Amplified Head Rotation in Virtual Reality and the Effects on 3D Search, Training Transfer, and Spatial Orientation

Eric D. Ragan, Siroberto Scerbo, Felipe Bacim, and Doug A. Bowman

Abstract— Many types of virtual reality (VR) systems allow users to use natural, physical head movements to view a 3D environment. In some situations, such as when using systems that lack a fully surrounding display or when opting for convenient low-effort interaction, view control can be enabled through a combination of physical and virtual turns to view the environment, but the reduced realism could potentially interfere with the ability to maintain spatial orientation. One solution to this problem is to amplify head rotations such that smaller physical turns are mapped to larger virtual turns, allowing trainees to view the entire surrounding environment with small head movements. This solution is attractive because it allows semi-natural physical view control rather than requiring complete physical rotations or a fully-surrounding display. However, the effects of amplified head rotations on spatial orientation and many practical tasks are not well understood. In this paper, we present an experiment that evaluates the influence of amplified head rotation on 3D search, spatial orientation, and cybersickness. In the study, we varied the amount of amplification and also varied the type of display used (head-mounted display or surround-screen CAVE) for the VR search task. By evaluating participants first with amplification and then without, we were also able to study training transfer effects. The findings demonstrate the feasibility of using amplified head rotation to view 360 degrees of virtual space, but noticeable problems were identified when using high amplification with a head-mounted display. In addition, participants were able to more easily maintain a sense of spatial orientation when using the CAVE version of the application, which suggests that visibility of the user's body and awareness of the CAVE's physical environment may have contributed to the ability to use the amplification technique while keeping track of orientation.

Index Terms—Virtual reality, spatial orientation, rotation amplification, 3D interaction, search, cybersickness

1 Introduction

Virtual reality (VR) systems can provide high-fidelity simulations of visual, auditory, and haptic sensory stimuli to enhance the perception of synthetic, computer-generated environments. In many VR scenarios, the user needs to be able to look around (i.e., control the orientation of the viewpoint) in a fully surrounding virtual scene while also maintaining a sense of spatial orientation in the environment. For example, many first-person games involve looking around to monitor for enemies while continually traveling in an intended direction towards a target destination. As another example, a training simulation involving room-clearing might require trainees to not only move through a virtual building, but to also look quickly in multiple directions to ensure that a room is clear before moving on.

However, it is not always possible to support 360° viewpoint control with fully natural head movements—this would require a fully surrounding display (i.e., a display with a 360° field of regard). Tracked head-mounted displays (HMDs) and six-sided CAVE-like displays do meet this requirement, but such systems are not always ideal. For instance, HMD use is not always desired because it blocks off users from the real world, and full surround-screen systems are not always practical due to cost, space, and complexity. Additionally, the most realistic interactions might not always be preferred [8]. For example, even in systems supporting full 360° viewing, users may not always want to continually use full physical rotation; anecdotally, we have observed that many VR users often choose to rely on virtual navigation techniques (e.g., joystick control) more than physical movement. This could be attributed to convenience, accessibility, or laziness, and similar preferences might be the norm for home VR use with currently available commercial VR devices.

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As an alternative to traditional fully-tracked rotational viewing, some have suggested the use of amplified head rotations as a semi-natural way to control viewpoint orientation in VR systems without a 360° display range (e.g., [26, 21]). The idea is to map the user's physical head rotation to a larger rotation of the virtual camera by applying a simple scaling factor or a more complicated non-linear mapping [26]. For example, in a three-screen VR system with a 180° horizontal viewing range, the user's head turns might be amplified two times (2x) so that the 360° virtual environment could be seen with head movements alone.

In this paper, we present a controlled experiment in which we evaluated the effects of rotation amplification on spatial orientation in a 3D search task. Due to the importance of VR for training systems, we studied training transfer by testing the implications of transitioning users to traditional unamplified viewing after practicing the search task with amplified head rotations.

The use of VR for training of real-world tasks, skills, and decision-making has become popular in a variety of domains (e.g., [3, 53]). It is often desirable for systems training real-world tasks involving body movements to use the same natural, high-fidelity movements during training, as it is believed that this will increase training transfer for navigation and orientation [40]. Because it uses physical head movements for view control, amplified head rotation could provide higher-fidelity control than joystick or mouse techniques, and the more natural interaction might have benefits for training transfer. However, amplification also presents an unrealistic mapping between body movements and viewpoint changes to the trainee, which could cause disorientation or negative transfer effects.

To study these issues, we designed a controlled experiment involving 3D search in a maze-like environment that required users to maintain spatial orientation for optimal search (Figure 1 shows an example of the search environment). This paper is an updated and extended version of a previous work-in-progress conference paper [9] that discussed the research method and preliminary results. In the current paper, we present the results of the full study with a complete presentation of results and extended discussion.

2 Related Work

VR systems often take advantage of enhanced displays and allow users to interact via natural physical body movements. A number of studies

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Fig. 1. A user selecting a target object on a shelf in the maze-like virtual environment used for the experiment.

provide data about how display properties and interaction techniques affect performance on different tasks [7, 8]. Of such studies, many have focused on tasks involving spatial understanding and navigation (e.g., [1, 4, 12, 49]). For instance, Ragan et al. [36] showed that head tracking combined with a large display area significantly decreased errors in small-scale spatial judgment tasks. Studying spatial orientation and VR, Chance et al. [12] found that the added proprioceptive cues available while walking with a tracked HMD helped participants maintain orientation and keep track of locations within a virtual environment (VE). Also involving 3D navigation, Tan et al. [48] found evidence that navigation proficiency was significantly better when viewing a VE on a large, projected display rather than on a standard computer monitor. Relating to navigation and training transfer, Ruddle, Payne, and Jones [40] found that participants better navigated real buildings after practicing with tracked HMDs rather than with desktop monitors. While some of these studies show that realistic physical rotation enabled by head tracking helped users' performance, our work focuses on the study of spatial orientation and training effectiveness with semi-natural interaction techniques.

Simulation-based training is a common application of immersive VR systems [41]. By providing realistic sensory stimuli, simulation, and interaction, VR provides a means of limiting the differences between the training environment and the environment in which actual task performance will take place. Studies have provided evidence of training transfer after virtual training for a number of task areas, such as surgical training [17, 42] and flight training [16, 18]. For example, Hart and Battiste [18] compared flight school performances of participants who trained with either a specialized flight-training game, a commercial video game, or no additional game training. They found that participants were least likely to resign or be removed from flight school after training with the specialized game, and the commercial flight game group had the largest number of non-continuing students. Such results raise questions about how the design and fidelity of the training system influence the effectiveness of training. Though VR training is common, evaluating effectiveness has been challenging [41], and little is known about what factors affect training transfer.

In our previous work related to display properties and learning, we found no evidence that practicing a procedure memorization task helped recall for a later real-world task any more than practicing in a virtual environment [37]. However, learning with a larger display area and wider *field of view* (FOV) in VR resulted in significantly faster and more accurate recall of the learned sequence of actions. In another previous study involving training, we studied how display FOV affects training transfer for a visual search and scanning task [35]. The results showed that reduced FOV did negatively affect search performance, but it did not influence training transfer when performing a different version of the task. While the study provided new knowledge of how display and scenario realism can affect search and training effectiveness, the project did not consider effects due to interaction differences.

It is not well understood how the interaction fidelity of view control may affect training transfer. For example, must the physical rotation exactly match the corresponding rotation of the virtual world? This question is highly relevant because of hardware and physical space constraints for VR systems. To account for limited physical walking space with a tracked HMD, for instance, redirected walking methods artificially adjust the virtual rotation of a scene, guiding the physical direction of walking to allow the illusion of walking through a VE much larger than the tracked space [38]. While redirected walking may employ any of a variety of types of adjustments, rotational gains, which amplify the amount of virtual rotation caused by physical rotation [45], are of interest to our work. While redirected walking is generally used with HMDs, head rotation amplification has also been used with large displays to allow viewing of fully-surrounding virtual spaces without horizontally-surrounding displays [26]. Additionally, Freitag et al. [15] recently demonstrated the use of rotational gains in a large (5.25x5.25 m floor) five-sided CAVE.

Several other researchers have studied the effects of amplified head rotations. Studies have shown that users generally find amplification to be intuitive and usable [21, 33]. For visual search task performance, Mulder and van Liere [30] found that performance with amplified head rotations in fishtank VR was not significantly different from other techniques for controlling viewpoint orientation. Using an HMD with a narrow FOV, Jay and Hubbold [21] found improved performance with the use of rotation amplification as compared to the standard one-to-one mapping for a search and selection task. While this study only considered one level of amplification, our research considers multiple levels of amplification as well as different display types.

With a technique designed to present CAVE users from turning beyond the display range, Razzaque et al. [39] investigated the use of automatic rotational adjustments to center a user's view towards the front wall of a CAVE while using *walking in place* for travel. In their study comparing the automated rotation with manual rotation via joystick, the researchers found no significant differences in participant sickness. Williams et al. [50] also considered the use of amplification to compensate for limitations to VR systems. They studied the occasional use of amplified rotation as a means of resetting a user's orientation when users physically reached the edge of the tracked area. In their work, participants physically walked in a tracked space wearing an HMD, and 2x amplification was enabled when participants needed to turn around at the edge of the space. The researchers tested the implications of the resetting technique (along with others) on a spatial memory and orientation task, and the results demonstrated negative effects of the amplification technique. However, the occasional application of amplification for resetting is a different usage than the constant amplification scenario we study in experiment presented in this paper. Prior studies have found evidence that people get used to amplified visual rotation and calibrate their physical turning to adjust [24].

Other researchers have studied how different amounts of amplified head rotation influence tolerance or noticeability. Jaekl et al. [20] used an HMD and asked users to adjust the level of amplification until the display felt "world-stable". Although there was a great deal of variance among users, in general there was a preference for some amplification, with an average preferred amplification of 1.26x. Similarly, Bolte et al. [5] tested pitch and roll attenuations and amplifications ranging from 0.6x to 1.4x in light of varying software FOVs and asked participants whether they perceived any mismatch between scene movement and head rotation. Attenuations were noticed significantly faster than amplifications, especially in the highest levels of software FOV. On the other hand, Steinicke et al. [44] found that attenuations of yaw rotations were less noticeable. In other research, Steinicke et al. [45] studied whether users could detect rotational adjustments during redirected walking with HMDs, and they found that rotational gains within the range of 0.67 and 1.24 were not noticed by participants.

Two recent studies addressed similar questions involving rotation amplification and training. Ngoc and Kalawsky [31] compared flight simulation task performance between a triple-monitor display and a single-monitor setup with non-linear rotation amplification. The study detected little difference in flight behavior, mental workload, and simulator sickness between conditions, though the researchers did report a significant effect on flight turning behavior. Overall, participants were quick to adapt to the amplified rotations, but additional data is needed on if and how amplification affects performance and training transfer with tasks such as visual scanning, room clearing, or wayfinding.

In the other highly related study, Kopper, Stinson, and Bowman [23] studied the effects of HMD FOV and rotational amplification on performance of two tasks. No main effects of amplification were detected for a target-search task, in which participants had to find suspicious targets while moving through an urban environment. However, the results did show an interaction between FOV and amplification that suggests that amplification may work better with smaller fields of view. The study's other task was a counting task, in which participants had to rotate in place to count the number of surrounding target objects. For this task, amplification did have a significant main effect on performance, showing more counting errors with greater levels of amplification (the worst performance occurring with the maximum level of amplification used, 3x). If these results hold for other tasks, it may be detrimental to use amplification in a VR training system. In the work described in this paper, we explore a similar task in more detail, and we also consider implications beyond training scenarios.

3 Head Rotation and Amplification

Head rotation amplification is an interaction technique for controlling the orientation of the virtual camera, or the viewpoint, that maps the user's physical head rotation to a larger virtual rotation. This is motivated by three limitations of existing VR displays and interaction techniques:

1. Many types of VR displays do not offer a 360° range of visible coverage accessible by natural physical head movement (we note that this range is sometimes referred to as *field of regard*). For example, a standard CAVE-like display has three vertical screens (one in front of the user, one on the left, and one on the right) leading to a 270° horizontal display range when the user is standing in the center (we note that perceived FOV and field of regard with projected-screen systems can vary depending on the user's physical position, but for simplicity in this discussion, we assume the use case with the user at the center of the display). Dome displays may offer approximately 180° of display range. Other multi-screen setups have between 90° and 180° horizontal range. Single projection screens or single monitors typically have less than a 90° FOV or display range. Only tracked HMDs (which keep the displays in front of the user's eyes no matter which way the user turns) and completely surrounding screen-based systems such as fully horizontally surrounding CAVEs (e.g., [13]) or spherical displays (e.g., [19]) offer a 360° visible range. However, these systems are not always practical due to cost, lack of support for multiple users, or space requirements. Thus, many VR displays cannot offer a fully natural technique for rotating the viewpoint in the virtual world.

2. The most common interaction techniques for viewpoint rotation in displays without a 360° display range are not based on head movements at all. Instead, they use devices like a mouse or joystick. A typical mouse-based technique maps the displacement of the mouse to a rotation of the camera (pitch and yaw); this technique is used in many first-person video games. Console video games and CAVEs often use a rate-controlled joystick mapping, where the displacement of the joystick is mapped to the rate of rotation of the camera. These mappings are usable and familiar, but they lack real-world interaction fidelity and thus may not be ideal for training systems or other applications where high levels of realism are desirable.

3. Even with tracked HMDs offering 360° viewing, it is not always easy or desirable to use full 360° physical rotation. For instance, most types of HMD systems involve the use of video cables connecting the HMD to a computer, and continually turning 360° can cause the cables to become tangled or wrapped around the user. Additionally, some users may wish to remain seated and limit physical movement for extended periods of comfortable VR use. Such scenarios may be more likely with the recent popularity of consumer-level HMDs for home use. It would be difficult to turn 360° when lounging on a couch or while seated at desk and maintaining use of a mouse or keyboard for input.

Amplified head rotation is seen as a compromise that mitigates the effects of these limitations. Several design choices must be made when implementing a head rotation amplification technique. First, the designer must choose between linear and non-linear mappings. Linear mappings are easy to implement and provide a consistent user experience no matter which direction the user turns or faces. Non-linear mappings, on the other hand, may be more appropriate when there is a preferred viewing direction (e.g., toward the front wall of a CAVE). The level of amplification will be very low when the user faces in this direction and will only increase when the user turns to face an area near the edge of the display.

Additionally, the designer must determine what components of head rotation to amplify. Most often, amplification is applied to yaw (rotations about the vertical axis) because in most virtual environments the user needs to turn the view left and right to view other parts of the world. It may also be appropriate to amplify pitch (rotations about the left-right horizontal axis) since most displays are also limited in their vertical viewable range, and because some environments and tasks require looking up and down as well as left and right. If only yaw (or pitch) is amplified alone, users may have more trouble controlling the view due to the mismatch in mappings, but more research is needed to verify this. We assert that roll (rotations about the depth axis) should never be amplified because roll rotations do not cause the direction of gaze to change (so no amplification is needed to keep the user from looking away from the display), and because amplifying roll has caused disorientation and cybersickness in our experiences.

Amplification has a number of potential benefits. Obviously, it is designed to provide more natural viewpoint control in non-surrounding displays. It may also offer reduced fatigue and faster performance since viewpoint rotations can be achieved with smaller head movements. The human brain can adapt to mismatches between vision and proprioception (i.e., feedback from the eyes and the muscles [43]), so amplification may not cause any problems in task performance or spatial understanding after a brief acclimation period.

On the other hand, amplification has some known and hypothesized disadvantages. It sets up a non-continuous rotation space when used with fixed displays. In other words, suppose the user turns to one edge of the display to see one part of the virtual environment. Then, to see the area just adjacent, the user must turn a large amount in the opposite direction to face the other edge of the display. Continuous rotation in the same direction is not possible. We also hypothesize that the mismatch between visual and proprioceptive feedback may disorient users and cause them to lose their way in the virtual environment [2]. Finally, if users train and adapt to the amplified rotation mapping, this may cause a decrease in performance, disorientation, or errors when they perform the task in the real world with the non-amplified mapping. Prior research has demonstrated such after-effects of exposure to VR systems even with minimal differences between the virtual and real visual stimuli (e.g., [43]). We examine these hypotheses in our experiment.

4 Method

We conducted a controlled experiment investigating the effects of amplification and display type on spatial orientation and performance on a search task. After first performing the task with the assigned amplification and display, participants then completed the same task in an unamplified 360° HMD to assess training transfer.

4.1 Goals and Hypotheses

The primary goal of the experiment was to determine how amplification affects performance, training transfer, and spatial orientation for a task involving visual search and target counting. We were interested in both the general effects of amplification (by comparing amplified and non-amplified conditions) and in differences between different levels of amplification. We hypothesized that using any amount of amplification will decrease performance compared to the control condition with one-to-one view control. We also hypothesized that small amounts of amplification will be tolerable, but that larger amplifications might cause trainees to become disoriented and to have decreased task performance and training transfer.

A secondary goal of the experiment is to investigate whether the effects of rotation amplification differ for two different display types: a surround-screen CAVE display and an HMD. We tested different displays because differences in display properties (such as weight, form factor, or visual quality) may cause the results of amplification to vary in different systems. In our experiment, we studied amplification by simulating different levels of display coverage up to 360°, but we only tested up to 270° in the CAVE because our CAVE did not support 360° physical viewing.

4.2 Apparatus

The CAVE conditions used a four-sided Visbox VisCube display with three 10x10-foot walls and a 10x10-foot floor. All four screens displayed passive stereo imagery (based on Infitec technology) at a resolution of 1920x1920 pixels. When projecting stereo, the CAVE had a 60 Hz refresh rate. Participants wore stereo glasses that limited the horizontal FOV to approximately 100° and limited vertical FOV to approximately 80°. For the HMD conditions, we used an nVis SX111 HMD with wireless video. This HMD features dual displays (one per eye), each with a resolution of 1280x1024 pixels and a 50° binocular overlap. The total horizontal FOV of the HMD was 102°, and the total vertical FOV was 64°. The HMD has a 60 Hz refresh rate. Wireless video was provided by two Sensics low-latency (1 ms) HD1080 wireless video links placed in a backpack along with the HMD video control unit. The total weight of the HMD was 1.3 kg, and the backpack weighed 2.8 kg.

Figure 2 shows both display configurations in the same image, though the CAVE screens were not used while participants used the HMD during the study.

For all conditions, head orientation was tracked with a wireless Intersense IS-900 head tracker. Translational head tracking was disabled in all conditions, and all participants were instructed to stay at the center of the CAVE during the study. The decision to disable translational head tracking was made to prevent participants from adjusting viewing patterns by using physical translations and to limit variance in FOV or field of regard in the CAVE due to physical position.

Participants also held a wireless tracked IS-900 wand controller in the dominant hand. Participants used the trigger button on the wand to select targets in the environment. The tracking system updated with a 120 Hz update rate. The software for the experiment was written using X3D and rendered with the Instant Reality Simple Avalon Viewer with plugins to interface with the IS-900 tracking system. The application ran at 60 frames per second in both the HMD and the CAVE systems.

4.3 Task and Environment

To study the effects of amplification on search performance and orientation, we needed a task that required visual search of a 360° environment and that had the potential to disorient users. Thus, we designed a difficult visual search and counting task. We asked participants to search through a multi-room warehouse (see Figure 3) and mark all instances of target objects (warhead, explosives, rifle on a tripod, and rocket launcher, as seen in Figure 4). To mark objects on the shelves, participants first pointed at the objects using raycasting. Shelf objects were highlighted with a partially transparent red box to show which object would be selected (shown in Figure 1). Participants could then press the trigger button on the wand to confirm the selection.

Fig. 2. This figure shows a user in the 270° CAVE while wearing the HMD setup. In the study, users only used one display at a time.

Fig. 3. The environment used for visual search task was a multi-room arrangement of shelves that participants had to search.

Although most conditions of the experiment involved rotation amplification for viewing, pointing direction was never amplified in any condition. In other words, the virtual pointing direction was always consistent with the physical pointing direction. Because amplified head rotation affected the environment but not the pointing ray, either hand movement or head movement (or both) could be used to adjust aiming in conditions with amplification enabled.

We instructed participants to try to find and mark all of the target objects in the environment, we also emphasized that they should try not to mark targets more than once. We also encouraged participants to complete the task quickly, but not at the expense of search coverage.

The walls in each room consisted of four-level open shelves containing a mixture of target and non-target objects (see Figure 3). Since the shelves were open from both sides and one object deep, objects could be seen and marked from either side of the shelf. Thus, it was possible to mark objects from multiple rooms. Because the instructions emphasized the importance of avoiding marking any target more than once, participants had to be aware of where they have already searched and marked.

The rooms were arranged in a three-by-three grid (a diagram of an example layout is shown in Figure 5), with doorways placed between some rooms to ensure that every room was reachable. Trials

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Fig. 4. The four target objects used in the search task.

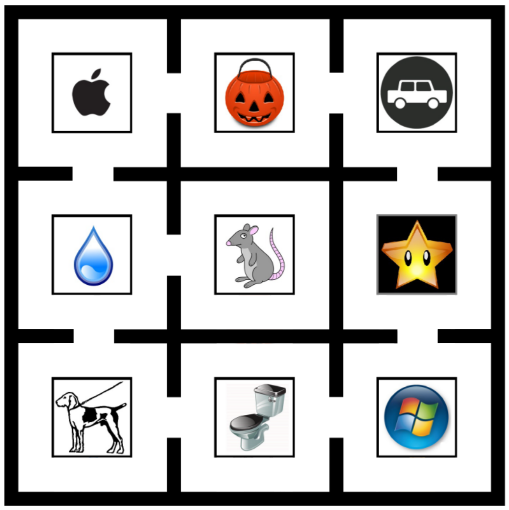

Fig. 5. An example layout showing the arrangement of "rooms" of shelves and the open pathways between rooms. Each room had a unique landmark image, and each trial had unique set of images.

used different layouts with different configurations of doorways. Each layout's doorways were manually chosen to ensure different configurations. Each room had a unique visual marker placed in the center to serve as a landmark to help participants remember which rooms they have visited. The particular layout of Figure 5 was used for familiarization and to explain the task to participants, and the layouts used for the trials had different configurations of pathways or dead ends.

All layouts were generated and finalized prior to the study, and all participants experienced the same layouts in the same order. Each phase of the experiment used a unique environment with unique object layouts and different landmark markers, but all environments had exactly 55 targets. Target selections and placements in each layout were initially created with a pseudo random distribution, but manual alterations were made reduce instances of target clusters.

To travel between rooms in the environment, participants used the wand controller to point through an open doorway and click the trigger button, which started an interpolation of the viewpoint to the new location.

4.4 Experimental Design

The experiment varied display type and amplification level as the two independent variables. Combinations of display and amplification were assigned following a between-subjects design. Each participant first used the assigned condition to perform the task for the *practice* trials, so the results from the practice trials provide a straightforward comparison of differences between the displays and amplification levels. After the practice session, and regardless of the experimental condition used for the practice trails, all participants completed additional *assessment* trials with an unamplified 360° HMD. The results of the assessment session allow us to study transfer from the experimental conditions to a situation with more natural 360° viewing.

The experiment followed a 2x3-1 between-subjects design, which resulted in five conditions and each participant completing the study with only one assigned condition. Amplification level was varied in three levels, with every level corresponding to an appropriate physical range that would allow 360° virtual viewing with rotation in the physical space. The levels of amplification and display range used in the practice session were:

- 1x amplification with 360° horizontal display range (i.e., no amplification),
- 1.5x amplification with 270° horizontal display range, and
- 4x amplification with 120° horizontal display range.

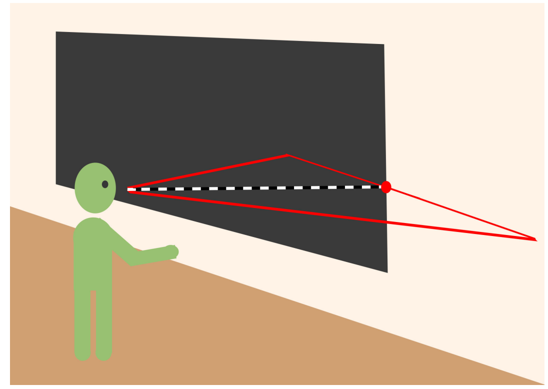

Fig. 6. When rotating all the way towards the edge of a display area, half of the field of view will be beyond the display area.

The levels of amplification were chosen for each display range so that users could turn in either direction and still be able to look behind them. For all conditions, we wanted users to be able to see 180° behind them by rotating in either direction, and it would be impractical to require users to turn all the way to the edge of the display area because this would mean that half of their visual FOV would be looking off of the screen (see Figure 6). To avoid this issue and to provide a more practical implementation, we accounted for a 15° buffer zone at both edges of the horizontal display range when calculating the amplification factor. For example, in the 120° conditions, 30° of the total horizontal display range was used as buffer space (15° at each edge), leaving a 90° display range to be mapped to the entire 360° virtual range. A 4x amplification factor was required to view the 360° by rotating in the 90° range, which is how we arrived at the 4x amplification level for conditions with 120° total display range.

For the *displays* variable, we compared two types of displays: a CAVE display and the HMD. Because the CAVE has a 270° horizontal display range, we were unable to test an unamplified (1x) version of the CAVE display, leading to the 2x3-1 design.

To study differences due to display range viewable with physical rotation, we implemented virtual blinders in both the CAVE and HMD conditions to limit the display range. The blinders were necessary in the CAVE conditions to limit the display area to the desired range. Because we wanted to test the effects of the displays with the same amplification techniques, we chose to also modify the HMD version of the application to include virtual blinders that matched the non-visible region of the CAVE version. To make this clear throughout the paper and remind readers that we tested the combination of both amplification level and visible range, we report the variable levels of amplification in terms of the visible range (i.e., 120°, 270°, or 360°) for both HMD and CAVE variations.

To allow for a fair comparison between the CAVE and HMD, we also added blinder geometry to the 270° and 360° HMD conditions to simulate the missing top and back screens from the CAVE. The 360° condition in the HMD did not require blinders because of the desired uninhibited 360° base case.

Procedure Summary	Approx. Duration (minutes)
Introductory paperwork	**18**
Informed consent	5
Background questionnaire	5
Spatial ability test (cube comparison)	8
Practice session (in assigned condition)	**38**
Instructions and familiarization	5
Practice trial 1	5
Break	5
Practice trial 2	5
Practice trial 3	5
Egocentric orientation test	3
Exocentric orientation test	2
SSQ sickness test	3
Break	5
Assessment session (always 360° HMD)	**19**
Instructions and familiarization	2
Assessment trial 1	5
Assessment trial 2	5
Egocentric orientation test	3
Exocentric orientation test	2
SSQ Sickness Test	2
Closing interview	**8**
Verbal interview	8

Table 1. A summary of the experimental procedure. Each participant completed the trials in the practice session using the assigned display and amplification level, but all participants completed the assessment with the 360° HMD.

This approach ensures that conditions vary only based on the factors of interest and ensures experimental control. Note that this approach of controlling VR systems to simulate other factors of systems can be referred to as "mixed reality simulation", and the approach has been used in numerous other studies (e.g., [10, 27, 34, 35]).

Dependent variables for search performance included completion time (i.e., when participants indicated that they thought they found all targets), the number of correctly identified targets, and the number of targets marked more than once. Additionally, metrics for orientation included an egocentric orientation test based on physical pointing and an exocentric orientation test based on a top-down view of the environment. We also counted the number of travel movements between rooms, which is related to search efficiency and orientation.

4.5 Participants

Forty participants completed the study. Thirty of the participants were male, and 37 were undergraduate university students. Ages ranged from 18 to 34 years. Participants' academic backgrounds varied widely and included computing, engineering, business, liberal arts, and the sciences. Eighteen participants were members of the Virginia Tech Corps of Cadets. Eight participants were assigned to each of the five conditions

Since we expected the possibility of sickness effects from VR usage, and we were concerned that cadets might be more inclined to under-report symptoms, we distributed participants across conditions based on membership in the Corps of Cadets. In addition, we distributed participants by gender. While not perfectly balanced, participants were distributed by gender and membership of the Corps of Cadets balanced across conditions as well as possible. Consequently, each condition had either three or four participants in the Corps of Cadets, and each had either five or six males.

4.6 Procedure

Each participant completed the study in a single period lasting between 75 and 90 minutes. Table 1 provides a summary of the steps of the procedure along with the approximate time taken for each step.

Upon arrival, participants were required to review and sign an informed consent form before beginning the experiment. Participants then completed a background questionnaire to collect information about basic demographics and experience with video games and VR. Next, participants took a three-minute cube comparison test (from the Kit of Factor-Referenced Cognitive Tests [14]) to provide an estimation of spatial ability.

Participants were then briefed on the environment and task. The experimenter showed the participants the target objects (shown in Figure 4) and then introduced them to the assigned display technology and level of amplification. To establish familiarity with the display and interaction techniques, participants experienced an introductory warehouse environment, complete with shelves, shelf objects, and landmark objects. For this familiarization, we wanted participants to understand how to use the head rotation to view the environment, but we also did not want to explicitly tell participants that the head rotation was amplified. Therefore, to familiarize participants with the head tracking and amplification, the experimenter had participants physically turn in both directions to virtually look 180° behind them in the introductory environment, but the experimenter did not verbally explain the amplification.

Participants then practiced marking shelf objects and traveling to different rooms. After participants demonstrated proficiency with viewing and interaction, the experimenter explained the instructions for the search task, emphasizing the importance of counting every target, avoiding recounting targets multiple times, and telling the experimenter when they thought they marked all the targets in the environment.

Participants then completed the first full practice trial. After this trial, participants were required to take a five-minute break (we required breaks in an effort to limit sickness). Then, participants performed two more practice trials.

Immediately after the third practice trial, participants were asked to complete the egocentric and exocentric orientation tests. The orientation tests used the same warehouse environment in which the participants just completed the third trial. To begin, all participants were teleported to the same starting position for the orientation test. Next, the experimenter instructed participants to follow a given path through the warehouse, with the path indicated by a list of landmark objects. For example, using the example layout shown in Figure 5, sample instructions might include the steps "go to the dog" and "go to the toilet". The last position of the path was the center of the 3x3 room layout. When participants reached the last position, they were instructed to turn and face the direction of a given adjacent landmark object. At this point, environment visibility was toggled off, and the egocentric part of the orientation test began. Participants were required to continue facing the original gaze direction while using the wand controller to physically point in the direction of the other landmark objects from along the path. The requirement that participants continued to face the original direction was enforced to limit confusion from amplified rotation that could have occurred if participants looked around while pointing. Even though the displays did not show the environment during this test, it was more straightforward to only involve physical pointing since wand pointing was never amplified.

The experimenter verbally specified a landmark object, and the participant would then point and confirm that they were pointing in the intended direction. The experimenter then triggered the software log of the direction before moving on to the next landmark object. In the orientation test, objects were given in a predetermined jumbled order. The given object order was constant for each layout for all participants, and object orderings were manually chosen in such a way that did not align with the order the landmarks could be encountered while navigating the layout.

After the egocentric pointing task, participants moved to a nearby computer and took the exocentric orientation test. The exocentric task

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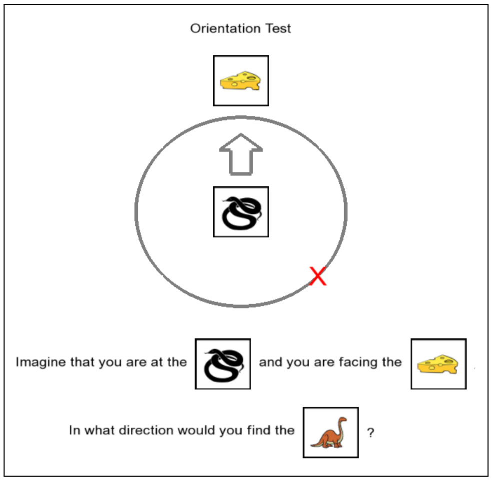

Fig. 7. A screenshot from the exocentric orientation test. Participants moved the position of the red X on the perimeter of the circle to indicate the intended direction.

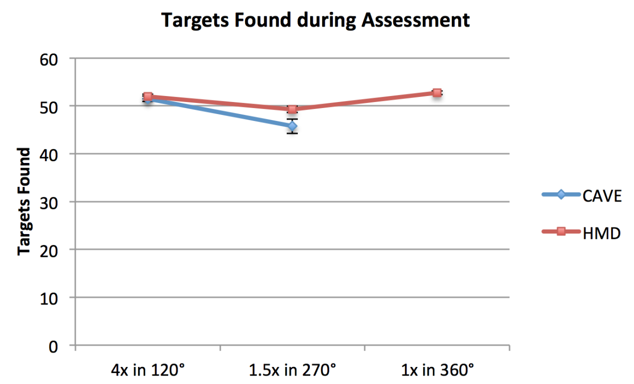

Fig. 8. The average number of targets found for the search task was fairly high across conditions, but participants who practiced in the 270° conditions had significantly worse performance in the assessment.

asked participants to indicate the directions of the same objects as in the egocentric pointing task, but from a top-down perspective. To do this, the test application showed participants a circle with the landmark of the final location at the center (see Figure 7). At the top of the circle was the landmark object used to indicate the gaze direction during the preceding pointing task. Having the two given landmarks as references, participants were asked to click on the edge of the circle to indicate the directions of the other landmark objects.

After the orientation tests, participants completed a simulator sickness questionnaire (from [22]). Participants were then required to take another five-minute break.

After the second break, participants performed two assessment trials in the HMD with no amplification (after another brief instruction trial explaining the new controls). After the final assessment trial, participants again took both types of orientation tests for the last trial. Next, participants completed the simulator sickness questionnaire for a second time, and then finally participated in a semi-structured interview about their thoughts about the rotation, understandings of the warehouse layout, sickness symptoms, and any other thoughts about the experience.

5 Results

We wanted to test for effects of both display type and level of amplification, as well as for interaction effects between the two, on the dependent variables. We decided that the use of full factorial analyses would be inappropriate for the experiment's design (2x3-1) because the missing cell could lead to confounds, non-unique models, and a reduced ability to detect interactions.

Instead, for each outcome, we used a two-way independent factorial ANOVA (type III sum of squares) for the complete 2x2 portion of the design (that is, excluding the baseline condition in which participants practiced in the 360° HMD). To account for the excluded condition, we followed with a one-way independent ANOVA to test for differences among the five individual conditions. We also note that the distributions of many of the outcomes did not originally meet the assumptions for parametric testing, so transformations were applied to correct the distributions for the use of parametric ANOVAs. However, all charts, means, and standard deviations present the non-transformed data for easier interpretation. Error bars in all charts represent standard error of the mean.

For the sake of simplification, we only report test details for the significant and near-significant test results in the following subsections.

5.1 Search Performance Results

To test for the effects of display type and level of amplification on search performance, we considered the number of targets found, the number of repeated targets, and completion time during the practice phase of the experiment. For each of these outcomes, we averaged each participant's results from the trials to calculate separate metrics for the practice trials and for the assessment trials.

5.1.1 Search Performance during Practice

No significant effects of display or amplification were detected for any of the performance outcomes during practice. Tested measures include the number of targets found, the number of targets marked repeatedly, and completion time. Neither the two-way factorial ANOVA nor the one-way independent ANOVA found significant effects for any of the search outcomes. The mean completion time of practice trials was 5.58 minutes (SD = 1.60).

5.1.2 Search Performance during Assessment

To study the effectiveness of training with display systems using rotation amplification, we considered the search performance results from the assessment phase, where all participants used the HMD without amplification. Figure 8 shows the average targets found during assessment based on practice condition. For the number of targets found in the assessment, a log transformation was applied to satisfy the assumptions of parametric testing. The two-way factorial ANOVA (excluding the 360° HMD practice condition) found a significant effect of amplification with $F(1,28) = 4.73$, $p = 0.038$, and $\eta_p^2 = 0.14$. The conditions that practiced with 120° found more targets in the assessment (M = 51.72, SD = 2.97) than those that practiced with 270° (M = 47.50, SD = 6.12). The effect size was medium-large (Cohen's d = 0.77). The test did not detect a significant effect of display on targets found, and no evidence of an interaction was found. The one-way ANOVA comparing all conditions found a significant effect with $F(4,35) = 3.13$, $p = 0.027$, and $\eta_p^2 = 0.23$. A post-hoc Tukey HSD test found that the number of targets found in the 360° HMD group (M = 52.75, SD = 2.24) was significantly better than in the 270° amplified CAVE group (M = 45.75, SD = 8.60), and the effect size was large (Cohen's d = 1.36).

For repeat targets marked in the assessment phase, a log transformation was applied for the ANOVAs. No significant effects were detected for repeated targets.

For average completion time in the assessment, the data met the assumptions of normality and homogeneity of variance, so no transformation was applied. Neither analysis approach detected a significant effect for time due to the experimental factors. Mean completion time was 4.89 minutes (SD = 1.89) for the assessment trials.

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5.2 Orientation Results

The analyses suggest that amplification and display differences affected orientation and travel during practice, but the effects did not persist in the assessment phase. In this section, we present the results of the egocentric pointing test and the exocentric direction test as the experiment's primary indicators of orientation. Additionally, the number of travel movements is related to orientation because users were expected to make more transitions between rooms if they were having trouble keeping track of where they already searched and where they needed to go.

5.2.1 Orientation after Practice

The egocentric pointing test involved physically pointing to six locations specified by the landmark blocks. Accuracy of the results of the egocentric pointing test were unfortunately reduced by a data capture issue that only made it possible to determine whether participants correctly identified whether each object was in front of them or behind them. To account for this limitation, the pointing results were simplified to an approximate error score that was calculated as the sum of the incorrect responses for each test, with the maximum being six errors. We analyzed the orientation results in the same manner as the performance metrics, using a factorial two-way ANOVA and a one-way ANOVA.

For the analysis of egocentric pointing errors from the orientation test after the practice trials, no transformation function was necessary to meet the assumptions of parametric testing. The two-way ANOVA without the 360° HMD practice condition found a significant effect of display on egocentric orientation with the test producing $F(1,27) = 49.43$, $p < 0.001$, and $\eta_p^2 = 0.65$. Pointing errors were lower in the CAVE (M = 1.0, SD = 1.13) than with the HMD (M = 3.81, SD = 1.11), with a large effect (Cohen's d = 1.51). The factorial ANOVA failed to find an effect of amplification, and no interaction was detected. The one-way ANOVA for all conditions detected a significant effect, yielding $F(4,34) = 9.87$, $p < 0.001$, and $\eta_p^2 = 0.042$. A post-hoc Tukey HSD found both CAVE conditions to be significantly better than all HMD conditions. The egocentric pointing results after practice are shown in Figure 9.

For the other orientation test, the exocentric directional test from the computer application, the average angular error was computed for the six directional tasks. These test results were then analyzed using the non-transformed data. Figure 10 shows the exocentric orientation results from the practice session. The two-way ANOVA without the 360° HMD condition found a significant effect of display on errors in the post-practice orientation test, with the ANOVA yielding $F(1,27) = 5.80$, $p = 0.023$, and $\eta_p^2 = 0.18$. Errors were lower in the CAVE (M = 85.04, SD = 14.12) than with the HMD (M = 95.36, SD = 15.43), and the effect was large with Cohen's d = 0.79. The test did not detect an effect of amplification, and no evidence of an interaction was found. The one-way ANOVA with all conditions found a significant effect with $F(4,34) = 2.96$, $p = 0.034$, and $\eta_p^2 = 0.26$. A post-hoc Tukey HSD showed that the only significant pair-wise difference was between the 360° HMD condition and the 270° CAVE condition, with $p = 0.049$.

We call attention to the fact that orientation outcomes were notably poor for the egocentric and exocentric orientation tests. Many participants commented on the difficulty of the orientation tasks, noting that it felt like guessing. Figure 9 shows that HMD conditions had worse average pointing error than would be expected by random chance (i.e., 3 out of 6 objects), though this highlights the significantly better pointing results from the CAVE participants. Similarly, Figure 10 shows that results for the exocentric orientation test were not far from chance (90° error).

Lastly, we compared the average number of times that participants moved between rooms in each trial from the practice session. For the ANOVA tests, a transformation of $f(x) = \frac{1}{x^2}$ was applied to the data. The two-way ANOVA without the 360° HMD condition found a significant interaction between display types and amplification level, with $F(1,28) = 5.38$, $p = 0.028$, and $\eta_p^2 = 0.16$. Figure 11 shows the interaction. The 120° HMD condition had more movements than

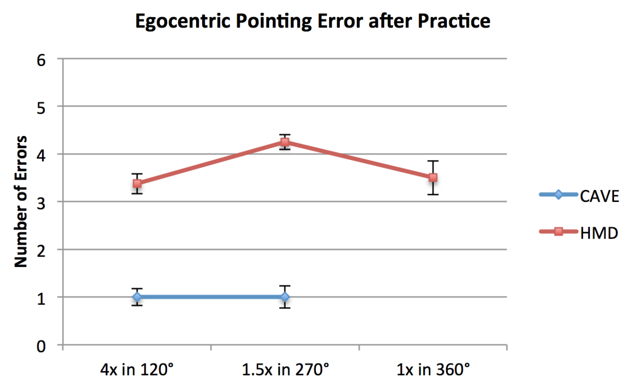

Fig. 9. The results from the egocentric orientation test show the average number of pointing errors when participants were asked to physically point to six target objects. The plot shows the HMD conditions had significantly more errors in the practice session.

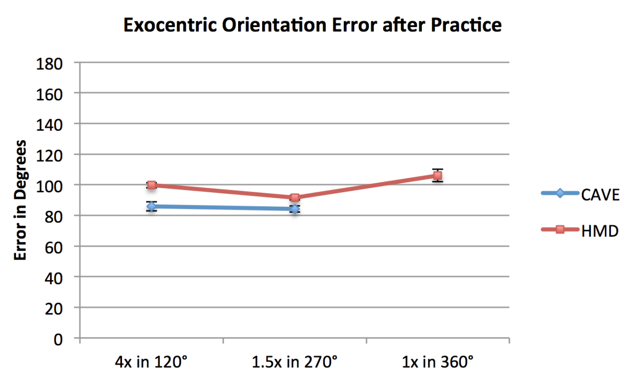

Fig. 10. The results from the computerized exocentric orientation test from the practice session shown as average error in degrees. HMD conditions had significantly more errors.

the 120° CAVE condition, but the 270° CAVE condition had more movements than the 270° HMD condition. A post-hoc Tukey HSD did not detect significant differences between any pairs of conditions.

The follow-up one-way ANOVA for analysis of travel movements in practice for all conditions did not detect a significant effect. The test yielded $F(4,35) = 1.79$ and $p = 0.15$.

5.2.2 Orientation after Assessment

Participants completed a second set of orientation tests (both the egocentric pointing test and exocentric directional test) after the two assessment trials in the 360° HMD. Orientation test results and travel movement results were calculated for the assessment trials in the same way as done for practice. Analyses also did not find any evidence of significant effects of display type or amplification on orientation or travel movements.

We do note that orientation test performance was generally poor for both the egocentric and exocentric tests from the assessment session. Exocentric pointing errors were close to random (M = 3.03, SD = 0.86). The exocentric orientation error was also close to random in the assessment (M = 96.70, SD = 16.70).

5.3 Sickness

Participants completed the simulator sickness questionnaire (SSQ) [22] twice: once after completing the practice trials and then again after completing the assessment trials. The SSQ provides a total sick-

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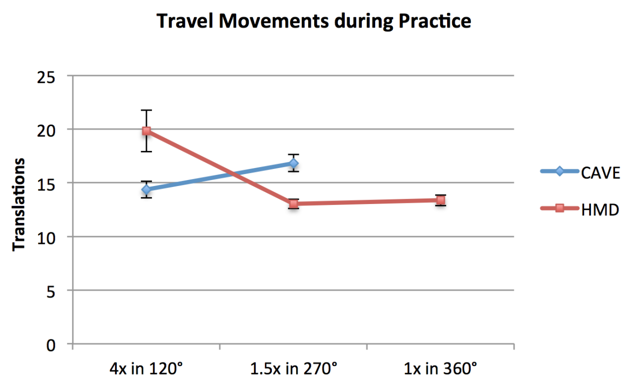

Fig. 11. The graph of the average number of travel movements during practice trials shows a significant interaction between amplification and display.

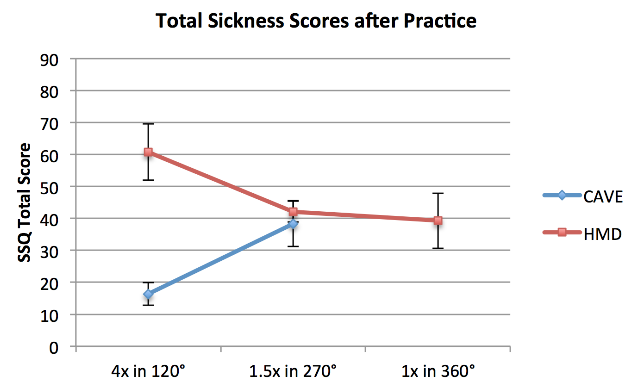

Fig. 12. Average SSQ sickness test scores after practice. Sickness was significantly worse with HMD use, and the interaction graph between amplification level and display type shows a noticeable difference for the 120° amplification conditions after practice.

ness score as well as three additional scores for the categories of symptoms grouped under nausea, oculomotor, and disorientation. We note that we a baseline SSQ test was not administered before beginning the practice session.

5.3.1 Sickness Scores After Practice

For the purposes of analyzing the results of the first sickness test after the practice session, we assume low starting levels of sickness before beginning any VR activities. Thus, we use a zero SSQ score as an assumed baseline, but we note that this assumption cannot be verified by our method.

All sickness scores from the practice session were transformed with $f(x) = \sqrt{x}$ to meet the assumptions of parametric testing. A two-way factorial ANOVA found a significant effect of display, with $F(1,28) = 65.80$, $p = 0.02$, and $\eta_p^2 = 0.18$. Sickness was worse with the HMD (M = 51.43, SD = 40.21) than the CAVE (M = 27.35, SD = 32.80). However, looking at the interaction graphically (see Figure 12), the real difference is between the 120° CAVE and HMD conditions. For many people, sickness effects were worse with the highest level of amplification when using the HMD. In contrast, the highest level of amplification in the 120° CAVE had the lowest average sickness effects of all conditions.

The two-way ANOVA failed to detect the interaction, with $F(1,28) = 2.52$ and $p = 0.12$, which we suspect is due to problems with homogeneity of variance across conditions. The test also did not detect an effect of amplification. A one-way ANOVA with all conditions found a near-significant effect with $F(4,35) = 2.45$ and $p = 0.06$.

In addition to the analysis of total sickness scores, we also analyzed the SSQ's category scores for nausea, oculomotor, and disorientation. Not surprisingly, the effects for each of the categories were the same as for the total sickness scores, showing significantly worse sickness for HMD conditions—notably due to the 120° HMD condition.

We note that we also tested for correlations between sickness and completion time, and the tests found no evidence of a correlation.

5.3.2 Sickness Scores After Assessment

Participants took the SSQ a second time after completing the assessment trials with the 360° HMD. Figure 13 shows the average SSQ scores from the second test. To analyze the results, we calculated the change in sickness scores after the assessment by subtracting the scores from the first SSQ test from the scores from the second test. Figure 14 shows that the sickness scores mostly increased, as might be expected from extended time in the VR setting.

No data transformations were applied for statistical analysis of sickness changes. The two-way ANOVA detected a significant effect for display differences with $F(1,28) = 5.19$, $p = 0.03$, and $\eta_p^2 = 0.16$. Evidence of an effect of amplification was not found, and no interaction effect was detected for sickness change.

On average, sickness increased more for those who practiced in the CAVE conditions as well as for those who used the 360° HMD

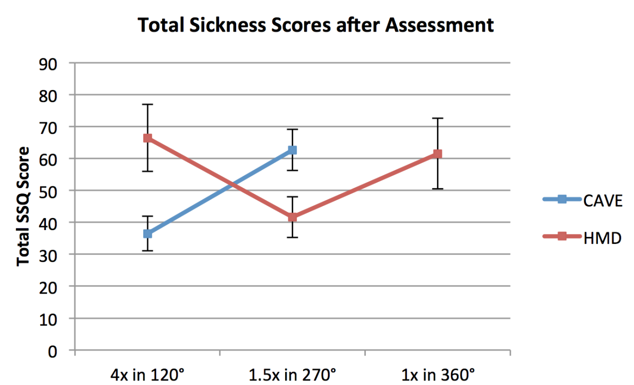

Fig. 13. Average SSQ sickness scores after the assessment.

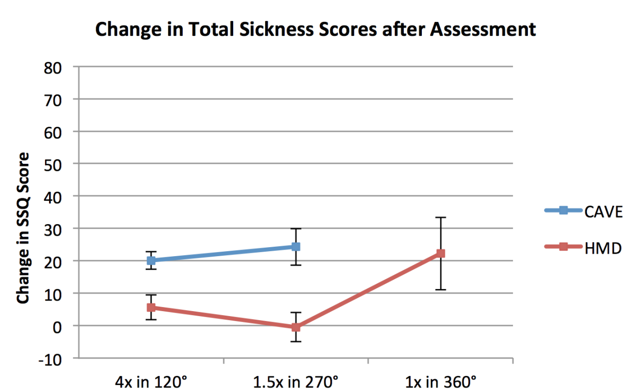

Fig. 14. Compared to the practice session, the SSQ sickness scores generally increased after the assessment. The increase is most noticeable for the CAVE conditions and the 360° HMD condition. Note that the plot's vertical axis extends into negative values.

for practice. On the other hand, scores were similar for those who had practiced with the amplified HMD conditions. Figure 14 shows the difference in sickness increase for participants who practiced in the 360° HMD condition as compared to the near-zero average increase of those in the amplified HMD conditions. These results can be thought of as relative to the sickness effects from after practice. Though sickness generally increased regardless of condition, perhaps the reported increases were lower for the 120° and 270° HMD conditions because participants felt somewhat better than after the practice session. That is, the lack of increase for those who switched from the amplified HMD conditions to the 360° HMD might suggest that improving the interaction realism made the experience more tolerable, which prevented the reported symptoms from worsening.

As with the other metrics, we also performed a one-way analysis of all conditions, but the test detected no effects for sickness changes.

Additionally, we again tested for correlations between sickness scores and assessment completion time, finding no significant effects.

5.4 Game Experience and Correlations

We used participants' self-reported estimates of time spent playing 3D video games to test for correlations between gaming and other metrics. Participants reported gaming time as the average number of hours spent playing 3D games in a typical week. The gaming data was heavily skewed due to most participants reporting little 3D gameplay, so we used nonparametric Spearman correlation tests.

Participants who played more 3D games had lower sickness scores. There was a significant correlation between gaming and total sickness scores for both post-practice ($\rho = 0.36$ and $p = 0.02$) and post-assessment ($\rho = 0.34$ and $p = 0.03$) SSQ tests, though there was no significant correlation between gaming and sickness change.

Higher gaming time was also significantly correlated with more efficient completion of the assessment session. Participants who played more games both completed the assessment more quickly (ρ = 0.44 and $p < 0.01$) and made fewer movements among rooms in the environment (ρ = 0.44 and $p = 0.02$).

There were no significant correlations found for any of the practice metrics. Interestingly, there were no significant correlations between gaming and any of the orientation measures.

5.5 Qualitative Results

No participants reported having any major problems using the amplified CAVE conditions, suggesting that they were generally easy and intuitive to use. Most participants did comment on the strangeness of virtually turning all the way around without making complete physical turns. It was common to hear that it was distracting to reach the edge of the screen and then have to turn back in the other direction to see the rest of the environment. These comments demonstrate that amplified rotation is not completely natural and is not without limitations.

For the 32 participants who practiced with amplified rotation (either in the CAVE or HMD), we asked them if they preferred that or the 360° HMD version used in the assessment. Most (21 participants or 66%) preferred the 360° HMD. Ten participants (31%) preferred the amplification; of those ten, eight preferred the amplified CAVE and two preferred the amplified HMD over the 360° HMD version. In other words, of all participants who practiced in an amplified CAVE condition, half of them preferred the amplified CAVE to the non-amplified HMD. Of all participants who practiced in an amplified HMD, roughly 12% preferred the amplified version.

Surprisingly, one participant who practiced using the 1.5x HMD did not notice a difference between the amplified and non-amplified versions of the HMD—even though the amplified version had blinders that limited the visible range to 270°.

Participants who preferred the CAVE version explained that they thought the task was easier, the resolution seemed clearer, and they liked not having to wear the heavy HMD. Participants had different opinions about the ease of maintaining orientation knowledge when turning. Some explained that it was easier to tell which direction they were facing in the HMD because of non-amplified physical turning. On the other hand, some said that encountering the edges of the screen when rotating with the amplified CAVE conditions was sometimes helpful for knowing which direction they were facing. Since the mappings between the physical and virtual rotations were constant and linear, it was possible to use physical landmarks (e.g., seams between screens and the edge of the screen) to determine the global viewing direction in the virtual space.

6 Discussion

In general, the results and observations from our study demonstrate the feasibility of using amplified head rotation over a limited display range to explore a 360° virtual environment. Higher levels of amplification allow easier viewing by reducing the amount of physical movement needed, but less physical rotation also decreases the benefit of proprioceptive cues gained by real motion. Despite the reduced realism of amplified rotation, participants were able to quickly adjust to the modified interaction technique. However, the experiment found evidence that differences in amplification, visible range, and display type can influence the effectiveness and usability of amplified head rotation. In this section, we interpret the results of the study and discuss possible explanations. We also discuss practical implications of the use of amplified head rotations in virtual reality systems.

6.1 Search Performance

We had hypothesized that adding any amount of amplification would negatively affect search performance and orientation, and we expected larger amounts of amplification to exacerbate problems with disorientation. However, this was not the case. The results from the practice phase (during which amplification was enabled) showed that the amplification did not noticeably affect the number of targets found during the search task. On the other hand, those who practiced in the middle condition with 270° found significantly fewer targets in the assessment phase than those who practiced with the high 4x amplification in 120° or without amplification in 360°. This suggests that participants who practiced with 270° had a more difficult time establishing an effective search strategy, so they were less prepared for the assessment tasks. This result was especially interesting because search performance in the assessment after practice with the highest level of amplification (4x amplification in 120°) was similar to those who practiced with matched 360° rotation. Thus, the middle level of amplification was more problematic than the highest level for learning to thoroughly search the environment.

We turn to our observations and qualitative participant responses to better explain the problems with the 270° condition. As compared to the familiar 360° matched rotation, the 270° rotation condition does not allow users to continually rotate physically in one direction in order to continually rotate virtually in the same direction without encountering the break in the display (i.e., the missing back wall of the CAVE or the virtual blinders in the HMD). Thus, when physically turning far enough to reach the break, the user must choose to either rotate back in the other direction or to rotate through the non-display or blinder region. Neither approach is ideal, but our observations found that participants almost always opted to reverse rotation rather than traverse the non-display region.

Note that this problem exists with both the 120° and 270° amplified conditions. Although it would seem that the issue would be more problematic in the 120° setup due to the larger size of the break or non-display area, this was not the case. As it turns out, because participants preferred to backtrack their rotation through the visible area, the higher level of amplification and smaller visible region in the 120° setup made it easier and faster to reverse the physical rotation and adjust the virtual view as desired. It would seem that even though the 270° case could be considered to be a more realistic interaction, the middle-of-the-road compromise between realism and limited display area resulted in awkward use. We hypothesize that this might also partially explain the slight increase in orientation error in the 270° conditions with the HMD from the egocentric pointing test (see Figure 9).

6.2 Spatial Orientation and Sickness

Also concerning spatial orientation, it is interesting to note the lower orientation error in the CAVE setup than with the HMD (see Figures 9 and 10). Participants were significantly better at maintaining orientation in the CAVE for both the egocentric pointing and exocentric directional tests. This was not expected, as the different display configurations were implemented to be extremely similar: amplification levels were controlled, and non-visible regions were the same through the use of blinders. Yet, orientation error was even higher in the 360° HMD condition than in the amplified CAVE conditions. We attribute the better orientation in the CAVE to the availability of physical directional cues. In the CAVE, participants could always see the separate physical screens and their edges. Additionally, they could see their own bodies to help maintain awareness of where they were facing and how much they had turned; the HMD condition did not include a virtual avatar.

Another difference between the displays was the vertical FOV; vertical FOV was limited to approximately 80° in the CAVE and approximately 64° in the HMD. While horizontal FOV was similar for the displays, the search task did involve scanning up and down the shelves to find the targets, and the tighter vertical FOV would have required slightly more head movement. We suspect that this difference was not a major contributor to the observed orientation results because we think most of the orientation issues were related to navigating among rooms in the environment, but we cannot determine for sure.

It should be noted that the outcomes for the orientation tests were relatively high (sometimes even worse than what would be expected with random guessing). This was particularly true for the HMD trials and was even observed in the assessment conditions without amplification. These results highlight the difficulty of maintaining orientation and spatial understanding of the environment in the warehouse setting of our study, and less confusing environments might not have such difficulty.

Still, the poor overall results make the significantly better results from the CAVE conditions in the practice session more pronounced. One interpretation of the strong sense of orientation in the CAVE conditions is that amplification might be more appropriate for large-screen or surround-screen systems than for HMDs because users can maintain their orientation and use the additional cues to better control the virtual rotation. On the other hand, for many applications, designers or developers may not want users to retain any sense of the physical world. For instance, this could be the case when a high sense of presence is desired. Another implication involves training scenarios. If users are expected to learn navigation strategies or how to maintain their orientation using environmental cues of the virtual space, it might be detrimental to have supplemental system cues that assist with orientation.

In addition to the egocentric pointing and exocentric orientation tests, we also consider the number of translational movements between rooms in the environment to be related to the ability to maintain spatial orientation, based on the logic that users who could easily keep track of where they have and have not searched would require less travel through the environment. Most notably, the average number of movements was highest while using the 120° HMD setup (see Figure 11). This could relate to problems with the high amplification and lack of physical cues making it easy to lose confidence of search coverage.

The high amount of movements in the 120° HMD may also be related to the high sickness effects in that condition (see Figure 12). It could be that orientation problems encouraged participants to make more movements, and then the additional movement contributed to increased sickness. It is also likely that the highest level of amplification (4x) was a contributing factor to the sickness effects in the 120° HMD condition, but it is important to note that the high amplification did not seem to be a problem with the CAVE with regard to sickness (see Figure 12). In fact, the amplified 120° CAVE had the lowest reported levels of sickness; this was surprising, as we were concerned that the 120° CAVE would cause significant discomfort due to the high discrepancy between the physical and virtual world. We suspect that the low sickness in the 120° CAVE is due to the ease of rotation and the low involvement of physical movements. While the 120° HMD also involves little physical rotation, the HMD implementation had other issues that could contribute to worse sickness, with the lack of physical directional cues as an example. More importantly, however, we suspect the discomfort associated with the heavy HMD, the presence of a light source so close to the eye, and the existence of visual artifacts from the HMD display. It is known that a variety of display and interaction issues can contribute to sickness in VR [25], and the effects in our study are likely a result of an amalgam of related factors.

Considering participant differences, participants who played more 3D video games performed the search task more effectively (i.e., they found more targets) and efficiently (i.e., they made fewer translational movements), which was not surprising since these participants probably had more practice with navigation and search tasks through 3D games. It is also interesting to note the gamers tended to experience fewer sickness symptoms, which suggests that experience in 3D environments provides some level of tolerance to sickness in virtual scenarios. We were surprised to find that gaming time was not correlated with orientation outcomes, as we expected that experience navigating virtual 3D spaces during games might better prepare users for similar exploration in our VR task.

We do note that because participants were not perfectly balanced across conditions according to gaming hours, and given the significant correlations with gaming, it is possible that the study outcomes were affected by the gaming distribution. We did do post-study analyses on gaming distribution to consider possible effects on the results, but we found no evidence for or against the notion that gaming hours might have skewed the effects due to display and amplification level. While participants were not balanced by gaming, no condition stood out as having an exceptionally different composition of gamers. All conditions had between 50% and 87.5% of participants in each group who reported regularly playing 3D games for at least one hour each week. In addition, four participants reported playing games for at least 10 hours each week. By chance, these participants were spread across the conditions, with four of the five conditions having one of the ”high gaming” participants (only the 270° CAVE condition did not).

Still, the study is limited in that we cannot determine exactly if and how the differences in gaming hours influenced the sickness and performance outcomes across conditions. Additional studies of rotation amplification is needed to generate more conclusive evidence about how different people with adapt to semi-natural interaction techniques.

6.3 Practical Implications of Amplified Head Rotation

The results of this experiment provide new knowledge of the implications of using rotational amplification in VR applications. We wanted to study amplification with the CAVE configuration to explore the feasibility of providing semi-natural view control interaction for large display or multiple-monitor systems. The study results with the CAVE conditions provide evidence that the addition of extra physical orientation cues helps to make rotation amplification feasible for viewing 360° of space within a smaller viewing range. One of the primary benefits of such a system for VR is that users are not cut off from the real world, as is often the feeling when using an HMD. Large-display systems allow others to directly observe what a user is experiencing with the system, and the user can also retain greater awareness of the observers. This may be desirable in cases where it is important to maintain communication or receive feedback during system use, as may often be the case for training scenarios.

The orientation results of the study also showed that participants were able to maintain spatial orientation in the CAVE environment. This could mean that large-screen or surround-screen systems could be appropriate for training purposes involving navigation and orientation. On the other hand, if the ability to maintain orientation was due to users taking advantage of orientation cues from the real world, as we suspect is the case, then it could be considered a detriment for users to become accustomed to using cues that would not be available to them in real environments.

Because our experiment was designed to study the effects of rotational amplification on spatial orientation, the environment and search task were designed to require a significant amount of rotation in the virtual space. Participants needed to make 360° rotations within tight spaces to thoroughly search the maze-like arrangement of warehouse shelves. However, many types of applications involve more open environments, less frequent turning, and more consistent movement towards the direction of a given destination. With less rotation, it would be expected that the effects of amplification are less noticeable or impactful on the user experience or spatial orientation. From their study or rotational gains in a five-sided CAVE, Freitag et al. [15] recommend gain factors between 0.85 and 1.18 in a CAVE. Their studies detected no negative effects of sickness near this range, though they did find evidence of reduced spatial knowledge. Prior studies with redirected walking have found the detection threshold for rotational gains to be 1.24x [45], though detection does not necessarily equate to negative side effects. On the other hand, prior research has also contributed evidence that rotational adjustments can influence performance on simple cognitive tasks [11]. Similarly, research with other types of semi-natural travel and virtual walking techniques have also found evidence that less realistic interactions can interfere with cognitive tasks [28, 51]. Thus, when considering amplified rotation, it would be important to continue studying cognitive factors in different scenarios and for different tasks.

We also want to note considerations related to testing both the CAVE and HMD scenarios and using the simulation approach to make the display configurations similar. The simulation approach demonstrates that the effects of amplification in both display variations were not consistent, which points to the importance of considering all display properties for VR systems. Similarly, the differences caution that findings from studies using a particular display type might not always be applicable to alternative displays. While we controlled for FOV and range of display coverage in our comparison, we could not account for other differences such as resolution, brightness, form factor, or end-to-end latency. Though we reported the hardware and software used for our experiment, we regret that we were unable to measure end-to-end system latency for the application. While the results of the study are meaningful for understanding the effects of rotation amplification on spatial orientation and sickness, it is possible that lower latency will improve the effectiveness of amplification methods. With recent and upcoming advances in display technology and new HMD models, we expect sickness issues to become less problematic.

Also important for interpreting the study's findings for HMDs is the use of virtual blinders. For the goals of the experiment, virtual blinders were added to the HMD conditions in order to establish consistency with the CAVE conditions for fair comparison. However, using amplification for real applications would not require blinders in an HMD. This difference could likely influence how users choose to rotate when using amplification; for example, users might prefer to continue rotating in one direction rather than reversing directions. Thus, perhaps the problems with sickness or orientation associated with high amplification in the HMD might also be different. In ongoing work, we are interested in studying the implications of amplified rotation in HMDs with more ideal configurations for comfortable use. Further research may be more relevant for better understanding the feasibility of adopting semi-natural interaction techniques for comfortable and convenient use of VR. Use cases include home situations in which users want to limit the necessary amount of physical movement, such as when viewing a 3D environment with an HMD while relaxing on a couch.

It would also be interesting to study the combination of different types of semi-natural viewing techniques and how they influence spatial orientation, usability, and sickness when used together. For example, Peck et al. [32] studied how the use of distractors in the environment could be used to make orientation adjustments less noticeable, and other researchers studied methods that make changes to the environment as a means of accommodating physical travel and view control [46, 47]. Other work has also studied ways to make orientation adjustments during saccadic eye movements as a way to make them less noticeable [6]. Other researchers have considered using dynamic levels of rotation amplification in VR (e.g., [52, 26, 39]). Zhang and Kuhl [52], for instance, studied discrete and continuous changes between gain factors, but more research is needed to understand human sensitivity to different types of rotation changes. Giving more attention to the implications for cognitive factors, Marsh et al. [29] presented an approach that dynamically adjusts the level of realism in semi-natural interaction based on the estimated cognitive load for the user at a given time. Additional research could investigate how such techniques could facilitate comfortable yet semi-natural interaction for different purposes, such as for home VR systems or as part of training programs.

7 Conclusion

Amplified head rotation is an interesting approach to semi-natural interaction using head movements to control viewpoint pitch and heading to enable 360° virtual rotation. We conducted a controlled experiment that allowed the comparison of amplified and unamplified viewing conditions for a search task requiring the user to maintain spatial orientation in a 3D environment. The experiment studied display configurations with different ranges of viewable area and the corresponding levels of amplification needed for 360° virtual rotation. Using a mixed-reality simulation approach, the study compared the different amplification configurations in both CAVE and HMD displays.

The findings demonstrate the feasibility of using amplified head rotation to view 360° of virtual space, as participants were able to easily understand the viewing technique and quickly adjust to the semi-natural interaction. However, the study found that differences in amplification, visible range, and display significantly affected spatial orientation, sickness, and training transfer for the search task. Noticeable problems were identified with the combination of high amplification (4x), a 120° visible range, and an HMD. Further, participants were able to more easily maintain a sense of spatial orientation when using the CAVE version of the application, which suggests that the CAVE's physical environmental cues and visibility of the user's body might have contributed to the ability to use the amplification technique while keeping track of orientation. In future work, it would be interesting to test whether the presence or absence of different types of static cues serve as a reference frame influencing the effectiveness of amplified rotation. For instance, an HMD could be used to simulate the physical seams of a CAVE. A self-avatar could also be simulated in an HMD, but thought would need to be given to determining how to rotate the avatar's body with respect to the world with amplified rotation.

All things considered, rotation amplification has promise for supporting comfortable and semi-realistic viewing. Amplification with large-display or surround-screen systems makes it possible to use physical view control for 3D rotation without inhibiting the sense of the real environment, and amplification with HMDs may be appealing for a variety of application areas such as entertainment or training.

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