

The Influence of Head Tracking and Stereo on User Performance with Non-Isomorphic 3D Rotation

Joseph J. LaViola Jr.^{1†} and Andrew S. Forsberg² and John Huffman³ and Andrew Bragdon²

¹University of Central Florida, School of EECS, Orlando, FL USA

²Brown University, Department of Computer Science, Providence, RI USA

³Brown University, Center for Computation and Visualization, Providence, RI USA

Abstract

We present an experimental study that explores how head tracking and stereo viewing affect user performance when rotating 3D virtual objects using isomorphic and non-isomorphic rotation techniques. Our experiment compares isomorphic with non-isomorphic rotation utilizing four different display modes (no head tracking/no stereo, head tracking/no stereo, no head tracking/stereo, and head tracking/stereo) and two different angular error thresholds for task completion. Our results indicate that rotation error is significantly reduced when subjects perform the task using non-isomorphic 3D rotation with head tracking/stereo than with no head tracking/no stereo. In addition, subjects performed the rotation task with significantly less error with head tracking/stereo and no head tracking/stereo than with no head tracking/no stereo, regardless of rotation technique. The majority of the subjects tested also felt stereo and non-isomorphic amplification was important in the 3D rotation task.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: User Interfaces - Evaluation/Methodology

1. Introduction

Effectively rotating objects in 3D space is an important part of many 3D user interfaces. In fact, rotating 3D objects is part of one of the fundamental 3D interaction tasks (i.e., selection and manipulation) used in 3D applications [BKLP04]. Given this task is a common component of many 3D user interfaces, it is important to evaluate and understand how 3D rotation techniques perform under different conditions so guidelines can be established. These guidelines can then assist 3D user interface designers in choosing appropriate 3D rotation techniques that maximize speed and efficiency while minimizing rotational error.

One approach to rotating objects in 3D space is to use non-isomorphic mappings [BKLP04]. Non-isomorphic mappings let users interact with virtual world objects at an amplified scale, in contrast to isomorphic mappings (i.e., one-to-one mappings) that maintain a direct correspondence

with the physical and virtual worlds. For example, with a non-isomorphic mapping, a user rotating a tracked input device 20 degrees about the y -axis in the physical world would rotate the corresponding virtual object 40 degrees (with the appropriate amplification factor). In the isomorphic case, the virtual object would be rotated only 20 degrees. Thus, although isomorphic mappings are the most natural in terms of interaction in the physical world, they have significant shortcomings due to limited ranges of input devices and anatomical constraints of users.

Although there has been work on testing whether or not non-isomorphic 3D rotation has an effect on user performance in both 3D desktop [PWF00] and immersive virtual environments (VEs) [LK07], the specific effects of stereoscopic viewing and head tracking on non-isomorphic 3D rotation has not been rigorously explored. Thus, we present a usability study that explores how user performance with both isomorphic and non-isomorphic 3D rotation is affected by different VE display modes (no head tracking/stereo, stereo only, head tracking only, both head tracking and stereo).

† jjl@cs.ucf.edu

In the next section, we discuss work related to non-isomorphic mappings and non-isomorphic rotation. Section 3 describes our experiment in detail along with statistical results. Section 4 presents a discussion of our experimental findings and ties them to prior work. Finally, Sections 5 and 6 present future work and conclude the paper.

2. Related Work

Non-isomorphic mappings can be applied to both the translation and rotation of virtual objects in 3D user interfaces. For translation, there have been several non-isomorphic techniques for both translation of virtual objects and navigation through virtual environments [BH97, PSP99, PBW196, ZLFK02]. Other non-isomorphic mapping techniques for translation can be found in [BKLP04].

In contrast with non-isomorphic translation, non-isomorphic 3D rotation techniques have received less attention. In addition to our own work [LK07], early studies by Chen et al. [CMS88], and Hinckley et al. [HTP*97], explored user performance with different 3D rotation techniques. However, their work did not focus on non-isomorphic mappings using 3D input devices. Chen et al. focused on the effectiveness of 3D rotation with 2D controllers while Hinckley et al. compared 3D rotation using 6DOF tracking devices with two standard 2D rotation techniques: ARCBALL and the Virtual Sphere. Ware and Rose also conducted studies with 3D rotation [WR99]. Their work was focused on understanding the differences between rotating virtual objects and real objects.

Poupyrev et al.'s [PWF00] work introduced a mathematical framework and design guidelines for developing non-isomorphic 3D rotation techniques and was the first to conduct an experiment exploring their effectiveness. This work spawned further research into the development and evaluation of non-isomorphic rotational mappings. For example, LaViola et al. [LFKZ01] and Jay and Hubbold [JH03] both developed non-isomorphic rotation techniques for amplifying head rotations in virtual environments to counteract field of view problems. LaViola et al. developed a technique that gave users a full 360 degree field of regard in a surround screen virtual environment that had only three walls. However, they did no evaluation to determine the effectiveness of their technique. Jay and Hubbold developed a similar technique that targeted field of view problems in head mounted displays. Their experimental results showed significant performance improvements for a visual search task but that users cannot interact normally without the corresponding body movements amplified to the same degree as the head movements. In both these cases, the work focused on navigation rather than rotation of virtual objects.

More recently, Froehlich et al. [FHSH06] used a non-isomorphic rotational mapping as part of the design of desktop-based input devices, the GlobeFish and Globe-

Mouse, for creating larger rotations and increase the sensitivity of smaller rotations. They pilot tested several scaling factors from one to five and found three to be most appropriate for their devices but did not report any performance results for the other factors. Dominjon et al. [DLBR06] compared non-isomorphic rotation with a hybrid haptic-based approach for performing rotations. They used a scaling factor of four and found that their approach had better performance than the isomorphic approach. However, as with Froehlich et al., Dominjon et al. did not experiment with non-isomorphic rotation techniques in an immersive VE where stereo and head tracking are important components of the display configuration. To the best of our knowledge, this paper presents the first study to directly compare how different immersive VE display modes affect users when performing 3D rotation tasks with a non-isomorphic mapping.

3. Experimental Study

We conducted an experimental study to explore how non-isomorphic 3D rotation of virtual objects affects user performance in the context of immersive VEs. In a previous study [LK07], we expanded Poupyrev et al.'s [PWF00] experimental design to evaluate different non-isomorphic amplification factors and to see how user performance was affected with different accuracy thresholds. In addition, we wanted to understand the benefits of non-isomorphic 3D rotation in an immersive VE.

Although the results from our previous study show that subjects could perform a 3D rotation task 15% faster using a non-isomorphic rotation technique (with an amplification factor of three) than with isomorphic rotation with no statistically significant loss in accuracy, it is unclear how the immersive VE contributed to this performance gain. Thus, for the current study, our goal is to explore how head tracking and stereoscopic vision impact user performance when rotating virtual objects using isomorphic and non-isomorphic 3D rotation techniques.

3.1. Subjects and Apparatus

Sixteen subjects (9 male, 7 female) were recruited from the Brown University population with ages ranging from 18 to 50. Of the 16 subjects, 14 were right handed and two were left handed. 11 subjects had little or no experience with 6DOF input devices. Since hand-eye coordination is related to the participants' ability to perform the experimental task, we also asked participants if they played video games, had ever used a six DOF tracker for rotating 3D objects, and to rate their level of expertise with tasks requiring sensitive motion. For video games, eight out of the nine males and three out of the seven females answered yes to this question. For using the six DOF tracker, six subjects said they had used one in the past (all six were males), with 10 subjects (seven females) having no experience with the device.

Nine subjects claimed they had a moderate amount of experience with tasks requiring sensitive motion while five subjects rated their experience as low and two as high. The experiment took 40 to 50 minutes per subject and all subjects were paid 10 dollars for their time.

The experiments were conducted in Brown University's surround screen virtual environment (SSVE) with three walls and a floor at a resolution of 1024x768 per wall. The refresh rate was 120Hz (60Hz per eye). A 6DOF Polhemus FASTRAK magnetic sensor was placed inside a rubber ball and used as the input device for rotating the virtual objects. A Wanda, a three button navigation device, was used as a triggering device in the non-dominant hand.

3.2. Experimental Task

The experimental task users perform follows from the orientation matching task used in our last experiment [LK07]. Participants were instructed to rotate a solid shaded 3D model of a house from a randomly generated orientation into a target orientation (see Figure 1), which has been used in several studies in the past [CMS88, HTP*97, PWF00]. The house filled a visual angle of approximately 5-10 degrees for a viewing distance of about 4 feet initially, but for the head-tracked condition the angle may be much larger if they got close to the house. Subjects were told that while they should not rush, they should aim to minimize their time and maximize their accuracy. The target orientation was such that the house lay flat on a checkerboard plane, and its front (indicated by a door) faced the opening of the SSVE. The house was designed to provide maximum cues to understanding its orientation from any angle, with asymmetric placement of windows, its chimney, and the coloring of its walls. In addition, text on the screen indicated whether head tracking and stereo were enabled and which type of rotation (isomorphic or non-isomorphic) was active.

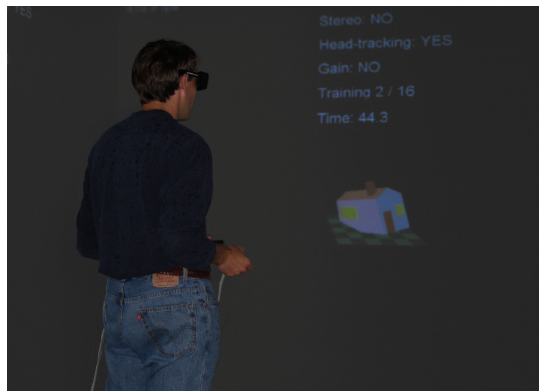


Figure 1: A subject rotating the house model to its target orientation.

Users could rotate the house when the button on the



Figure 2: The target orientation in the house rotation task.

Wanda was depressed. The user would start or stop the rotation by pressing or releasing the button on the Wanda. The user could iteratively rotate the house by holding the button, rotating the ball device, releasing the button, repositioning the ball device, holding the button, etc. as many times as necessary. Each time the user released the button, the orientation error, defined as the angular distance between the current and goal orientations was calculated using

$$\frac{2(180)}{\pi} \arccos((q_g(q_{d_i})^{-1})_w) \quad (1)$$

where q_{d_i} is the current orientation quaternion and q_g is the goal orientation quaternion as shown in Figure 2. When the error was below the threshold, the house would immediately disappear and reappear in a new random orientation, indicating that the trial had been accomplished.

3.3. Experiment Design and Procedure

We used a 4 x 2 x 2 balanced, within subjects factorial design where the independent variables were VE display mode (i.e., the four permutations of head-tracking and stereo on or off), rotation amplification, and the orientation error threshold. The coefficient of amplification varied between either one (isomorphic rotation) or three (non-isomorphic rotation). Note that we chose the value three for the non-isomorphic rotation amplification coefficient because it was found to be most preferred, faster, and provided the best accuracy in our previous study [LK07]. The orientation error threshold was either six or 18 degrees. We used the same set of 10 random house rotations each of which had error between 70 and 180 degrees (see Figure 3). The orientations in the initial set of house orientations appeared to be too easy to rotate to the target orientation, so we replaced them with more difficult ones. Each subject completed 10 repetitions of each of the 16 conditions for a total of 160 trials.

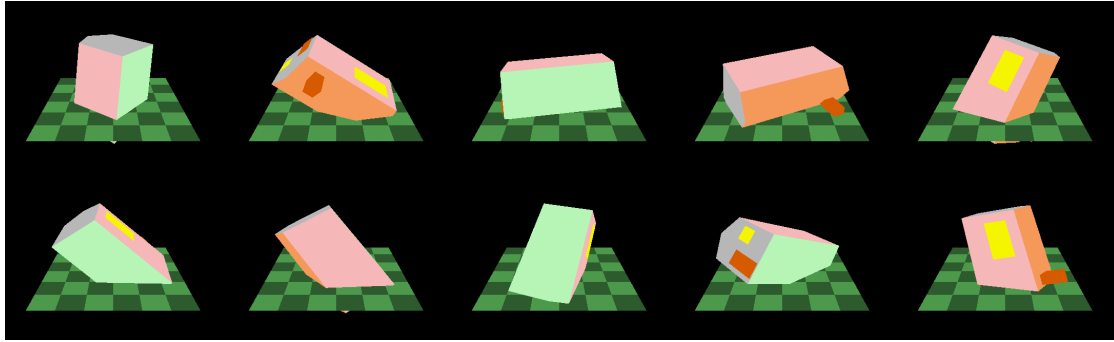


Figure 3: The 10 initial starting orientations for the house rotation task.

The dependent variables were task completion time and final orientation error. Completion time is the time from the user first pressing the Wanda button until releasing the button while the orientation error is below the error threshold. Orientation error is the angular distance between the orientation of the house upon completing a trial and the house's target orientation.

The experiments began with a pre-questionnaire, followed by an explanation of the SSVE, the devices involved, the experimental task and procedure, and the techniques involved in accomplishing the task. There was then a training session where the subject was given one trial under each of the 16 conditions to be tested (each possible combination of four VE display modes, two amplification coefficients and two error thresholds). This allowed the user to get used to the techniques, devices, and conditions in the experiment. Subjects were told they could study the initial orientation as long as they wanted, but when they pressed the Wanda button the first time to rotate it, a timer would be displayed and start counting until they matched the target orientation.

After the training session, subjects were asked whether they felt comfortable with the isomorphic and non-isomorphic rotation techniques. In each case, the subject said yes and the experiment was started. The subject then performed 16 sets of 10 trials, each set represented one of the test conditions, and each of the 10 trials within a given set had the same display mode, amplification coefficient, and orientation error threshold. To control for order effects, the ordering of the 16 sets was randomized through a Latin square design for each of the 16 subjects.

In this study the house was positioned so it was centered on the front wall of the SSVE display. In [LK07] the house had been positioned in the center of the SSVE, but in piloting this study some subjects were distracted by the "jump" in perceived house position as the viewing condition altered between stereoscopic and monoscopic. Specifically, with stereo viewing the house appeared in the center of the SSVE (as it was meant to), but with monoscopic viewing accommodation and convergence depth cues dominate and

the house appeared to be four feet further away on the front screen of the SSVE. We addressed this by translating the house from the center of the SSVE to the front wall of the SSVE so the perceived "jump" in position was minimized between the stereo and mono viewing conditions.

In the post-questionnaire, subjects were asked how important head tracking, stereo, and rotation amplification was in completing the rotation task. A five point Likert scale was used (very low, low, moderate, high, and very high). They were also invited to give other comments they had on the study.

3.4. Results

A repeated measures three-way analysis of variance (ANOVA) was performed for each of the dependent variables with display mode (DM), amplification coefficient (AC), and error threshold (ET) as the independent variables. Table 1 summarizes the main effects of the independent variables as well as their interaction for both completion time and error. Note that for error under DM, the sphericity assumption was violated resulting in a Greenhouse-Geisser correction. Display mode, amplification coefficient, and error threshold significantly affected both task completion time and error. There were no significant interaction effects between the three independent variables. The results for the error threshold condition makes intuitive sense, since subjects often had to perform more than one clutching step to obtain a correct target orientation during trials with the six degree threshold requirement. Thus, subjects took longer to complete the task. For error, the nature of the error threshold condition created a significant effect because subjects had to be more accurate with the six degree threshold than the 18 degree threshold.

We conducted a post-hoc analysis on display mode (DM) for both completion time and error to gain a better understanding of its effect on user performance in our rotation task. We performed pairwise comparisons using Holm's sequential Bonferroni adjustment [Hol79] with six compar-

Effect	Time	Error
DM	$F_{3,13} = 3.33$ $p < 0.05$	$F_{1,79,13} = 8.193$ $p < 0.05$
AC	$F_{1,15} = 4.68$ $p < 0.05$	$F_{1,15} = 13.8$ $p < 0.05$
ET	$F_{1,15} = 11.77$ $p < 0.05$	$F_{1,15} = 15.46$ $p < 0.05$
DM × AC	$F_{3,13} = 0.191$ $p = 0.902$	$F_{3,13} = 0.307$ $p = 0.82$
DM × ET	$F_{3,13} = 0.617$ $p = 0.608$	$F_{3,13} = 1.76$ $p = 0.168$
AC × ET	$F_{1,15} = 0.001$ $p < 0.975$	$F_{1,15} = 0.091$ $p = 0.767$
DM × AC × ET	$F_{3,13} = 0.637$ $p = 0.595$	$F_{3,13} = 1.96$ $p = 0.134$

Table 1: The main and interaction effects for display mode (DM), amplification coefficient (AC), and error threshold (ET) for both time and error. Note that for error under DM, the sphericity assumption was violated resulting in a Greenhouse-Geisser correction.

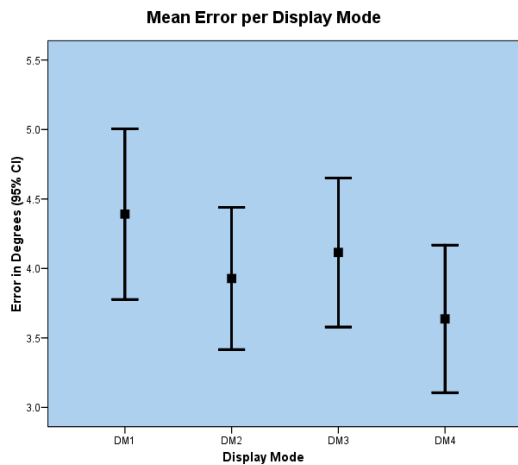


Figure 4: Mean rotation error (in degrees) and 95% confidence intervals for each display mode with error threshold and amplification coefficient collapsed. Significant differences were found between DM4 and DM1, DM4 and DM3, and DM2 and DM1.

isons for each dependent variable at $\alpha = 0.05$ for no head tracking/no stereo (DM1), no head tracking/stereo (DM2), head tracking/no stereo (DM3), and head tracking/stereo (DM4).

For task completion time, subjects completed the rotation task significantly faster ($t_{15} = -3.149, p < 0.0083$) under the no head tracking/stereo (DM2) mode (4.25 seconds) than

with the head tracking/stereo (DM4) mode (4.6 seconds). All other pairwise comparisons were not significant.

For error (see Figure 4), subjects completed the rotation task with significantly less error ($t_{15} = 4.39, p < 0.0083$) under the head tracking/stereo (DM4) mode (3.63 degrees) than with the head tracking/no stereo (DM3) mode (4.11 degrees) and with significantly less error ($t_{15} = 3.39, p < 0.0125$) than with the no head tracking/no stereo (DM1) mode (4.39 degrees). In addition, subjects also performed with significantly less error ($t_{15} = 3.47, p < 0.01$) under the no head tracking/stereo (DM2) mode (3.92 degrees) than with no head tracking/no stereo (DM1). All other pairwise comparisons were not significant. These results indicate that stereo plays an important role in user performance when performing both isomorphic and non-isomorphic 3D rotation tasks.

We also conducted a post-hoc analysis on the amplification coefficients (AC) in each display mode (DM) for both completion time and error to further explore how the isomorphic and non-isomorphic rotation techniques are affected under the different display conditions. We performed pairwise comparisons using Holm’s sequential Bonferroni adjustment [Hol79] with 10 comparisons for each dependent variable at $\alpha = 0.05$. Four comparisons are used to test for significance between isomorphic rotation (AC1) and non-isomorphic rotation (AC3) within each display mode with the remaining six comparisons testing for significance between AC1 and AC3 across display modes. Figures 5 and 6 show the mean completion time and error across the different display modes respectively.

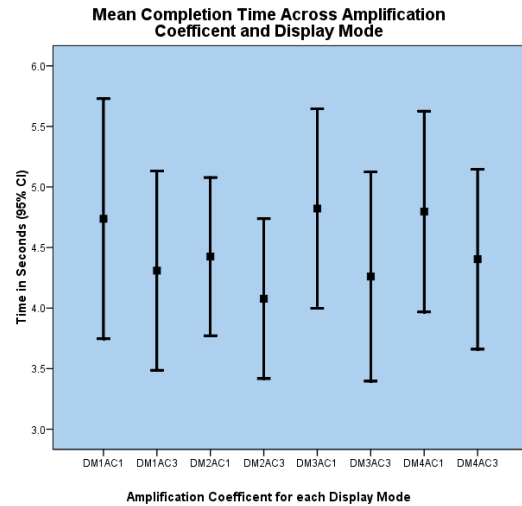


Figure 5: Mean completion times (in seconds) and 95% confidence intervals for each amplification coefficient in each display mode with error threshold collapsed. There were no significant differences found in this data.

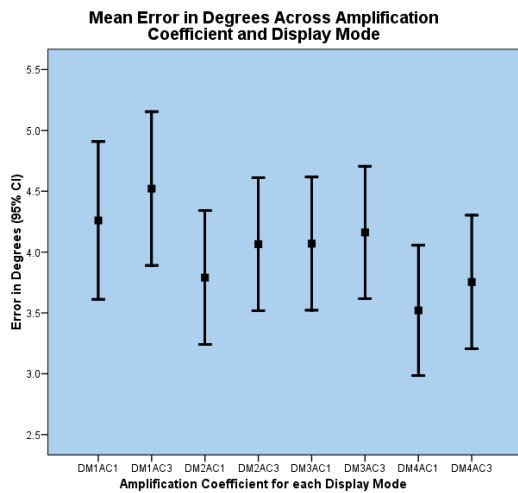


Figure 6: Mean rotation error (in degrees) and 95% confidence intervals for each amplification coefficient in each display mode with error collapsed. Subjects were significantly more accurate when using non-isomorphic rotation in DM4 than in DM1.

For task completion time, we did not find any significant differences for the 10 pairwise comparisons due to the Bonferroni correction. However, Figure 5 does show a trend in the data where for each display mode, subjects, on average, took less time to complete a rotation task using the non-isomorphic (AC3) technique than with the isomorphic (AC1) technique. Subjects completed the rotation task 9.9% faster with the non-isomorphic technique than with the isomorphic technique in DM1, 8.5% faster in DM2, 13.2% faster in DM3, and 8.9% faster in DM4.

For error, we found that subjects were significantly more accurate ($t_{15} = 3.487, p < 0.005$) when using the non-isomorphic technique under the head tracking/stereo display (DM4) mode (3.75 degrees) than under the no head tracking/no stereo display (DM1) mode (4.52 degrees). This result indicates that the combination of head tracking and stereo plays an important role in a subject's ability to accurately perform *non-isomorphic* rotation tasks. In addition we found no significant differences in accuracy between the isomorphic and non-isomorphic rotation techniques for each display mode (DM1: $t_{15} = -1.54, p = 0.14$, DM2: $t_{15} = -1.49, p = 0.16$, DM3: $t_{15} = -0.98, p = 0.33$, DM4: $t_{15} = -2.28, p = 0.038$).

In addition to the dependent variables in our experiment, subjects filled out a post-questionnaire and were asked to rank, using a five point Likert scale, how important they felt stereo, head tracking, and rotation amplification affected their ability to perform the orientation matching task. The importance rankings, shown in Figure 7, show that 11 out of

16 subjects felt stereo was moderately to highly important in completing the rotation task, while nine out of 16 felt amplification factor was highly to very highly important. The results were mixed on the importance of head tracking in the experiment as the rankings were fairly well spread over the five point scale in a normally distributed fashion.

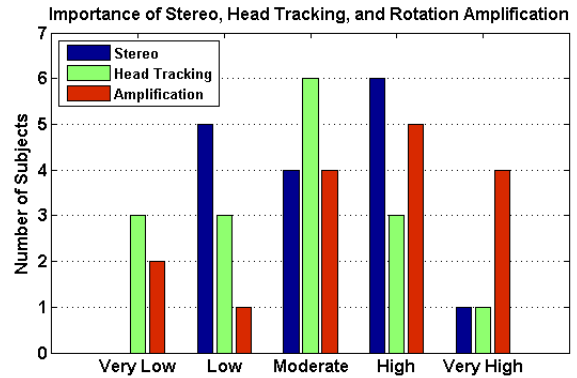


Figure 7: Subject ranking on the importance of stereo, head tracking, and rotation amplification in completing the orientation matching task.

Subjects were also asked to comment on their experiences during the study. Many subjects reported that the wire attached to the rubber ball interfered with their range of motion, although not prohibitively - and several subjects suggested that a wireless device would be easier to use. Five subjects reported that gain was more useful for making large rotations than small adjustments, and two subjects reported that a way to vary gain would improve the non-isomorphic technique's usefulness. Four subjects reported that head tracking became less useful once they became better acquainted with the detailed geometry of the house, as they were able to use cues such as the window and location of the chimney to better judge the initial orientation of the house without using head tracking. In fact, not everyone made use of head tracking; one subject reported, "I don't think I moved my head the entire time I was in there." One respondent reported that "neither technique felt as natural as tumbling a real object. I also wanted to use both hands." One subject reported that they oriented the wired-end of the rubber ball to be in the same direction as the house, and then rotated it back towards their chest, much like tumbling a real object, as a shortcut to increase their efficiency.

4. Discussion

From our experimental results, there are some interesting comparisons to be made with our current study and with our previous study [LK07] and Poupyrev et al.'s study [PWF00]. In terms of rotation accuracy, subjects completed the rotation tasks (both with isomorphic and non-isomorphic rotation) with an average of 6.8 degrees of error in Poupyrev

et al.'s study. With this study, no head tracking or stereo was used. In our current study, in the no head tracking/no stereo (DM1) display mode, subjects completed the rotation task with an average error of 4.39 degrees, and if we separate the trials with an error threshold of six degrees from those with a threshold of 18, we get average errors of 3.81 and 4.97 degrees respectively. In addition, with our current study, we did not have trials where the initial orientations were anything less than 70 degrees which is in contrast with Poupyrev et al.'s experiment. If we look at task completion time, Poupyrev et al. reported 5.15 seconds for isomorphic rotation and approximately 4.75 seconds for non-isomorphic rotation. In our current study, subjects completed the rotation task in 4.74 seconds on average for isomorphic rotation and 4.31 seconds for non-isomorphic rotation. These numbers are similar to the error numbers in that it took less time to complete the task in our study under the no head tracking/no stereo display mode than in Poupyrev et al.'s study. We believe these discrepancies could be attributed to the size of the house presented on the display. Thus, performing the task when the size of the house shown to the user is small may make the rotation task more difficult compared to a larger sized house. Other factors such as tracker lag and refresh rate could contribute as well.

With our previous study, in the condition when the initial house orientation was randomly chosen between 70 and 180 degrees, subjects took 2.59 seconds on average when using an isomorphic approach to complete the rotation task and 2.18 seconds using the non-isomorphic approach. In our current study, subjects took 4.97 seconds on average when using the isomorphic approach and 4.4 seconds when using the non-isomorphic approach in the head tracking/stereo display mode (DM4). In addition, with our previous study, we found that subjects could complete the rotation task 15% faster with a non-isomorphic rotation (amplification factor of 3) than with isomorphic rotation with no statistically significant loss in accuracy. In the head tracking/stereo display mode (DM4) in the current study, subjects completed the rotation task only 8.9% faster. We suspect that there are two possibilities for these discrepancies. First, in [LK07] the house was placed in the center of the SSVE. In our current experiment, we had to place the house on the front wall of the SSVE to mitigate the "jumping" effect when trials transitioned in and out of stereo. Thus, in the current study, the house was potentially further away from the user, reducing its perceived size. This possibility, along with the comparisons of task completion time and error rates with the Poupyrev et al. study, suggest that, in addition to stereo, perceived house size may be another important factor in performing the rotation task. Second, it is possible that the 10 difficult initial house orientations we chose for this experiment could be a contributing factor to the task completion time differences.

Our data analysis also indicates stereoscopic viewing to be more important than head-tracking in performing the rotation task. However, it is also interesting to note that sub-

jects performed the rotation task 13.2% faster with non-isomorphic rotation than isomorphic rotation under the head tracking/no stereo mode. Thus, head tracking still plays a subtle role in the rotation task. This may be due to the relative simplicity of the house geometry and texture. Some subjects commented that over time they would first look for features on the house like the chimney, yellow window, or front door and knew what rotation was needed from that. It seemed from these comments like they were not carefully trying to understand the 3D structure of the house in any way, but instead trying to find a hint from the simple features for what rotation was needed. Oddly, this strategy would suggest there would be little difference between stereoscopic or monoscopic viewing as the features would be readily apparent in either mode—yet, subjects performed faster in the stereo condition. In any case, future work could explore varying the complexity of the target geometry, and possibly modifying the shape per trial.

5. Future Work

Our study suggests several avenues of future work. First, the results from this experiment suggest that the perceived size of the house may play an important role in task completion time. Therefore, conducting a study to test isomorphic and non-isomorphic rotation across varying house sizes is an interesting area of future work. In addition, focusing the study more on the manipulation aspect of the task, one might stop displaying the house while the Wanda button is depressed. This may lead subjects to plan and execute the rotation task more carefully.

We varied the amplification factor between one and three. This was a software amplification. If the radius of the ball were varied a similar effect might be achieved mechanically (it would be easier to rotate a larger number of degrees with a smaller ball than a larger ball). The physical shape of the tracked prop will also likely affect performance. A sphere prop is easy to manipulate but does not reflect the features of the target house object. Comparing a sphere and house-shaped prop would be interesting and is motivated by work like [GHP*95].

We believe modeling the virtual environment interaction technique after how a subject would do the task in the real world might yield faster and easier task performance. In the virtual environment subjects held a ball and button in their hands. The ball is rotated by one's fingers primarily, and it is not possible to use two hands or alternate hands for doing the task. In the real world, the subjects hand would initially be empty. They would first grab the house, then rotate using their whole arm, and possibly more of their body. Finally they would release the house once it reaches the target orientation. Depending on the initial orientation subjects might choose to grab it with either their left or right hand. They might also use two hands in orienting the object.

6. Conclusion

We have presented an experiment which explores how stereoscopic viewing and head tracking affect user performance when using isomorphic and non-isomorphic rotation to complete 3D orientation matching tasks. Our experiment compared both isomorphic rotation with non-isomorphic rotation techniques utilizing four different display modes (no head tracking/no stereo, head tracking/no stereo, no head tracking/stereo, and head tracking/stereo) and two different angular error thresholds for task completion. Our results indicate stereo plays an important role in rotation accuracy when performing 3D rotation tasks, regardless of rotation technique, and that both head tracking and stereo are important to rotation accuracy when non-isomorphic rotation is used. In addition, the majority of the subjects tested felt stereo and non-isomorphic amplification is important in completing the 3D rotation task. Although this work broadens the knowledge of non-isomorphic rotation in immersive VEs, our results show that there are still a number of areas for future experimentation that will provide even greater insight into this domain.

7. Acknowledgements

This work was sponsored in part by grants from Microsoft Research, IARPA, and DOE/LANL.

References

- [BH97] BOWMAN D. A., HODGES L. F.: An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *SI3D '97: Proceedings of the 1997 Symposium on Interactive 3D Graphics* (New York, NY, USA, 1997), ACM Press, pp. 35–38.
- [BKLP04] BOWMAN D., KRUIFF E., LAVIOLA J., POUPYREV I.: *3D User Interfaces: Theory and Practice*. Addison-Wesley, 2004.
- [CMS88] CHEN M., MOUNTFORD S. J., SELLEN A.: A study in interactive 3-d rotation using 2-d control devices. In *SIGGRAPH '88: Proceedings of the 15th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 1988), ACM Press, pp. 121–129.
- [DLBR06] DOMINJON L., LECUYER A., BURKHARDT J.-M., RICHIR S.: Haptic hybrid rotations: Overcoming hardware angular limitations of force feedback devices. In *Proceedings of IEEE Virtual Reality 2006* (Los Alamitos, CA, USA, 2006), IEEE Computer Society, pp. 167–174.
- [FHSH06] FROELICH B., HOCHSTRATE J., SKUK V., HUCKAUF A.: The globefish and the globemouse: Two new six degree of freedom input devices for graphics applications. In *CHI '06: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2006), ACM Press, pp. 191–199.
- [GHP*95] GOBLE J. C., HINCKLEY K., PAUSCH R., SNELL J. W., KASSELL N. F.: Two-handed spatial interface tools for neurosurgical planning. *Computer* 28, 7 (1995), 20–26.
- [Hol79] HOLM S.: A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics* 6 (1979), 60–65.
- [HTP*97] HINCKLEY K., TULLIO J., PAUSCH R., PROFIT D., KASSELL N.: Usability analysis of 3d rotation techniques. In *UIST '97: Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 1997), ACM Press, pp. 1–10.
- [JH03] JAY C., HUBBOLD R.: Amplifying head movements with head-mounted displays. *Presence: Teleoperators and Virtual Environments* 12, 3 (2003), 268–276.
- [LFKZ01] LAVIOLA J. J., FELIZ D. A., KEEFE D. F., ZELEDNIK R. C.: Hands-free multi-scale navigation in virtual environments. In *SI3D '01: Proceedings of the 2001 Symposium on Interactive 3D Graphics* (New York, NY, USA, 2001), ACM Press, pp. 9–15.
- [LK07] LAVIOLA J. J., KATZOURIN M.: An exploration of non-isomorphic 3d rotation in surround screen virtual environments. In *Proceedings of the IEEE Symposium on 3D User Interfaces 2007* (2007), pp. 49–54.
- [PBWI96] POUPYREV I., BILLINGHURST M., WEGHORST S., ICHIKAWA T.: The go-go interaction technique: Non-linear mapping for direct manipulation in vr. In *UIST '96: Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 1996), ACM Press, pp. 79–80.
- [PSP99] PIERCE J. S., STEARNS B. C., PAUSCH R.: Voodoo dolls: Seamless interaction at multiple scales in virtual environments. In *SI3D '99: Proceedings of the 1999 Symposium on Interactive 3D Graphics* (New York, NY, USA, 1999), ACM Press, pp. 141–145.
- [PWF00] POUPYREV I., WEGHORST S., FELS S.: Non-isomorphic 3d rotational techniques. In *CHI '00: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2000), ACM Press, pp. 540–547.
- [WR99] WARE C., ROSE J.: Rotating virtual objects with real handles. *ACM Trans. Comput.-Hum. Interact.* 6, 2 (1999), 162–180.
- [ZLFK02] ZELEDNIK R. C., LAVIOLA J. J., FELIZ D. A., KEEFE D. F.: Pop through button devices for ve navigation and interaction. In *Proceedings of IEEE Virtual Reality 2002* (Los Alamitos, CA, USA, 2002), IEEE Computer Society, pp. 127–134.