the scene rotation at times when it was not necessary, but this did not produce any noticeable effects in our measures. Thus, based on the results of our evaluation, we recommend 45 degrees as an approximate *angle threshold* to allow sufficient freedom in naturally looking around without undesirably activating the scene rotation. Our research did not identify any evidence of problems or suggestions for improvements in the *rotation delay* value (2–4 seconds) before the automated rotation activates, as both settings seemed to work well.

We emphasize that our recommendations for technique settings are limited by the specific values empirically tested; these recommendations are shared as approximations rather than optimal configurations. Based on all the measures together, we recommend a variation of the washout technique for seated VR that uses a relatively slow *rotation speed*. Our evaluation found a speed of 3 degrees per second to demonstrate success in significantly reducing physical rotation without producing the significant problems with sickness observed with the fast variation. As previously mentioned, this speed was chosen based on previous studies of motion detection using washout filters with motion platforms (i.e., [10, 28]). The context is different, however, since motion platforms move on their own while the rotational motion with our technique is due to the user physically turning themselves. But the speed did seem appropriate for an approximate threshold of noticeability with our technique and while watching immersive videos, as indicated by the detection results of only 39% of participants noticing the rotational adjustment in the slow trials. While it was not our goal to "trick" users into not noticing the rotation, and it is not a problem if people know they are turning, it is interesting that users may fail to notice the rotation. Failure to detect the rotational adjustments might indicate a lower likelihood of the technique being distracting to the viewing experience, though this is not known for certain.

The general positive results for the washout technique with the slow rotation speed also do not necessarily mean the technique will be preferred by everyone, and the recommended configurations from our evaluation are not intended to be interpreted as optimal settings or firm perceptual thresholds. As seen in the preference ratings for comfort and sickness (see Figure 7), preferences and effects vary. People are different; some are more likely to get sick with rotational adjustment, and some are more likely to be distracted. While impressions about our technique were generally positive, some people may prefer the discomfort of neck strain or awkward physical rotation in seated scenarios over techniques that impose rotational adjustments. Finally, while our evaluation included three different videos to provide some variety in testing, how suitable the technique would be for any given video may depend on the characteristics of the video. Different speeds of moving characters or the number of possible points of interest in the video might require further investigation.

7 Conclusion

We present an automated rotation technique for use of VR in seated positions to reduce the amount of physical turning necessary while viewing immersive movies. When the user rotates his or her head beyond a certain angle, the technique rotates the scene to bring the area of attention toward the user's physical forward direction. The results of the evaluation are promising for future use of the technique, especially for the intended use case of situations where a user is not able to physically turn or move about an environment. While our evaluation provides recommendations for parameterizations of the technique, future study would help to refine the preferred settings. For example, slower rotation speeds would likely further reduce the chances of the automated rotation being noticeable for the user. Additionally, it would be interesting to explore the effectiveness of the washout approach for longer immersive movies and for other types of VR games or immersive experiences. Further, it may be possible to allow faster rotation speeds while still limiting problems with increased sickness by using sickness mitigation technique studied by other (e.g., field of view reduction [6, 7]).

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