Towards an Understanding of the Effects of Amplified Head Rotations

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ABSTRACT

Amplified head rotations have been proposed as a method to overcome the limitations of narrow field of view (FOV) and field of regard (FOR) in virtual reality (VR) systems, but little is known about the effects of amplification on task performance with various VR displays. We performed an exploratory study using visual scanning and counting tasks to investigate the effects of amplification with varying FOV and the detectability of amplification by users. In the visual scanning task, FOV had a significant effect on performance, with a non-significant trend for an interaction between amplification and FOV. Amplification had a significant effect on performance in the counting task. We discuss the implications of these findings for designers of VR systems and propose further studies to clarify our understanding of the effects of amplified head rotations.

KEYWORDS: Amplification, amplified head rotations, FOV, visual scanning, perceptual mismatch, virtual reality.

INDEX TERMS: H.5.2 [Interfaces and Presentation]: User Interfaces—Graphical user interfaces, Evaluation/methodology.

1 INTRODUCTION

Typical virtual reality (VR) systems use a one-to-one mapping between the user's tracked head movements and the corresponding changes in the visual display. When the user turns her head 30 degrees to the left, her view of the virtual world rotates by the same amount. Such a mapping is natural and easy to understand.

In some cases, however, it may be preferable to *amplify* the effects of head movements (i.e., use a control-display (C/D) ratio less than 1.0) in order to overcome various limitations of the VR system. For example, in a head-mounted display (HMD) with a narrow field of view (FOV), using an amplified head rotation mapping can reduce the amount of head movement required of the user, resulting in decreased fatigue or faster performance [5]. In a surround-screen display such as a CAVE, where the field of regard (FOR) is often less than 360 degrees (e.g., when there is no rear wall), amplification can allow the user to look in any direction in the virtual world using only head rotations [7]. Typically, such displays must provide virtual rotation of the world using a joystick or similar device.

Amplified head rotations in VR systems trick the user into thinking that he has physically turned farther than he actually has. Amplification relies on the visual dominance effect, since it introduces a mismatch between the visual and proprioceptive cues sensed by the user. Although this is a very simple perceptual illusion, it could have subtle and important effects on task performance, spatial orientation, fatigue, presence, and cybersickness, among other factors.

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Furthermore, there are many interesting open questions about the use of amplified head rotations. When do users notice the amplification? What level of amplification is desirable, and how much amplification is too much? How do other factors interact with the effects of amplification? Do the benefits of amplification depend on the display that is used? A greater understanding of this simple illusion could also be helpful in designing more powerful techniques, such as redirected walking [13].

In this paper, we report on an exploratory experiment designed to evaluate the effects of amplified head rotations on visual scanning and counting tasks. In particular, we were interested in the interaction between the level of amplification and the FOV of the display, since prior work suggested that amplification might be most effective with a narrow FOV [5]. Varying both FOV and amplification allows us to simulate different types of VR displays. High levels of amplification could be used in low FOR displays such as single flat screens to allow users to view the entire surrounding environment with head rotations only. The experiment measured task performance and the participants' ability to detect the amplification.

2 RELATED WORK

The use of amplification (C/D ratios lower than 1.0) has a long tradition in both VR systems and other user interfaces. On desktop computers, amplification is used to allow users to point to any area of the display using only small mouse movements. This of course raises the issue of precision, which is typically addressed by an adaptive C/D ratio depending on the velocity of the movement [1]. This idea has been applied in VR as well; for example, the PRISM technique [1] uses a dynamic C/D ratio for the mapping between the user's 3D hand movements and the movements of a virtual hand. Poupyrev's Go-Go technique [11] uses a one-to-one mapping when the hand is close to the body, and a non-linear amplification when the hand moves away from the body.

Amplification has also been applied to head and body movements in VR. To overcome the problem of small tracking volumes, techniques such as Seven League Boots [4] amplify physical walking to allow the user to walk to faraway regions in the virtual world. Amplified head rotations have also been implemented in a variety of VR settings, including desktop systems [12], fishtank VR [10], HMDs [5], and surround-screen displays [7].

Only a small number of studies, however, have attempted to understand the benefits and drawbacks of amplified head rotations. In general, these studies have reported that users find amplification to be intuitive and usable [5][12]. Two studies evaluated the effect of amplification on visual search task performance. Mulder et al. [10] found that performance with amplified head rotations in fishtank VR was not significantly different from other techniques for controlling viewpoint orientation. Using a narrow-FOV HMD, Jay et al. [5] found improved performance with the use of amplification as compared to the standard one-to-one mapping. Our experiment also employs a visual scanning task, but unlike these studies, we evaluate the effects of different levels of amplification and the interaction between amplification and the display FOV.

Prior work compared different amounts of amplified head rotation. Jaekl et al. [6] used an HMD with a 60º diagonal FOV 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. [1] 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 the scene movement and their head rotation. Head movement attenuations were noticed significantly faster than amplifications, especially in the highest levels of software FOV. On the other hand, Steinicke et al. [14] found that attenuations of yaw rotations were less noticeable, while Jerald et al. [7] showed that scene movement in the opposite direction of head rotations (i.e., amplifications) should be avoided.

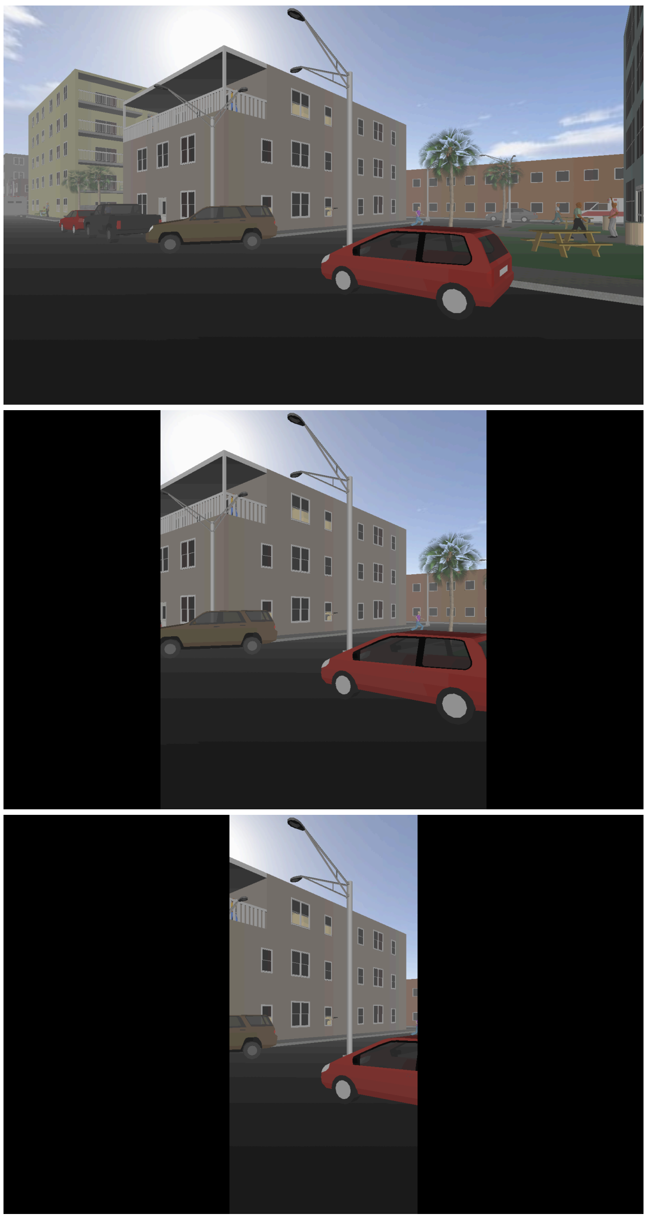

Figure 1. An example of the environments used for the visual scanning tasks. The images simulate the three levels of FOV used in the experiment (Top: 102º, Middle: 52º, Bottom: 30º).

The above research implies that at least with some displays, amplified head rotations will not be noticeable. Our work evaluates different levels of amplified head rotation, but to a higher degree, up to 3x. We also vary the physical FOV of the display (without introducing any scene distortion) and place an emphasis on task performance.

There have also been a number of studies on the effects of various levels of FOV in both virtual and real-world scenarios [e.g., 1,7]. In general, these studies have found negative effects of lower FOVs. Our experiment examines whether some of these negative effects on task performance might be mitigated by amplified head rotations.

3 EXPERIMENTAL DESIGN

To evaluate the effects of amplified head rotations, we designed two tasks: a visual scanning task where subjects had to locate threats on a busy city street (Figure 1), and a counting task where participants had to count the number of people surrounding a city intersection (Figure 2).

3.1 Goals and Hypotheses

Our overall goal was to study the effect of amplified head rotations and their interaction with FOV in a visual scanning task, and the effects of amplification alone in a counting task. We wanted to see whether participants would perceive variations in amplification, and whether the changes would have a positive or negative effect on performance. We predicted that subjects would quickly notice changes to FOV, but that amplification variations would be more difficult or even impossible to detect. We predicted a significant drop in performance for low FOV conditions; however we expected minimal changes in performance due to amplification. We suspected that amplification might actually improve performance in low FOV conditions, as participants would be able to see more of the environment with fewer head movements [5].

3.2 Tasks

The experiment involved two tasks: visual scanning and counting.

3.2.1 Visual scanning tasks

The visual scanning tasks were based on a military scenario involving looking for threatening people while driving down a city street. We placed participants in the middle of a street with buildings and side streets along one side. The system moved them along the street at a constant speed while they scanned for threats using the strategy they learned in a training phase.

The visual scanning strategy we developed aimed at maximizing visual coverage of the environment. The strategy consisted of using vertical head movements to visually scan the environment while moving down the street. When faced with an intersection or alley, we told participants to turn their heads to scan the opposite side of the intersection first, and then turn back to the initial side as they traveled past, continuing to use up and down head movements (see Figure 4). We instructed participants to follow their gaze with a crosshair that was controlled by a 6-DOF tracked hand-held wand, and to press a trigger button when they encountered a threat. During training, we held horizontal FOV constant at 102°, with no head rotation amplification.

For these tasks we employed a within-subjects design with two independent variables: horizontal FOV (102º, 52º, and 30°, accounting for the maximum HMD FOV, the maximum FOV with 100% binocular overlap and an FOV chosen to be very low) and amplified head rotations (C/D ratios of 1:1, 1:2, and 1:3 corresponding to amplifications of 1x, 2x, and 3x). As one of the goals of this study was to simulate different display characteristics, we chose to vary amplification more dramatically than previous studies [2][14]. With 2x and 3x amplifications, head rotations can be used to view the entire surrounding environment on displays that have physical FORs of 180º and 120º, respectively. Amplifications were applied to pitch, yaw and roll head rotations. We counterbalanced the ordering of the FOV and amplification conditions between subjects. Participants underwent nine series of four trials (36 trials total), with each series corresponding to a unique FOV and amplified head rotation configuration. The first trial in each series was an acclimation trial, not counted in the performance statistics, to allow the participant to adjust to the new configuration. This trial always used the training model, and the threats were in a constant position.

We created three base models to serve as the foundation for the remaining 27 trials. There were nine variations of each of the three base models, featuring unique building textures, people, cars, distractors, and threats. Only the street layout and building size remained consistent. We included one variation from each base model in every series of trials. We also varied the order of their appearance in the series, so that the sequence of base models varied throughout the experiment, but was the same for all participants. The order of the FOV and amplification conditions, however, was randomized between participants. For each trial, we measured the number of hits (correctly identified threats) and the number of false positives (non-threats identified as threats).

3.2.2 Counting Tasks

Since the visual scanning task only required scanning 180° of the environment, we chose to add an additional three trials that required a 360° rotation of the environment at the end of the experiment. The environment for these trials was a city intersection surrounded by buildings with three variations of cars and people (Figure 2). We asked participants to look around the environment and count the number of people. We placed the participants in the middle of the intersection to ensure they would need to turn a full 360° to scan for all people. Participants started each trial facing in the same direction in both the physical and virtual environments. We held the FOV constant during this portion of the experiment at 102°, and we varied the amplification within subjects at 1x, 2x, and 3x levels. Again, the order of the models was constant for all participants, while the order of the presentation of amplification was counterbalanced.

3.3 Apparatus

We used an nVisor SX111 HMD to display the environment. This HMD features dual SXGA displays (one per eye), each with a resolution of 1280x1024 pixels. The total horizontal FOV of the HMD is 102º, and the total vertical FOV is 64º. During the experiment, the vertical FOV was kept constant at 64°. Horizontal FOV was varied with the use of "virtual blinders" – black bars at the left edge of the left-eye view and at the right edge of the right-eye view. Because of the design of the HMD, not all conditions had 100% binocular overlap. Stereoscopic rendering was used for all tasks except for the first two training tasks (see section 3.4), as the spotlight used in those tasks could not be displayed correctly in stereo.

We controlled the crosshair in the environment using a wireless Intersense IS-900 wand, and we tracked the participants' head movements with a wired Intersense IS-900 head tracker.

We developed the software using the Vizard Virtual Reality Toolkit by WorldViz. The application ran on Microsoft Windows XP on a workstation with an Intel Core2 660 CPU at 2.40GHz and 2GB of RAM. The frame rate was fixed at 28 frames per second.

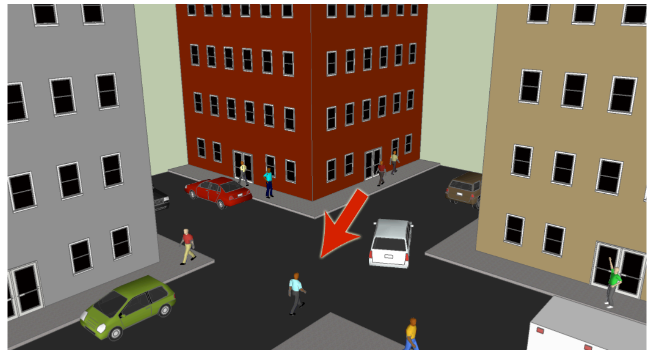

Figure 2. Environment used for the counting tasks. The participant was placed at the location marked by the red arrow.

Figure 3. Examples of threats used in the visual scanning tasks. Note that participants did not see these views; they were moving along the street and could only look for threats from that location.

We developed the models for the environment in Google SketchUp. Each model for the visual scanning task was 800 feet long, and had a depth of 75 feet (for side streets and alleys). We varied the buildings with regard to height (1-6 stories), shape, texture, and window/balcony patterns. We included a variety of street items (cars, trees, streetlights, garbage cans, benches, etc.), balcony items (chairs, tables, plants, etc.) and people (non-threats) to increase the visual complexity of the scene. In each model we included four to six threats in plausible locations (Figure 3). These locations included balconies, tops of buildings, windows, and alleys. We also positioned threats in locations where they were partially obscured by buildings and/or street items. However it should be noted that we positioned the threats to ensure they could all be spotted when participants followed the correct scanning strategy.

We exported the SketchUp models to Autodesk 3DS Max and added occluders to the models using the Open Scene Graph plug-in in order to improve the application frame rate.

3.4 Participants

We recruited six voluntary unpaid participants for the experiment. All participants were male, and their ages ranged from 20 to 26 years old (median age 20.5). All had experience with motion tracking games, however only one participant reported playing more than one hour a week (5 hours). Video game experience was variable, with two reporting less than an hour of play a week, and two reporting 10 or more hours a week. Only one participant had any practical experience with immersive VR.

3.5 Procedure

We greeted the participants upon arrival and gave them a consent form to read and sign. We then had them complete a short background questionnaire, followed by a color-blindness screening. We introduced participants to the task and showed them sample pictures of threats and non-threats they would encounter in the environment. We introduced the participants to the equipment, and asked them to put on and adjust the HMD. We gave the participants time to familiarize themselves with the HMD, head tracking, and how the wireless wand corresponded to the crosshair in the environment.

Once the participants were comfortable with the equipment they began the strategy training stage. There were four steps in the training process:

1. Blank buildings with arrows and a moving spotlight directing their gaze (Figure 4). We told participants to follow the arrows/spotlight with their eyes and the crosshair. (2 trials)
2. Textures/windows added to the buildings, arrows removed, and a spotlight. We told participants to follow the spotlight with their eyes and the crosshair. (1 trial)
3. Spotlight removed, people, cars and other distractors added to the environment. We told participants to continue the same visual strategy. (1 trial)
4. Threats added to the environment. We told participants to continue following the same visual strategy and to point and click the trigger button when they found a threat. (2 trials)

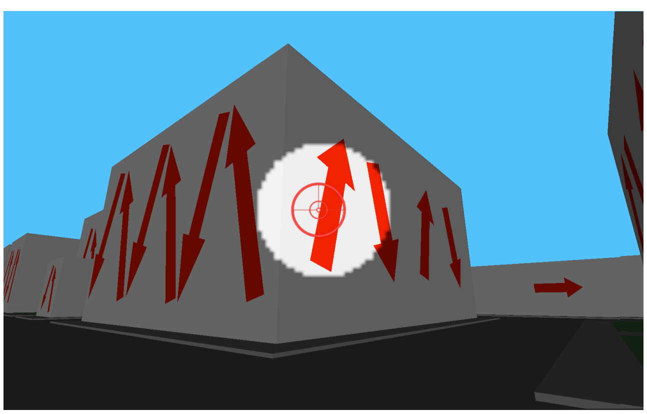

Figure 4. Environment used in the first phase of strategy training.

We provided feedback throughout the training to ensure that participants followed the correct visual scanning strategy. Once participants completed the training process they immediately began the visual scanning trials. In total there were 36 trials, and they had a required five-minute break after they completed 16 trials. Once participants completed all the visual scanning trials, we asked them what differences they noticed during the trials to find out whether participants noticed the variations in amplification and FOV. We then asked participants to once again put on the HMD to begin the three counting trials. We instructed participants to look around the full 360º in the environment and count the total number of people. Once completed, we again asked participants what differences they noticed between the trials. If participants did not mention the head rotation amplification, we also asked if they noticed anything out of the ordinary when they turned their head.

4 Results

There were a total of 162 data points used in the data analysis for the visual scanning tasks, 27 for each participant. The three data points per condition for each participant were averaged for the analysis, leading to a total of nine data points per participant.

An analysis of variance (ANOVA) with repeated measures was performed on the experimental data, and there was a main effect of FOV on the rate of threats found ($F(2,10)=4.56, p<0.05$), with the lowest FOV (30º) resulting in significantly worse performance than the other two FOVs. There was no main effect of amplification ($F(2,10)=0.518$, $p=0.61$) and only a marginally significant interaction between these factors ($F(4,20)=2.55$, $p=0.071$).

Figure 5 summarizes the results for threats correctly identified. We can see a trend toward better performance for the tasks performed with low FOV in the presence of amplification. When the FOV was at 30º, there was an average improvement in performance with amplification. As the FOV increases, however, the trend is not so clear. With 52º FOV, for example, it may seem that the highest amplification actually hurts performance, but a moderate amplification may help users. There is little difference in the performance means for the highest FOV (102º) in light of head rotation amplifications.

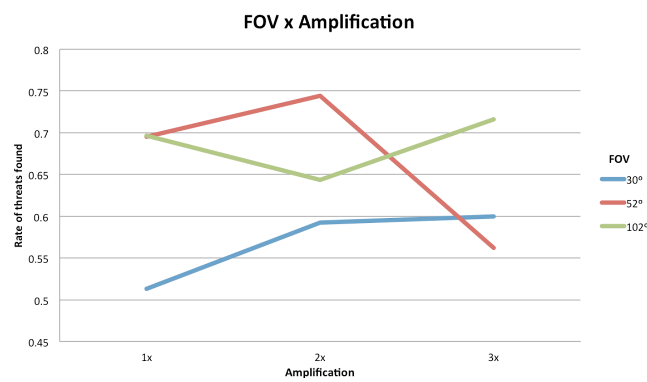

Figure 5. Summary of data from the visual scanning trials. Error bars are not displayed because, as there were no statistically significant differences, they largely overlap and only clutter the graph.

Another measure for the visual scanning tasks was assignment of false positives (indicating a threat in an area where no threat exists), but we found only ten instances of false positives. These ten instances seem to be randomly distributed among the conditions. Four of them occurred with both 30º and 102º FOVs, while the 52º FOV resulted in two false positives. Four of the false positives occurred with an amplification of 3x, with three in each of the other two amplification levels.

We found a significant effect of amplification on performance of the counting task ($F(2,8)=4.45$, $p=0.05$). With 1x amplification, three of five participants (there was a technical problem that prevented those tasks to work for one participant) counted the correct number of people, and the other two undercounted by one (mean error of -0.4). With 2x amplification, three participants counted the correct number of people, another undercounted by one, and the last overcounted by two (mean error of +0.2). At the 3x level of amplification, only two participants counted correctly, two overcounted by two, and one overcounted by four (mean error of +1.6).

We also asked questions of the participants to determine how noticeable the amplification effect was. When asked what they thought was different among the visual scanning tasks at the end of that session, three of the six participants indicated spontaneously that they felt the environment was "more responsive" or "faster for head movements" at times (both of the participants who reported playing video games 10 or more hours per week noticed this effect). After the 360º counting task, however, none of the five participants reported that they felt the amplification.

5 Discussion

The explanatory power of our pilot experiment is limited in several ways. We had a small number of participants and a measure of performance without much opportunity for clear separation among the conditions. In addition, our task depended more on vertical scanning than horizontal scanning, but our manipulation of the FOV was in the horizontal direction only. However, we can draw some preliminary inferences and hypotheses for future work from these results.

First, we found that amplification had no significant main effect on performance in the visual scanning task. This implies that large (up to 3x) amplified head rotations could be used in some virtual environments involving visual scanning without a performance penalty. Since amplification may have other beneficial effects (reduced head movements, reduced fatigue, decreased risk of getting tangled in wires), designers may want to consider its use. Of course, we do not know whether amplification might have other negative effects (e.g., on cybersickness or presence).

More important than the lack of a main effect, however, is the trend we found for an interaction between amplification and FOV. Although the nature of this interaction is not completely clear from our results, it is possible that amplification may improve performance with very narrow FOVs and either have no effect or even decrease performance with moderate to high FOVs. If this proves to be correct, it may imply that the visual-proprioceptive mismatch has a cost associated with it that is only outweighed by the benefits of amplification in low FOV conditions. Clearly, however, further work is needed to study this potential interaction.

On the other hand, we did find an effect of amplification on performance in the counting task, with the highest level of amplification leading to the worst performance. Participants tended to double-count some of the people in this condition, indicating that they were not sure whether they had searched the entire 360º space surrounding them. This is likely due to the mismatch between the proprioceptive and visual feedback – participants only had to turn 120º in the 3x amplification condition in order to view the entire environment.

Why was there minimal effect of amplification in the visual scanning task and a significant effect in the counting task? The main differences between the two tasks that may give rise to this are: a) the counting task required a complete 360º turn in the virtual environment, while the visual scanning task required only turns of +/- 90º, and b) the counting task took place in a symmetric environment where there were no obvious landmarks to indicate which direction the user is facing in the virtual world. Thus, our preliminary recommendation is to avoid very high levels of amplification when users must make large view rotations and when the environment doesn't offer sufficient visual cues to determine the orientation of the view.

Our initial findings on the detectability of amplified head rotations are also interesting. Only half of the participants reported that they noticed any amplification after the visual scanning trials, while all of the participants noticed that we were varying FOV. Interestingly, none of the participants (even those who detected varying "responsiveness" in the visual scanning tasks) mentioned anything about amplification or responsiveness after the counting tasks. Since those tasks were always performed with the full 102º FOV, we surmise that users may notice amplification more easily with a narrow FOV due to increased optic flow. Alternatively, the difference in detection rates between the tasks could be due to the speed of head movements required. The visual scanning tasks were done under time pressure since the "vehicle" was moving down the street, resulting in more rapid head movements. The counting tasks could be done using slower head movements (although we did measure the time to complete this task, we did not instruct participants to perform as quickly as possible). Amplification may be more noticeable with faster head movements.

Previous studies showed that users detected amplification at much smaller rates, sometimes lower than 1.5x [2,14]. We believe that such discrepancies from our study may be due to the fact that, in our experiment, participants weren't aware that there could be any differences in head amplification, while in the prior work, participants were instructed to tell when the differences in the head movement mapping were noticeable. Since participants weren't looking for mapping differences in our experiment, they did not allocate attention resources trying to find them and amplifications as high as 3x could be applied unnoticed. This indicates that amplification can be used to a large degree without distracting users from the main task.

The fact that many users could not detect even large amplifications could be helpful to VR designers looking to use more complex perceptual illusions, such as redirected walking [13]. Redirected walking techniques could benefit from the use of both amplified (C/D ratio less than 1.0) and attenuated (C/D ratio greater than 1.0) head rotations in order to keep the user inside the tracked physical area.

Certainly, a larger participant pool for a future experiment will lead to a clearer analysis, but also we believe that we need some modifications to the targets in our visual scanning task. Our environments each had four to six threats. These threats were generally spread far enough apart that most people found the same ones independently of the amplification or FOV values. In the future, we will place a greater number of threats in the environment in such a way that a narrow FOV coupled with no amplification would make the task extremely difficult. With this modification, the amplification may have a clear benefit to performance, as small head rotations would allow the environment to be searched more completely, and more threats could come into view before they disappeared behind a building.

In this initial study, we only varied the horizontal FOV, while the vertical was kept at its maximum of 64º. This resulted in an unnaturally tall and narrow display in the low FOV condition (see Figure 1, bottom). The reduced horizontal FOV affects the user's ability to look further up the street or to look back at areas already passed. Unfortunately, however, our visual scanning strategy was based primarily on vertical scanning, so that the narrow FOV probably did not have as large an effect on performance as it could have. We believe that stronger results can be derived if we keep the aspect ratio of the display constant by changing both horizontal and vertical FOV proportionally. Additionally or alternatively, we could apply amplifications only to a subset of all possible head rotations (e.g., only to yaw or pitch).

6 Conclusions and future work

We have reported on a preliminary experiment aimed at understanding the effects of amplified head rotations on visual scanning and counting tasks with varying display characteristics. The study is not fully conclusive, but indicates a likely interaction between the level of amplification and FOV for visual scanning performance, and a negative effect of large amplifications for the 360º counting task. In addition, we found that not all users notice amplifications even when the visual scene moves up to three times faster than the user's head. These results have important implications for designers of VR systems, particularly those considering the use of amplifications or more complex perceptual illusions.

In the short term, we are planning to run a complete experiment to assess the trends found in the study reported here. In the long term, we plan to study the effects of amplification in different VR displays (e.g., multi-monitor desktop setups, CAVEs), and how amplified head rotations affect cybersickness and presence.

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