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Touching Augmented Reality: Direct Object Manipulation for Marker-less AR on
Handheld Mobile Devices

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Abstract

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Supporting augmented reality (AR) on handheld mobile devices is interesting due to the low costs, low power consumptions, portability, and mobility. Until recently, AR has been accomplished on handheld devices through the aid of distinguishable visual markers in which computer generated virtual objects are displayed over these visual markers, this is referred to as marker AR. A major restriction with marker AR is that the entire visual marker must be visible through a camera of a handheld device at all times. Recent advancements in technology has overcome this limitation, and mobile devices now support marker-less AR on handheld devices in which visual markers are no-longer required. While there are significant work done and results available in addressing virtual object manipulation with marker AR, it is unclear how these findings will apply in marker-less AR applications. With the involved technology on mobile

devices being a recent development, there currently is a lack of results addressing virtual object manipulations in marker-less AR settings. The goals of this study are to analyze the distinct differences of virtual object manipulation in marker AR and marker-less AR, understand the implications of these differences, observe the results of these differences in actual user tests, and identify relevant results from marker AR virtual object manipulations to predict and verify the subset that can transition into marker-less AR. This study conducts user testing on five marker AR virtual object manipulation methods. Four methods are the latest results from marker AR research on handheld devices, and a fifth method is a proposed novel method attempting to address the distinctions between the two AR settings. User testing of these methods shows that no single method applies well in all marker-less AR test cases where the requirements of manipulating small scale objects are distinct, and orthogonal from those of interacting with relatively large scale objects. The gathered results suggests that for mark-less AR applications, methods for virtual object manipulations should be adaptive to the relative sizes of the target AR objects.

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Chapter 1. INTRODUCTION

Augmented reality (AR) is an enhanced version of reality created by the use of technology to overlay digital information on an image being viewed through a device [1]. Recent advancement in technology has brought AR to life lifting it straight out of science fiction. For a device to support AR, a device must be powerful enough such that the hardware update rate is high, the display delay rate is low, and the accuracy of visual computations is accurate [2]. Many modern devices do have the capabilities of supporting AR, but we're interested in AR on mobile devices. In this study, "*mobile devices*" are used to refer to devices that are typically held by a single hand such as smartphones, personal digital assistants, and tablets.¹ Modern mobile devices are typically integrated with powerful cameras, powerful computational units, and robust displays making them convenient platforms for AR. Supporting AR on mobile devices has benefits such as: low cost, low power consumption, portability, and mobility [2] [3]. As with all technology, mobile devices are constantly improving, and the associated AR applications are maturing as well.

1.1 MARKER AR

Due to previous hardware limitations, augmented reality on mobile devices has usually been accomplished through the aid of distinguishable visual markers [3] [4] [5]. Visual markers are unique patterns that are processed and recognized through efficient computer vision detection algorithms [6]. These visual markers are usually printed on paper and placed into the physical environment. Visual markers that are within the view of a mobile device's camera are recognized with their positions and orientations derived. This allows virtual objects to be superimposed into the physical environment along with being displayed on the screen of a mobile device. This approach to realizing AR is referred to as marker AR. The caveat with marker AR is that an entire visual marker must be within a mobile device's camera view at all times. Partial occlusion of a visual marker typically results in vision algorithms being unable to derive marker position and orientation. Without position and orientation, the mobile device is unable to superimpose virtual objects into the augmented reality scene.

¹ We are not referring to mobile devices such as wearable backpack PCs [21] or smart glasses [22].

1.2 MARKER-LESS AR

Recent technological advancements now allow mobile devices to sample and map the physical environment through other means without relying on visual markers. This new approach is named marker-less AR, and consumer friendly mobile devices capable of marker-less AR are now releasing on the consumer market place [7] [8]. Marker-less AR compatible mobile devices track the physical environment through a combination of computer vision techniques combined with multiple sensor inputs from various built in sensors. Without the need for visual markers, the restrictions of requiring a user to keep a visual marker within a mobile device's camera view is eliminated.

1.3 OVERVIEW OF THE STUDY

With the shift to marker-less AR on mobile devices, accompanied research findings should be reevaluated as some might not transition into marker-less AR. One of these areas is the approach of manipulating and interacting with superimposed virtual objects. Many studies have been conducted towards finding the best ways of manipulating virtual objects on mobile devices with marker AR. With marker-less AR technology being recent on mobile devices, there currently is a lack of results discussing virtual object manipulations in the marker-less AR setting. While it can be theorized that current marker AR virtual object manipulation methods may work just as well in marker-less AR, it is interesting to study this case as there are differences between the two AR settings. This study conducts user testing with seven marker-less AR test cases using five different virtual object manipulation methods involving 34 user participants. The gathered results suggests that virtual object manipulation methods in marker-less AR should adapt to the size of the virtual AR object that's being manipulated.

Chapter 2. LITERATURE REVIEW AND BACKGROUND

2.1 MANIPULATING VIRTUAL OBJECTS IN MARKER-LESS AR

Marker-less AR on mobile devices is in an infancy state. At the time of this study, the first consumer mobile device supporting marker-less AR just recently became available [8]. With such a short time span on the marketplace, there hasn't been enough time for researchers to gather results of best practices when it comes to marker-less AR object manipulation methods on these mobile devices. With the lack of marker-less AR results for reference, this study takes the approach of using the closest research results as a place to begin. It's important to note that interactions on mobile devices are different from those of desktop computers and immersive VR interfaces. Research results from user studies outside handheld environments may not be applicable when it comes to virtual object manipulations on mobile devices [4]. With that being said, the closest research results to use as a starting place for this study is the virtual object manipulation methods that were gathered using mobile devices in the marker AR setting.

2.2 MANIPULATING VIRTUAL OBJECTS ON A MOBILE DEVICE IN MARKER AR

One of the earliest studies in manipulating virtual objects in the marker AR setting using a mobile device employed different modalities for positioning and rotating a virtual object. The physical mobile device movements directly translated a virtual object, and the physical keypad inputs directly rotated a virtual object [4].

As mobile hardware improved, a later study in manipulating virtual objects took into consideration tilt input and front camera finger tracking. However, it was found that tilt input and finger tracking were more complicated for users to use when compared against the previous mobile device translation and keypad input methods [3].

With the widespread usage of multi-touch screens on newer mobile devices, more recent studies compared finger touch screen gestures against finger tracking in manipulating virtual objects in marker AR. Touch screen gestures outperformed finger tracking significantly [9]. Other studies examined using only the physical movements of a mobile device to translate and rotate a virtual object in marker AR [10] [11]. The results from these studies show that on current

mobile hardware, using only the physical movements of a mobile device to manipulate virtual objects in marker AR can be an effective technique.

A more recent study examined using a hybrid approach of touch screen gestures combined with the physical movements of a mobile device [12]. The results of this study suggest that a hybrid approach may perform better than just using touch screen gestures or physical device movements alone.

For this study, we adopt marker AR results as the starting point in our study using the latest four researched virtual object manipulation methods. The chosen methods for this study are the 3DTouch method [10], the HOMER-S method [10], the Hybrid method [12], and the center version² of the Integrated View Input (IVI) method [11]. Detailed information on these methods can be found in Section 3.1 of this paper.

2.3 MARKER AR AND MARKER-LESS AR CONSIDERATIONS

When compared to marker AR, marker-less AR does not suffer from the similar limitations of augmentable space [13], occlusion [14], limited user movement [15], and AR virtual object size. As such, operating in marker AR and marker-less AR are different.

2.3.1 *Augmentable Space*

With marker AR, users can only project virtual objects into the environment directly over visual markers. If users want more space to place virtual objects, users would have to use larger visual markers as the augmentable space size is directly tied to the size of the visual markers being used. Figure 2.3.1 depicts this limitation. The left side of Figure 2.3.1 shows the view from a mobile device in which a virtual object (a star) is being projected over a visual marker located on a table. In order to project more virtual objects into the scene, the user has to use a larger visual marker as shown in the right side of Figure 2.3.1. In contrast, marker-less AR does not have a similar requirement. Virtual objects can be projected to any location in the physical environment where the size of the augmentable space is only limited by the size of the actual physical environment itself.

² The integrated view input method has three variations. We chose to implement the center version because it was identified to be the most useable [11].

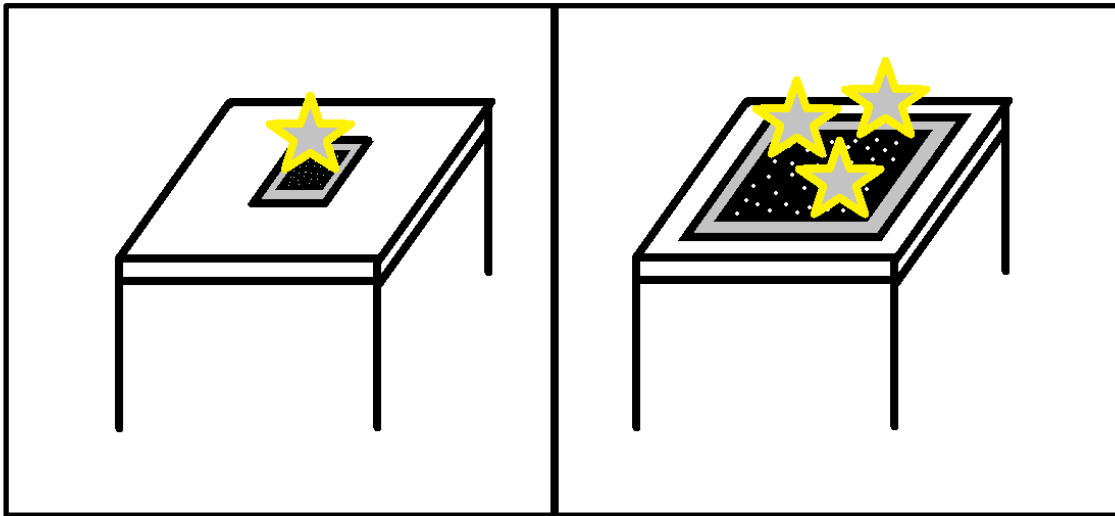


Figure 2.3.1 Augmentable space limitation in marker AR

2.3.2 Occlusion

Marker AR is not capable of projecting virtual objects into the physical environment when visual markers are behind or partially blocked by barriers. Mobile devices have difficulties in uniquely recognizing visual markers when visual markers are only partially visible. This occlusion issue causes virtual objects in marker AR to be binary; either a user sees the whole virtual object in the physical environment or the users does not see the virtual object at all. Figure 2.3.2 depicts this occlusion limitation. The left image in Figure 2.3.2 shows a virtual object being projected in the physical environment as it should be. The middle image in Figure 2.3.2 shows what the virtual object would look like if there is a barrier blocking a small part of the visual marker. The visual marker is recognized enough such that the entire virtual object is projected onto the environment, but the virtual object is incorrectly projected as it is blocking part of the barrier. The right image in Figure 2.3.2 shows what would happen if the visual marker is mostly covered up. The marker is not recognized and thus the virtual object cannot be projected. With marker-less AR, virtual objects are always projected into the physical environment and with proper inter-object occlusion support between physical and virtual objects as well. In marker-less AR, users can observe virtual objects that are partially blocked by physical barriers. This greatly increases the sense of immersion as virtual objects do properly interact with the actual physical environment.

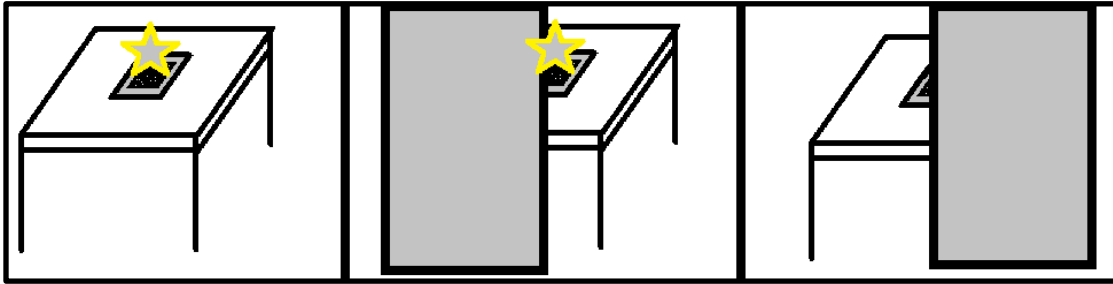


Figure 2.3.2 Occlusion limitation in marker AR

2.3.3 *Freedom of User Movement*

Freedom of user movement has also been a limitation with marker AR. Too much of a viewing angle while looking at a visual marker will cause a mobile device to not recognize the visual marker. The lack of user movement forces users to be constantly facing the visual marker while only being able to view virtual objects from certain angles. Figure 2.3.3 demonstrates this freedom of user movement limitation. The left side of Figure 2.3.3 shows the view from a mobile device in which a virtual object (a star) is being projected over a visual marker located on a table. The right side of Figure 2.3.3 shows what the scene would look like if the user would view the same table and the same marker from a different angle. This new viewing angle of the mobile device causes the mobile device to not recognize the visual marker so thus the virtual object isn't projected into the physical environment. Marker-less AR doesn't suffer from this limitation.

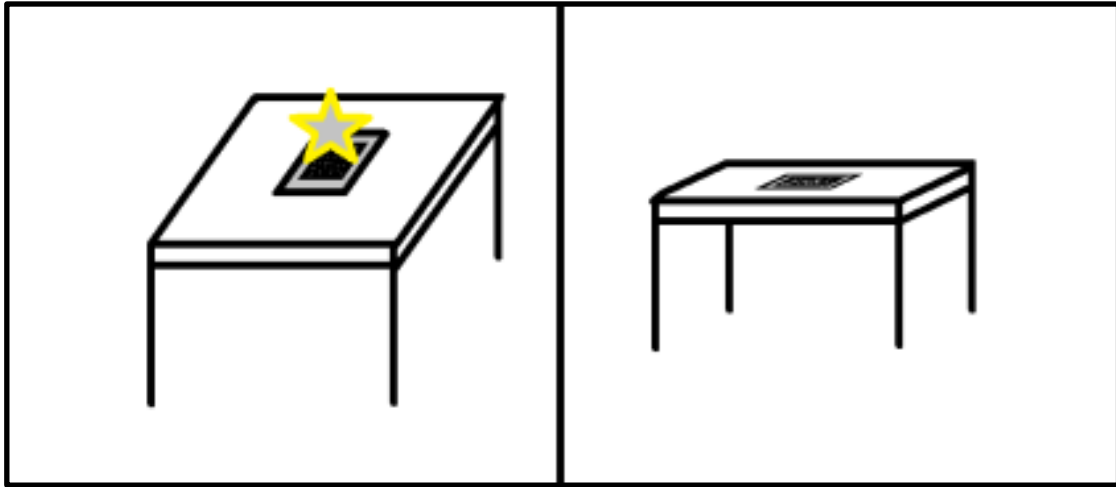


Figure 2.3.3 Freedom of user movement limitation in marker AR

2.3.4 *Virtual Object Size*

The inability to display large virtual objects is another limitation of marker AR. Large virtual objects usually extend beyond the display screen of mobile devices. In order to see these large virtual objects, users have to back away from the virtual objects or pan the mobile device in such a way to view the whole virtual objects. This causes issues as stepping back too far away or panning the mobile device too much runs the risk of losing the recognition of the visual marker. Figure 2.3.4 shows the limitation of virtual object size in marker AR. The left side of Figure 2.3.4 shows what a large object would look like when view through a mobile device, notice how the virtual object goes beyond the bounds of the mobile display screen. The right side of Figure 2.3.4 shows what would happen if the user took a step back to view the whole virtual object. At this new distance, the visual marker is no longer recognizable and thus the virtual object cannot be displayed. Marker-less AR does not have this restriction on virtual object size.

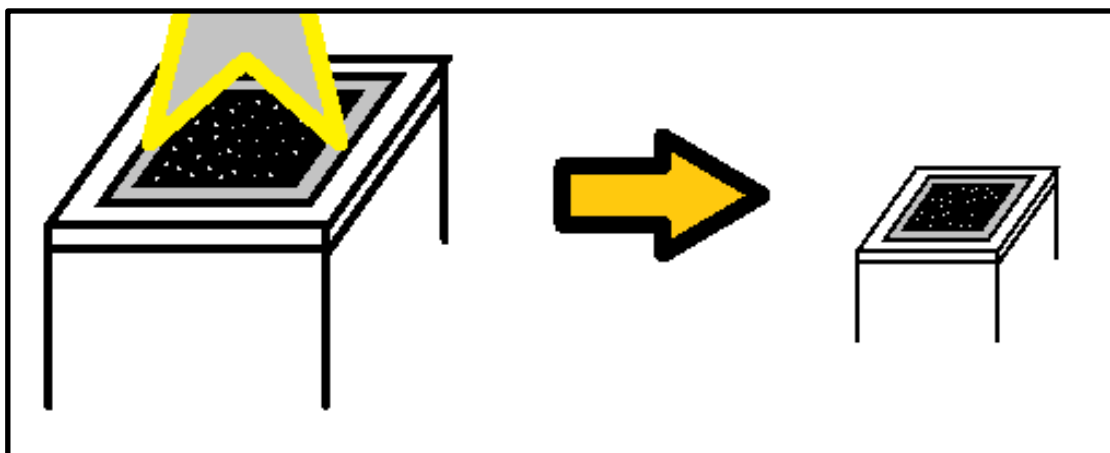


Figure 2.3.4 Virtual object size limitation in marker AR

Chapter 3. THE STUDY

The primary goal of this study is to observe, and understand how marker AR virtual object manipulation methods perform in the marker-less AR setting on mobile devices. We are specifically observing for trends and potential best practices for manipulating virtual objects with marker-less AR on mobile devices. We are focusing around the most basic virtual object manipulation tasks including selecting, positioning, and rotating a virtual object [16]. If users could accomplish these three basic object manipulation tasks, it is assumed users could combine these and accomplish more complicated tasks as well. This study implements the four latest marker AR object manipulation methods and tests them in marker-less AR. Based on the differences between marker AR and marker-less AR, a fifth and novel object manipulation method was derived and tested in this study as well. A visual explanation of each tested object manipulation method can be found on-line.³

3.1 THE FOUR VIRTUAL OBJECT MANIPULATION METHODS

3.1.1 *The 3DTouch Method*

The 3DTouch method is derived based on the idea that performance could be improved if interaction techniques followed the structure of the input device rather than the structure of the object manipulation task. With this in mind, the 3DTouch method directly maps finger touches and virtual touch points to enable intuitive virtual object transformations, thus making virtual object transformations easier to understand by users who have experience with mobile devices [10].

The 3DTouch method separates translation and rotation into two distinct modes. A user taps on a virtual object to select the object. The 3DTouch method then asks a user to select an object manipulation mode, either translation or rotation. A user then selects the object manipulation mode they would like to use, and touch screen gestures manipulate the virtual object accordingly. In translation mode, touch screen finger gestures translates the virtual object, and in rotation mode, touch screen finger gestures rotates the virtual object.

³ Video link: <https://youtu.be/9dztL0pUIIM>

3.1.2 *The HOMER-S Method*

While direct touch screen gestures are straight forward and easy to understand by mobile device users, there still exists the touch abstraction layer which is limited to the screen size of mobile devices. The HOMER-S method is derived based on the idea that object manipulations shouldn't be limited to the screen size of mobile devices and it focuses on all six degrees of freedom of movement [10].

The HOMER-S method focuses on locking virtual objects and it uses the physical movements of a mobile device to manipulate virtual objects. In this way, the HOMER-S method also separates translation and rotation into two distinct modes like the 3DTouch method. Physical mobile device movement and orientation directly manipulates virtual objects in each distinct object manipulation mode (translation or rotation).

3.1.3 *The Hybrid Method*

The Hybrid method is derived based on the idea that using a combination of the most efficiently found ways of manipulating virtual objects should perform the best. The Hybrid method employs two different modalities for object translation and rotation. Translation is accomplished through physical mobile device movements while rotation is accomplished through touch screen finger gestures. These different modalities of virtual object manipulations were found to be the most effective in previous studies.

3.1.4 *The Integrated View Input (IVI) Method*

The IVI method is derived based on the idea that numerous mobile devices have different characteristics. The IVI method is designed to keep the user interface as simple and clean as possible to tackle the issue of awkwardly holding a mobile device to select a virtual object. The IVI method does not define distinct modes for translation and rotation like the other manipulation methods. Instead, the IVI method translates and rotates a virtual object simultaneously depending on how a user moves a mobile device once an object is selected. This synchronization of translation and rotation makes the user interface very simple as it focuses only on having users touch the mobile device screen to select a virtual object that is in the center of the screen.

3.2 THE DERIVED FIFTH OBJECT MANIPULATION METHOD

The fifth object manipulation method in this study, the MOD IVI method, is of our own design. This method is based on the IVI method and it is designed to address the differences between the marker AR and marker-less AR settings. In order to address the issue of large augmentable space in marker-less AR, the MOD IVI method implements the ability to move a selected virtual object closer or farther from users by swiping up or down on the mobile device's screen. Users can also double tap the mobile device's screen to quickly reposition far away objects to exactly one meter in front of the user for quick selection in large spaces. In order to address the issue of selecting large virtual objects, virtual objects are displayed as semi-transparent during selection. This allows users to select and manipulate large virtual objects while retaining the observation of the entire physical environment along with all other virtual objects. In order to address the issue of occlusion, we adopted the IVI method's approach of only being able to select virtual objects if they are in the center of the screen. This was to ensure that even if users move a selected virtual object through a wall or behind an obstacle, users would always know that the virtual object is at least located in front of them as the virtual object is locked to the center of the mobile device's screen. In order to address the issue of freedom of movement, we adopted the IVI method's approach as well. We felt that using physical mobile device movements for translation and rotation allowed users the most freedom of movement.

Chapter 4. IMPLEMENTATION

4.1 HARDWARE

The mobile device used for this study is the Lenovo Phab 2 Pro [17]. This device incorporates Google's Tango technology [18], and this device is capable of sampling its physical environment with powerful built in sensors. At the point of writing this thesis, the Lenovo Phab 2 Pro is the first and only commercially available mobile device that supports Marker-less AR [8]. The device runs on the Android 6.0 Marshmallow operating system.

4.2 SOFTWARE AND IMPLEMENTATION FRAMEWORK

Figure 4.2.1 shows the software system library structure of our implementation. While the Android SDK provides system-level support, the 3D virtual object interactions are based on the Unity game engine framework. The Google Tango SDK depends on both the Android SDK and the Unity game engine framework as it presents the interface for marker-less AR specific functionality. The software application for this study was implemented on top of all three libraries.

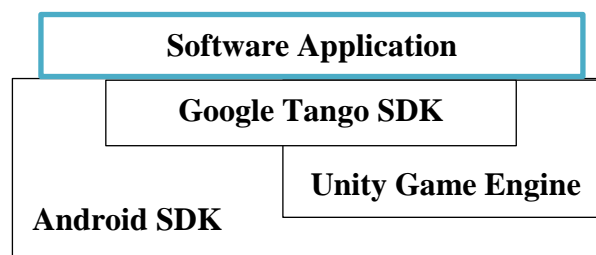


Figure 4.2.1 Software system library structure

4.3 IMPLEMENTATION RESULT

We implemented all five object manipulation methods and all seven user test cases in the marker-less AR software application built for this study. The software application was built to facilitate easy administration of user tests, while also keeping the display screen on the mobile

device uncluttered. Figure 4.2.2 shows a screenshot of the software application running in debug mode for testing and configuring user tests. Figure 4.2.3 shows a screenshot of the software application running in test mode during user tests. Mobile device User Interface (UI) design principles were not considered in our design as that was not the goal of the study.

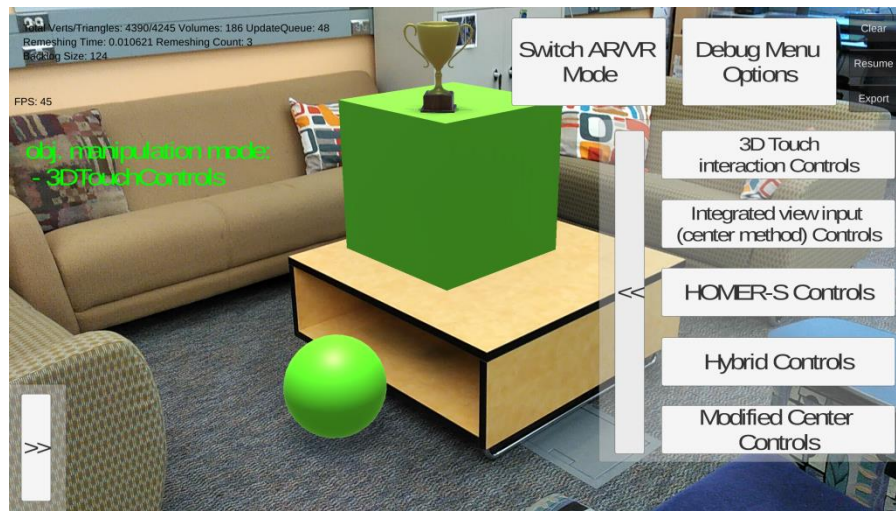


Figure 4.2.2 Marker-less AR software application running in debug mode



Figure 4.2.3 Marker-less AR software running in test mode

Chapter 5. TEST CASES

Seven user test cases were derived to study the adoption of marker AR virtual object manipulation methods in marker-less AR. The first three tests are adopted directly from prior marker AR studies [10] where the tests dealt with virtual object sizes that are common in marker AR. The last four tests were designed specifically for marker-less AR environments where the scale of virtual objects were not restricted by physical markers, and where AR interactions could include arbitrary movements and occlusion.

5.1 SMALL SCALE TESTS

Test one is the 2D translation test. The left photo in Figure 5.1.1 depicts the 2D translation test as users are instructed to select and translate a cube to a target position. The cube in the AR scene is 10cm in dimension and placed 35cm away at a 45 degree angle from the destination position. Test one is considered complete when the cube is translated such that it covers at least half the target area.

Test two is the 3D translation test. The middle photo in figure 5.1.1 depicts the 3D translation test as users are instructed to select and translate a cube to the top of a stack of cubes located 35cm away. The stack is 20cm tall and the cube is 10cm in dimension. Test two is considered complete when the cube is placed such that it stacks on top of the stack of cubes without falling off.

Test three is the 3D translation and rotation test. The right photo in figure 5.1.1 depicts the 3D translation and rotation test. Users are instructed to position a cylinder on a ramp such that the cylinder rolls down the ramp past a designated area. The cylinder is 10cm in length with a diameter of 5cm. The cylinder's initial orientation is at a 45 degree angle such that users must rotate the cylinder in order to complete the test. The ramp's height is 10cm with a slope of 30 degrees. Test three is considered complete when the cylinder rolls down the ramp and passes over at least half of the designated area.

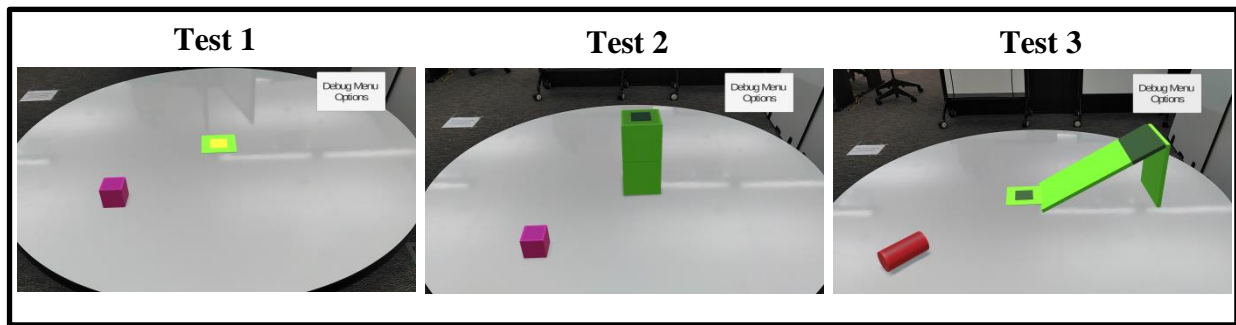


Figure 5.1.1 Small scale marker-less AR virtual object manipulation tests (test 1-3)

5.2 LARGE SCALE TESTS

Test four is the physical environment test. Figure 5.1.2 depicts the physical environment test as users are instructed to move a 50cm cube from one table to another table that is located 14 feet (4.26 meters) away. The choice for the distance between the tables is governed by the 15 feet (4.57 meters) effective distance of the hardware device employed during this study. In between the two tables lies a barrier dividing the two tables. The barrier acts as an obstacle such that users are required to navigate the environment in order to complete the test. Test four is considered complete when the cube is moved onto the designated spot on the destination table.

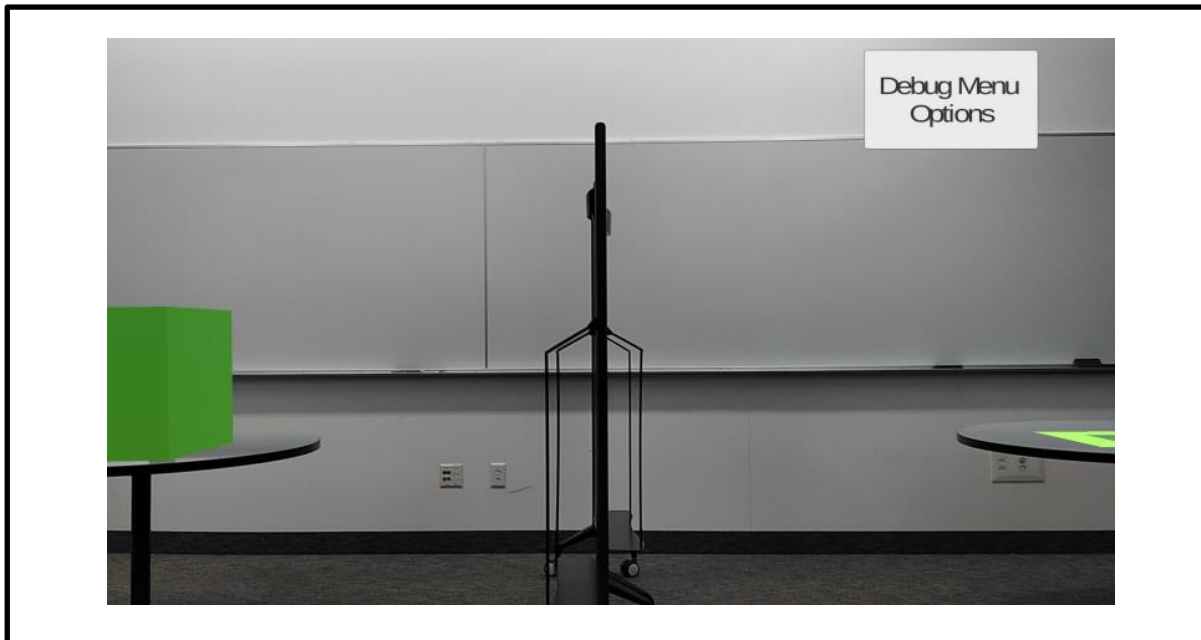


Figure 5.1.2 The large scale physical environment test (test 4)

Test five is the large object placement test. This test was designed to examine the manipulation of large objects with full freedom of user movement. Test five required users to pick up a 50cm cube off one table, and stack it on a stack of cubes (one meter tall) on another table. The combined height of the table with the stack of cubes is two meters above ground. The bottom left photo in Figure 5.1.3 depicts the stack of cubes on one table, and the bottom right photo in Figure 5.1.3 depicts the cube to be translated on another table. The starting position for the user is located in the center between the two tables facing the cube to be moved. This starting position ensured that users took full advantage of freedom of movement as users had to rotate their bodies at least 180 degrees to complete the test. The top photo in Figure 5.1.3 shows a diagram of test five. Test five is considered complete when the cube is stacked on top of the stack of cubes without falling off.

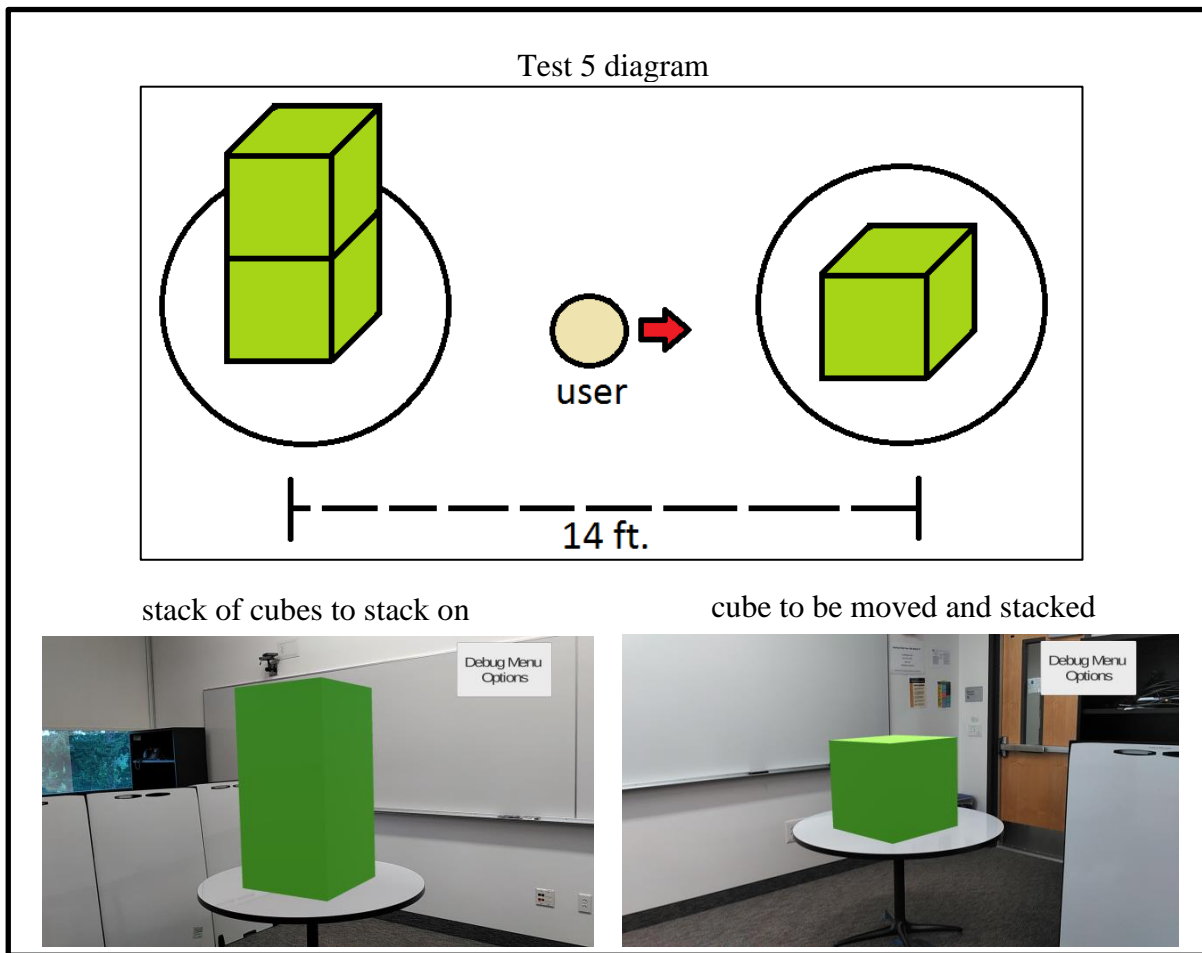


Figure 5.1.3 The large object placement test (Test 5)

Test six is the visual occlusion test. This test was designed to examine virtual object manipulations when the line of sight to the virtual object is partially occluded at times. In this test, users were instructed to move a 50cm cube from one table to another that is located 14 feet away while the user is constrained to a minimum distance of being at least 2 meters away from both tables. In between the two tables is a 2 meter long barrier designed to block the user's view. The top photo in Figure 5.1.4 shows a diagram of the visual occlusion test, and the bottom photo in Figure 5.1.4 shows the actual physical arrangement of the visual occlusion test. A strict requirement for this test was that users had to move the cube behind the barrier to the other table. This was to ensure that users experienced virtual object occlusion during the test, and the restriction on user movement was to ensure that users did not move around in such a way that they could complete the test without experiencing virtual object occlusion. Test six is considered

complete when the cube is moved onto the designated spot on the destination table such that the cube's travel path was behind the physical barrier.

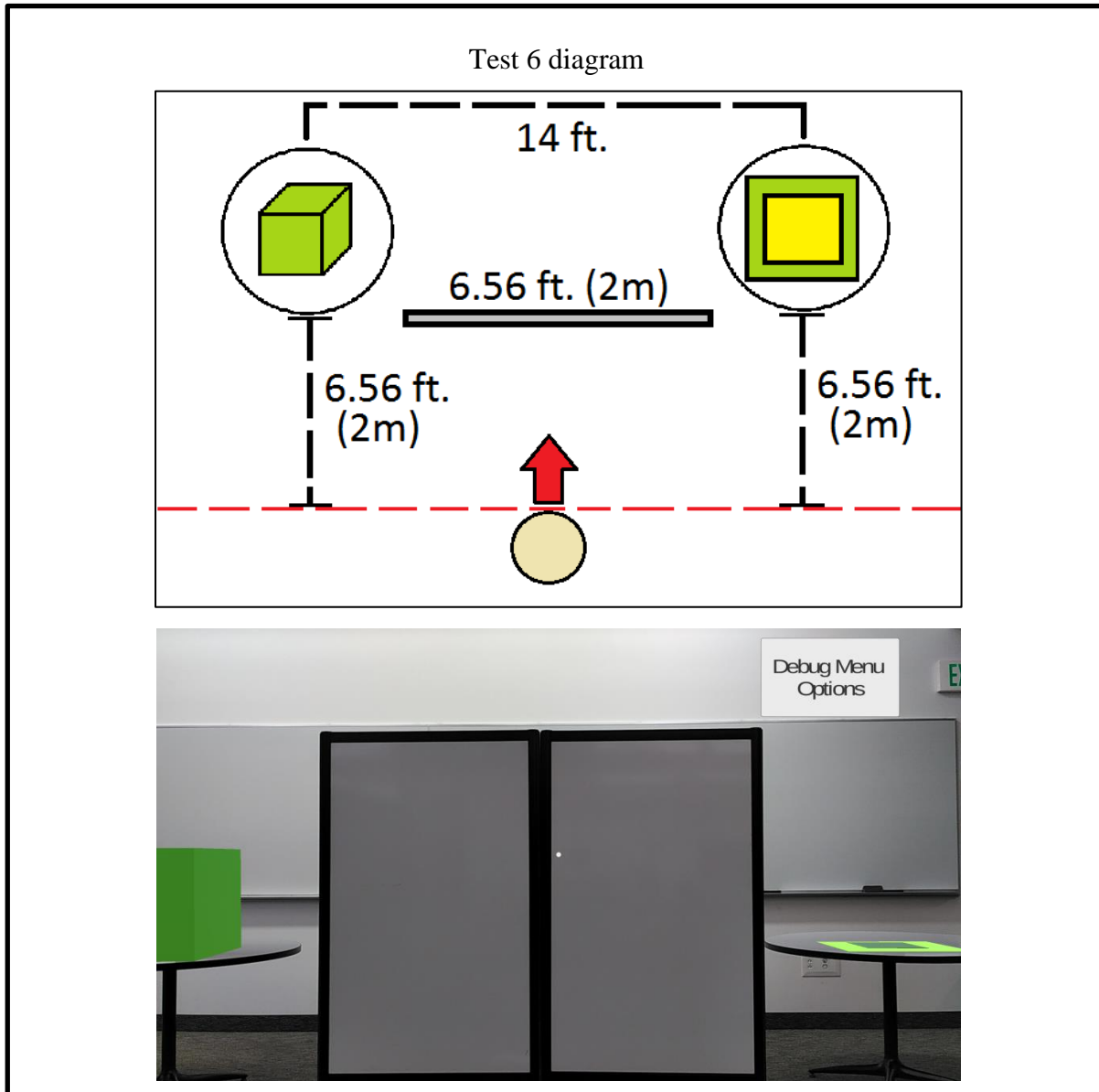


Figure 5.1.4 The visual occlusion test (test 6)

Test seven is the manipulation from a distance test. This test case was designed to mimic a possible real world scenario where user movement could be restricted by obstacles in the physical environment. In this test, users had to move a 50cm cube from one table to another table located 14 feet away while having to stand at a fixed location that is 10 feet between the two

tables. This was to ensure that users could see both the cube and destination spot as both were within the 15 feet hardware limit. The top photo in Figure 5.1.5 depicts a diagram of test seven. The bottom left photo in Figure 5.1.5 depicts a user's view of the cube standing at the fixed location, and the bottom right photo in Figure 5.1.5 depicts a user's view of the destination spot standing at the fixed location.

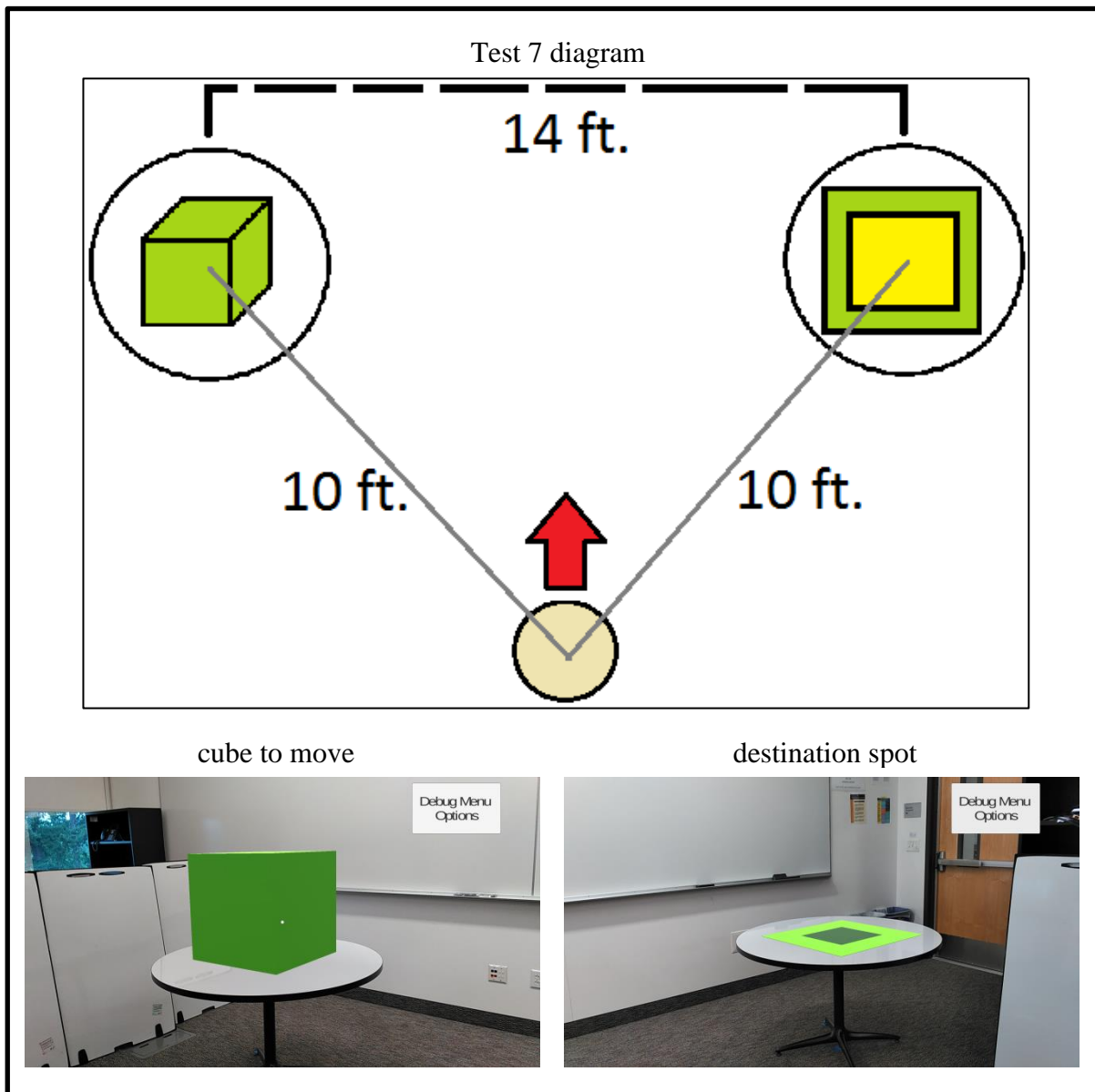


Figure 4.1.5 The manipulation from a distance test (Test 7)

Chapter 6. USER TESTING

6.1 USER TEST PARTICIPANT DEMOGRAPHICS

A total of 34 user testers participated in this study. The testers were exclusively university computer science undergraduate and graduate students. Half of the user testers were women and the other half were men. None reported to have any prior experiences with AR devices, but all reported to be experienced with mobile devices.

6.2 GENERAL TESTING PROTOCOLS

All users followed the exact same general testing protocols as detailed.

6.2.1 *Pre-Test Preparations*

Before any test began, the object manipulation method to be tested was taught to the user, and the user was given five minutes to practice. This practice time is adopted from a previous marker AR virtual object manipulation study [10].

6.2.2 *Test Procedures*

When a user is ready, the objective of the test is explained. The user is given the opportunity to walk around the environment to examine the virtual objects before they began. The user is not allowed to manipulate the virtual objects during this time, but they were encouraged to strategize approaches during this observation phase. The user was instructed to begin testing from a fixed starting location. A timer implemented in the software application kept track of the user's testing times. The timer was triggered by a user clicking a start button, and stopped by the successful completion of each test.

6.2.3 *Posttest Questionnaire*

Users were given a posttest questionnaire after they have completed all seven test cases. The questionnaire was used to collect qualitative feedback on how users felt during the tests, as well as feedback on how users felt about the virtual object manipulation methods they tested. The posttest questionnaire was adopted from a previous mobile device AR object manipulation

method study [10] with small modifications to fit this study's test scenarios. The questionnaire consists of multiple choice questions based around the 1-7 Likert scale. The questionnaire can be found in Appendix A.

6.3 PHASES OF TESTING

In this study we conducted two phases of testing. Based on the results and trends observed in Phase One of testing, Phase Two refocused and narrowed the targets tested. The results, trends, and reasons for refocusing our observations are discussed in detail in Section 7.2.5.

6.3.1 *Phase One of Testing*

In Phase One, we had each user test two object manipulation methods chosen at random out of the five. Each user went through all seven tests using one object manipulation method, and then they went through all seven tests again using the second object manipulation method. The goal of this testing phase was to observe how the five object manipulation methods performed in the marker-less AR environment, and to gain insights into any interesting trends. We tested a total of 14 users in Phase One.

6.3.2 *Phase Two of Testing*

Our focus shifted in Phase Two where we formulated new hypotheses based on the trends observed from the Phase One results. The new null hypotheses are as followed:

- H1. The 3DTouch and HOMER-S methods will perform the same in large scale object manipulations because they both showed similar performances in Phase One of testing.
- H2. The modified Integrated View Input (MOD IVI) method will perform significantly better than the original Integrated View Input (IVI) method in Marker-less AR because the MOD IVI method takes into consideration Marker-less AR factors.
- H3. Users are uncomfortable with using a smartphone to complete Marker-less AR tasks because they have limited experience with Marker-less AR on mobile devices.

H4. Users do not find ease-of-use, speed, and accuracy important when evaluating a virtual AR object manipulation method because they have limited experience with virtual AR object manipulation methods.

In Phase Two of testing we had each user test two object manipulation methods going through all seven tests again, but this time the user only went through all seven tests once. In the first three tests (the small scale tests) the user used one of two object manipulation methods, the IVI method or the MOD IVI method. For the last four tests (the large scale tests) the user used another object manipulation method, either the 3DTouch method or the HOMER-S method. We tested a total of 20 new users in Phase Two of testing.

Chapter 7. RESULTS AND DISCUSSION

7.1 DATA ANALYSIS

The collected test results were analyzed with Microsoft Excel using the Microsoft Excel Analysis ToolPak add-on [19]. The software package was used for its efficient capabilities in dealing with complex statistical analysis.

We used the unequal variance version of the T-Test in our data analysis due to the random factor involved in Phase One of testing (the random factor caused some object manipulation methods have a couple more data points than others). We set our alpha level at 0.05 for all T-Testing so that if we saw any significant differences, we could be 95% confident that the significant differences observed did not occur by pure chance. The one-tailed T-Test was used to verify differences in the performances of methods (e.g., MOD IVI vs. IVI), while the two-tailed T-Test was used to confirm similarities in testing results (e.g., 3DTouch and HOMER-S). The raw gathered test data can be found in Appendix B.

7.2 PHASE ONE RESULTS

The data was first examined with respect to the testing order in which the results were collected. We verified that the task completion time is independent from the order that a method was tested by a user. With the testing order not being an issue, all data sets are treated uniformly in all analysis.

Figure 7.1.1 through Figure 7.1.7 shows the box and whisker plots for test completion time in all seven tests conducted in Phase One of testing. Interesting trends can be observed from analyzing these results.

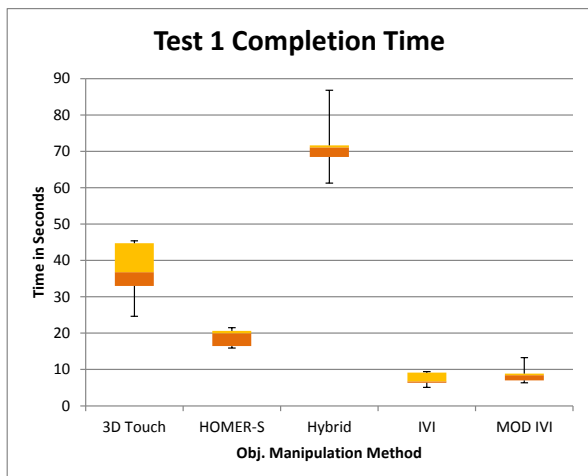


Figure 7.1.1 Task completion time for test one (phase one testing)

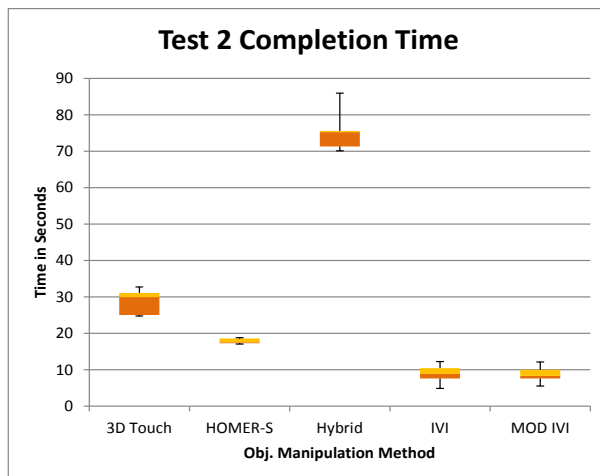


Figure 7.1.2 Task completion time for test two (phase one testing)

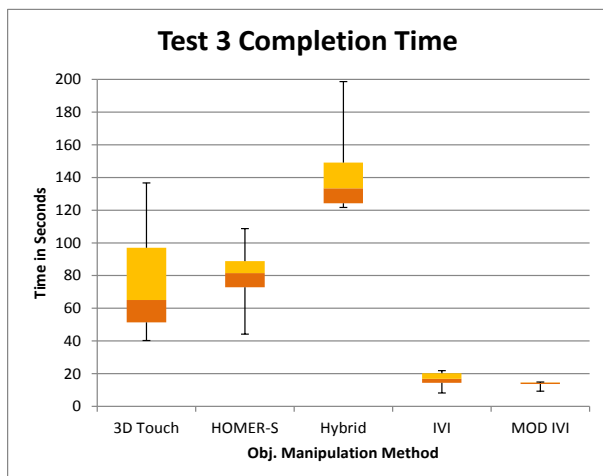


Figure 7.1.3 Task completion time for test three (phase one testing)

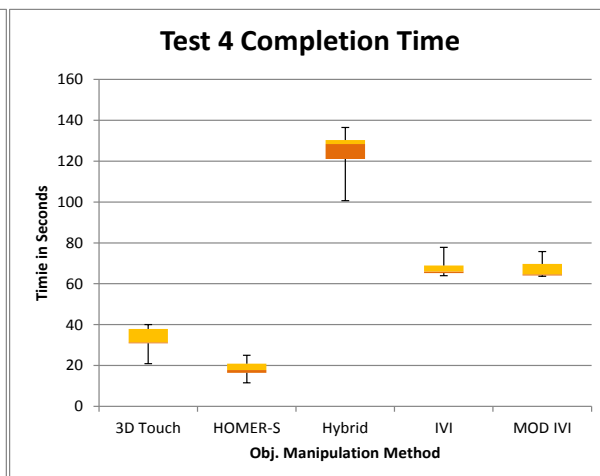


Figure 7.1.4 Task completion time for test four (phase one testing)

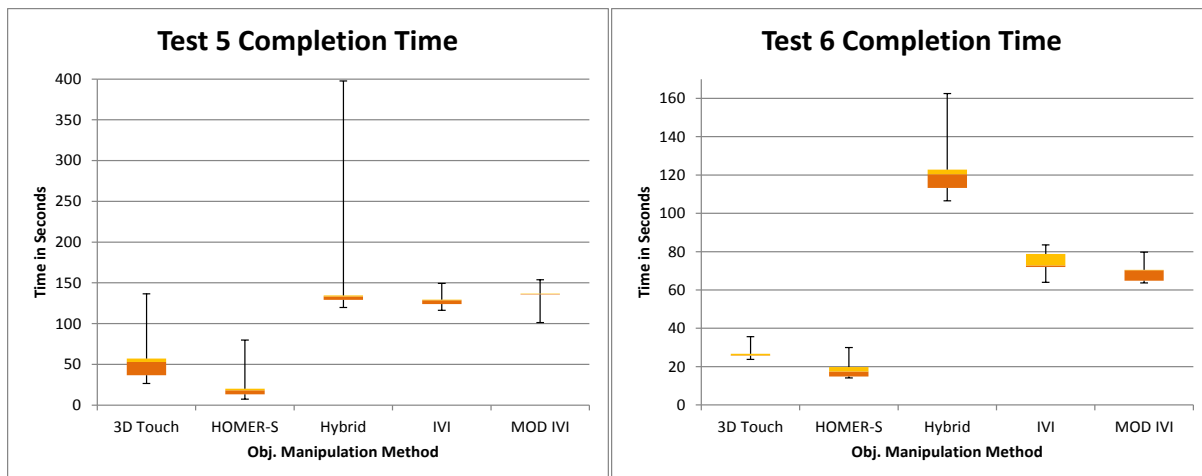


Figure 7.1.5 Task completion time for test five (phase one testing)

Figure 7.1.6 Task completion time for test six (phase one testing)

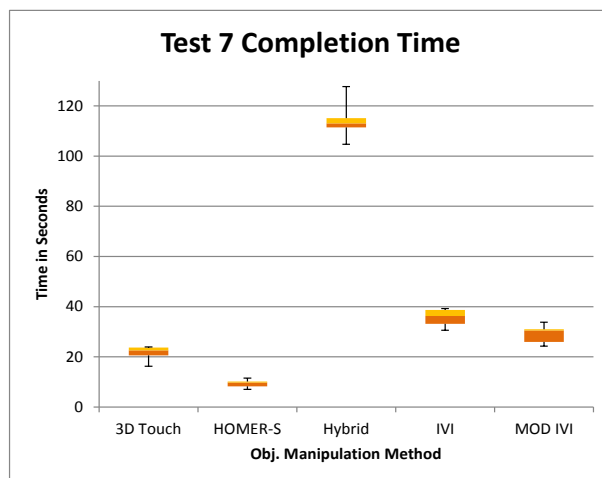


Figure 7.1.7 Task completion time for test seven (phase one testing)

7.2.1 Discernible Trends with the Hybrid Virtual Object Manipulation Method

The hybrid virtual object manipulation method showed some interesting results in Phase One of testing. With the exception of test five in Figure 7.1.5 (more information about this exception is discussed in Section 7.2.4), the box and whisker plots in Figure 7.1.1 through Figure 7.1.7 shows that the hybrid method took the longest time to complete each test case. In some test cases, the hybrid method took users twice as long or even longer (e.g., Figure 7.1.7). This suggests that the

hybrid method was the most inefficient overall for manipulating virtual objects in Marker-less AR.

The user feedback also identified the hybrid method to be the most unattractive method. Users were very vocal about the hybrid object manipulation method after the tests. Users stated that the hybrid method was very difficult to understand and use. Our observations agreed with the user feedback as we noticed that users were having a lot of trouble with the controls of the hybrid method during testing. When a virtual object is selected, the hybrid method protrudes a green beam from the virtual object to the floor of the augmented space to denote that the virtual object is selected. In our test cases we simulated real world gravity. With gravity involved, objects were on the ground when they were first selected. With no space between the virtual object and the floor for the green beam to be visible, users couldn't tell whether a virtual object was actually selected. This frustrated users, and this frustration led towards users being unable to focus and unable to keep track of the many different object manipulation modalities of the hybrid method. In previous studies, the test cases that were used to test the hybrid method did not simulate gravity, thus users could easily tell when an object was selected.

7.2.2 Discernible Trends with Small Scale Object Manipulations

In small scale tests (tests 1-3), the IVI method and the MOD IVI method performed better than all the other virtual object manipulation methods. Figure 7.1.1 through Figure 7.1.3 shows that the IVI method and the MOD IVI method performed almost two times better than the 3DTouch and HOMER-S method when it came to small scale tests, and this trend is fairly consistent throughout all small scale tests as well. During the small scale tests, we noticed that users had no problem rotating and translating virtual objects both at the same time because these objects were small, and the tests required small body movements. The IVI and MOD IVI merged translation and rotation into one mode which allowed users to accomplish the small scale tests in a very small number of fluid body movements.

7.2.3 Discernible Trends with Large Scale Object Manipulations

In large scale tests (tests 4-7), the 3DTouch method and the HOMER-S method performed better than all other virtual object manipulation methods. In Figure 7.1.4 through Figure 7.1.7 the spread of the data suggests that the 3DTouch and HOMER-S method performed almost two

times better than all the other object manipulation methods. This trend is fairly consistent throughout all large scale tests as well. The large scale tests require large body movements, and we noticed that users had a hard time conducting translations and rotations both at the same time in this regard. Users could rotate a virtual object desirably, but translating the object would then rotate the object out of orientation and this caused a lot of confusion. The 3DTouch method and HOMER-S method separates translation and rotation into two separate modes, and this separation made it easier for users to understand how large body movements directly manipulated virtual objects in large spaces.

7.2.4 Discrepancies in Test Five

As observed in Figure 7.1.5, the results from test five with the hybrid method had the largest spread. The primary reason for this discrepancy can be explained by one key variable in which we overlooked: user height. Recall that test five required a user to pick up a large cube off a table, and then place it on a stack of cubes that was located on another table behind the user. The top of the stack before placement of the target cube was 2 meters above ground, a significant height for many users. The IVI and MOD IVI methods both required a user to translate and rotate a virtual object simultaneously. This made it difficult for some users to accomplish the task. Translating the cube to the top of the stack usually meant auto rotating the cube in such a way that it would fall off the stack once the user unselected the object. This was the reason for the discrepancies shown in test five.

7.2.5 Changing Testing Protocols for Phase Two of Testing

Based on the results from Phase One of testing, the hybrid method was removed from further testing. We also decided to focus on analyzing the strengths of each object manipulation method. Based on the results observed in Figures 7.1.1 to 7.1.3, we decided to focus the IVI and MOD IVI methods around small virtual object manipulations, and based on the observed results in Figure 7.1.4 to 7.1.7, we decided to focus the 3DTouch and HOMER-S methods around large virtual object manipulations.

7.3 PHASE TWO RESULTS

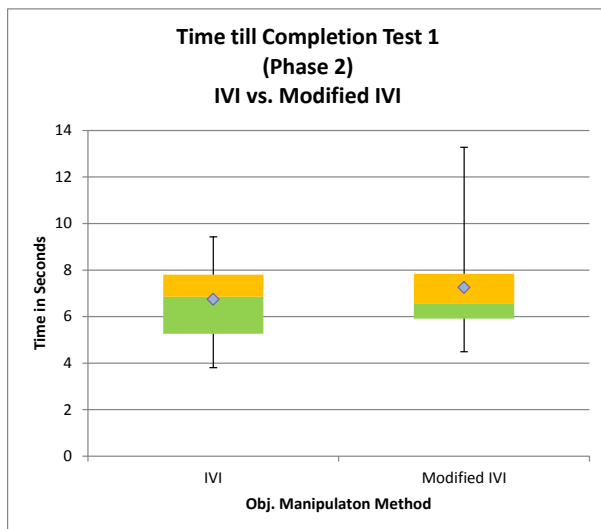
The combined data after Phase Two of testing uncovered some interesting results even though some results disagreed with some of our hypotheses.

7.3.1 *Small Scale Test Results*

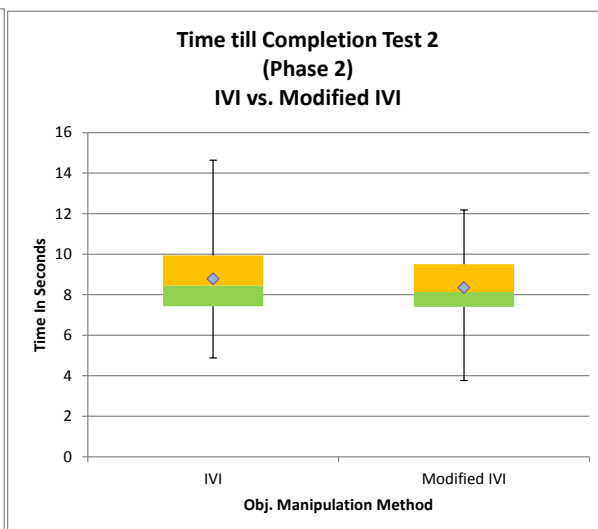
Table 7.3.1 shows the mean and standard deviation (in seconds) for all small scale tests, and the table also shows the one tailed T-Test p values for comparing the IVI and MOD IVI methods in all small scale tests. Figure 7.3.1 through Figure 7.3.3 shows the box and whisker plots of test completion time for the small scale tests (including the mean) comparing the IVI and MOD IVI methods.

Table 7.3.1 IVI and MOD IVI object manipulation method comparison table

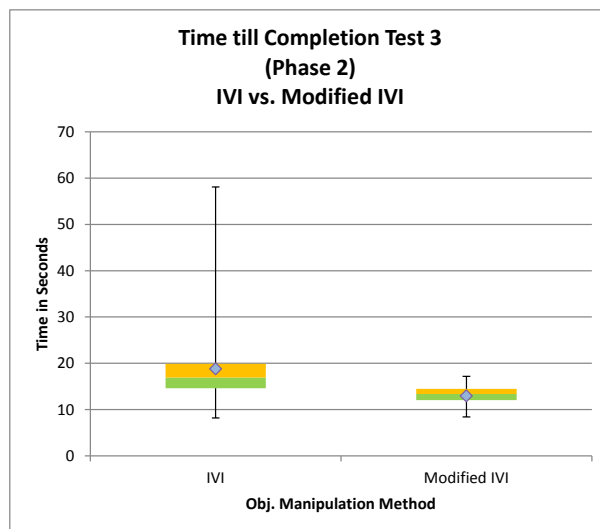
	Test 1		Test 2		Test 3	
	IVI	MOD IVI	IVI	MOD IVI	IVI	MOD IVI
Mean	6.7338	7.247333	8.785333	8.352667	18.82333	12.97667
Std. Deviation	1.552303	2.184044	2.394802	2.187898	11.22677	2.15313
one tailed T-Test (p value)	0.24		0.31		0.037	



**Figure 7.3.1 Test 1 comparison
between IVI and MOD IVI**



**Figure 7.3.2 Test 2 comparison
between IVI and MOD IVI**



**Figure 7.3.3 Test 3 comparison
between IVI and MOD IVI**

In Figure 7.3.1 and Figure 7.3.2, the box and whisker plots do not show any significant differences between the IVI and MOD IVI methods. The p value of the one tailed T-Test was 0.24 for test one, and 0.31 for test two. We conclude that there is no significant difference in task completion time when users only had to translate a small scale objects in marker-less AR. The p value of our one tailed T-Test for test three was 0.037. We conclude that there is a significant

difference between the IVI and MOD IVI object manipulation method when users were tasked to translate and rotate a small scale object in marker-less AR. With the disparity of the data half agreeing with our H2 null hypothesis, we draw two conclusions: we reject our H2 null hypothesis when users only had to translate virtual objects, and we accept our H2 null hypothesis when users had to translate and rotate virtual objects. Translating and rotating virtual objects require more environmental awareness as virtual object orientation plays a larger role. With this in mind, the transparency of the selected object with the MOD IVI method allowed users to better gauge the physical environment and the virtual ramp as they positioned the virtual cylinder to complete test three.

7.3.2 Large Scale Test Results

Table 7.3.2 shows the mean and standard deviation test completion time (in seconds), and the table also shows the calculated two tailed T-Test for comparing the 3DTouch and the HOMER-S methods in large scale object tests. Figure 7.3.7 through figure 7.3.10 shows the box and whisker plots of test completion time (including the mean) for the large scale object tests.

Table 7.3.2 3DTouch and HOMER-S object manipulation method comparison table

	Test 4		Test 5		Test 6		Test 7	
	3DTouch	HOMER-S	3DTouch	HOMER-S	3DTouch	HOMER-S	3DTouch	HOMER-S
Mean	39.29	18.78375	54.95153	30.41188	39.27235	18.9375	23.27641	11.37063
Std. Deviation	18.59094	2.873702	28.13432	17.28693	10.47935	4.309502	10.17066	2.389065
two tailed T-Test (p value)	0.00043		0.0066		0.00000037		0.00025	

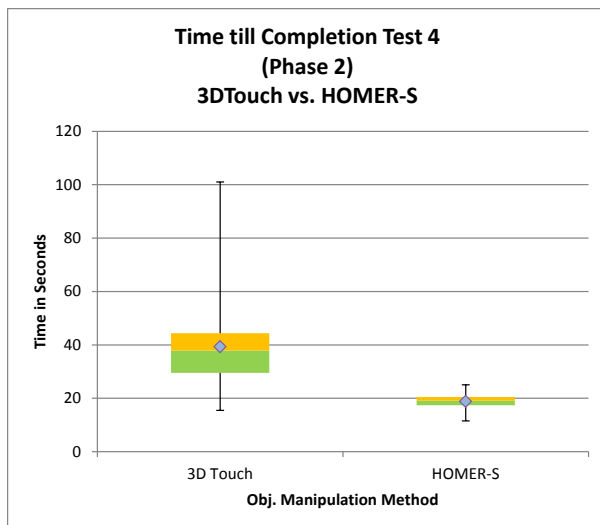


Figure 7.3.7 Test 4 comparison between 3DTouch and HOMER-S

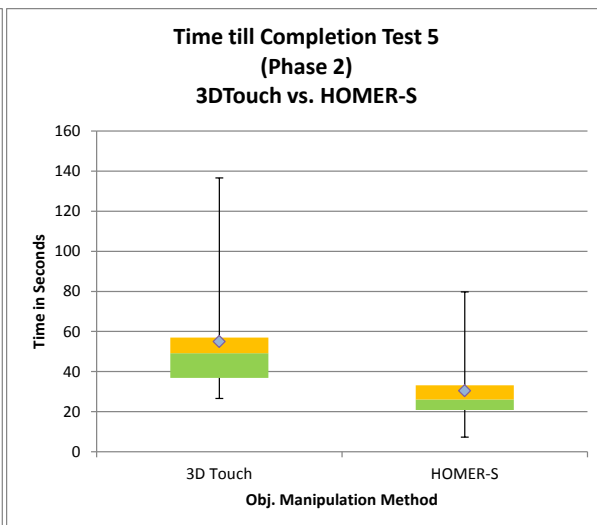


Figure 7.3.8 Test 5 comparison between 3DTouch and HOMER-S

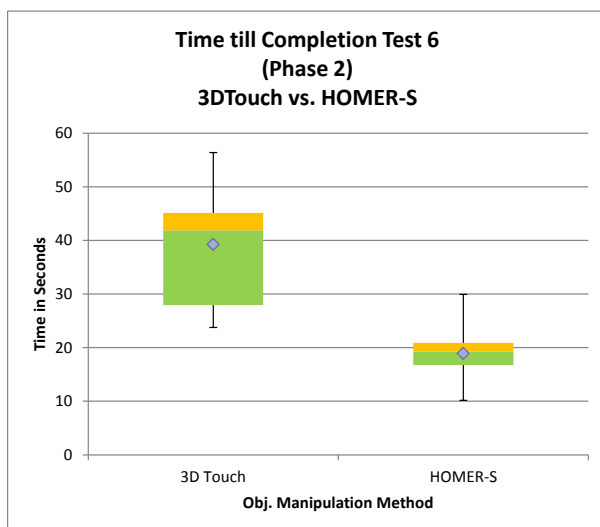


Figure 7.3.9 Test 6 comparison between 3DTouch and HOMER-S

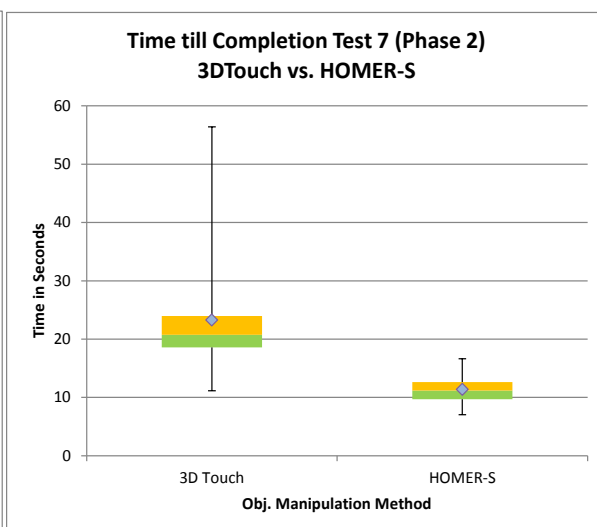


Figure 7.3.10 Test 7 comparison between 3DTouch and HOMER-S

The results clearly indicate that the 3DTouch and the HOMER-S methods perform differently in large scale tests. The HOMER-S method is the more efficient virtual object manipulation method when compared to the 3DTouch method. Based on the data, we can see that the two tailed p values from all the large scale tests fell under the 0.05 threshold. With this knowledge, we reject our H1 null hypothesis and conclude that the 3DTouch and HOMER-S methods do not perform

the same and they are significantly different from one another. We can also conclude that the HOMER-S method did perform better in all of the large scale tests. While the 3DTouch method did follow the common mobile device input structure of finger touch inputs, it seems that users prefer physical mobile device movements in manipulating virtual objects in marker-less AR. This preference could be the results of immersion as the actions of moving a physical device around to move a virtual object in augmented reality cognitively synchronizes better than trying to associate finger swiping with virtual object movements.

7.3.3 Discussion on the IVI and MOD IVI Object Manipulation Methods

We believe the MOD IVI method did not outperform the IVI method because users did not take advantage of the extra features we added onto the MOD IVI method. The small scale tests were derived from marker AR tests, so thus users approached the small scale tests the same way as the tests were approached in marker AR. Previous marker AR results have suggested that the IVI method is an effective object manipulation method in marker AR, and the MOD IVI method builds upon the IVI method. Since the small scale tests did not force users to experience marker-less AR factors (in which the MOD IVI method was designed to address), we did not see the MOD IVI method outperform the IVI method.

7.4 QUALITATIVE FEEDBACK RESULTS

Table 7.4.1 shows the average user Likert score and the p value for the qualitative user feedback gathered with the posttest questionnaire. The gathered raw qualitative feedback can be found in Appendix C.

Table 7.4.1 Qualitative Likert feedback result averages and p values

	practice time	comfortable-ness	ease of use	speed	accuracy
average	6.15	6.49	6.12	6.37	6.47
p value	9.6E-59	1.8E-87	8.8E-82	1.4E-93	1.7E-110

In the qualitative user feedback, user response suggests that five minutes of practice time was more than enough practice time for an object manipulation method. The average response across

all 34 participants was 6.15 with a p value of $9.6E-59$ (t-test assuming users found five minutes to not be enough practice time). User response also suggests that users were very comfortable with using a mobile device to accomplish marker-less AR tasks. Averaging all 34 participant responses gave comfortableness a score of 6.49 with a p value of $1.8E-87$ (t-test assuming users were not comfortable with using a mobile device for marker-less AR tasks). With these results, we reject the H3 null hypothesis as users do seem comfortable with using marker-less AR on mobile devices.

Users also felt that ease-of-use, speed, and accuracy were all very important factors towards assessing an object manipulation method as well. Averaging all responses across all 34 participants found that the importance of ease-of-use averaged 6.12 with a p value of $8.8E-82$. The importance of speed averaged 6.37 with a p value of $1.4E-93$, and the importance of accuracy averaged 6.47 with a p value of $1.7E-110$. With these results, we reject the H4 null hypothesis as the data does suggest that users do care about ease-of-use, speed, and accuracy when judging an object manipulation method.

In our posttest questionnaire we also had users give Likert scale feedback based on the usability and intuitiveness of the object manipulation methods they tested. We were cautious in interpreting these results as these results all averaged very high on the Likert scale across all object manipulation methods in terms of usability and intuitiveness. We speculate that the wow factor [20] may have contributed to the overwhelming positive results. While we did try to mitigate this wow factor by having each user test two object manipulation methods (so that each user had two virtual object manipulation methods to compare against each other) it is challenging to assess the degree of success in this effort. For this reason, we decided to focus our conclusions around our quantitative results.

Chapter 8. CONCLUSION AND FUTURE WORK

8.1 CONCLUSION

The primary goal of this study was to observe how marker AR object manipulation methods performed in the marker-less AR setting. We were able to observe trends and draw conclusions based on the data we collected from user testing. None of the tested object manipulation methods performed perfectly in all our tests. The IVI and MOD IVI methods performed better in small scale virtual object manipulation tests, and the 3DTouch and HOMER-S methods performed better in large scale virtual object manipulation tests. Users were quite comfortable with marker-less AR on mobile devices, and users do place strong emphasis on the ease-of-use, speed, and accuracy of an object manipulation method even though they have limited exposure to marker-less AR on mobile devices. We were unable to verify that the proposed MOD IVI method is an improvement over the IVI method.

8.2 LIMITATIONS OF THE STUDY

There are two primary limitations in this study. The first limitation corresponds to the demographics of the user test participants. All participants in this study came from technical backgrounds and they consisted of young adults. This limitation impacts our results as we did not examine a wider age range of user testers and we did not examine user testers of other backgrounds. The second limitation in our study is the wow factor. All user test participants were first time users of AR and thus they were very excited about experiencing AR. This limitation led towards the skewed qualitative feedback that we received from user test participants during the study.

8.3 FUTURE WORK

With the results gathered in this study, there are many different branching paths going forth. We could propose a solution towards merging the best aspects of all tested object manipulation methods in this study into a more powerful object manipulation method. We could conduct user tests in marker-less AR environments that more closely resembles real world environments. We

could conduct user tests with participants in different age groups to cover a wider age range. We could reexamine camera finger tracking due to the lifted limitation of occlusion in marker-less AR. We could focus on observing object scaling (as we did not cover that in this study), or we could propose a solution towards intuitively switching between object manipulation modes to take advantage of the results that we saw in this study. This was our first step towards finding the best possible ways of manipulating virtual objects in marker-less AR on mobile devices, and we are very curious to see where the research goes next from here.

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APPENDIX A

Post User Test Questionnaire

Object manipulation method tested: _____

1. How adequate do you feel the time allotted for practice was?

Not Enough			Enough			More than Enough
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7

2. How comfortable were you with using a smartphone for task completion?

Very Uncomfortable			Neutral			Very Comfortable
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7

3. How would you rate the object manipulation technique in usability? Speed? Accuracy?

Usability

Very Unusable			Neutral			Very Usable
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7

Speed

Very Slow			Neutral			Very Fast
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7

Accuracy

Very Inaccurate			Neutral			Very Accurate
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
1	2	3	4	5	6	7

APPENDIX B

Raw data of time till completion per test (all recorded times are in seconds)

Test1						
Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI	
Phase1	1	45.41	20.6	71.62	5.1	6.98
	2	24.61	15.92	86.79	9.43	6.37
	3	44.75	19.97	71.11	9.14	8.86
	4	32.99	16.47	68.46	6.35	8.41
	5	36.78	21.49	61.28	6.717	13.28
Phase2	6	33.28	22.35		3.8	10.58
	7	35.62			5.21	4.49
	8				5.31	6.95
	9				6.85	6.57
	10				7.21	5.46
	11				8.16	5.67
	12				7.86	6.2
	13				7.74	5.48
	14				5.1	6.15
	15				7.03	7.26

Test2						
Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI	
Phase1	1	32.73	17.03	75.21	7.61	5.53
	2	31.09	17.24	85.94	10.45	8.32
	3	29.96	18.59	70.11	12.25	9.98
	4	24.75	17.54	75.54	4.88	12.15
	5	25	18.79	71.31	8.85	7.61
Phase2	6	34.47	15.28		5.88	7.89
	7	33.73			8.27	3.76
	8				7.24	10.78
	9				14.64	12.18
	10				9.42	8.13
	11				10.64	7.18
	12				8.67	6.95
	13				8.46	7.65
	14				6.7	9.02
	15				7.82	8.16

Test3						
	Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI
Phase1	1	40.35	108.67	121.59	14.44	9.37
	2	65.05	72.9	133.38	16.85	13.69
	3	136.63	88.82	149.07	20.25	14.62
	4	51.41	44.18	198.57	8.19	14.6
	5	97.03	81.58	124.19	21.88	14.96
Phase2	6	75.92	91.11		58.1	12.43
	7	72.54			17.83	17.18
	8				10.06	8.42
	9				17.45	13.37
	10				14.79	12.97
	11				16.94	11.71
	12				19.62	12.48
	13				20.16	13.49
	14				9.14	14.35
	15				16.65	11.01

Test4						
	Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI
Phase1	1	40.02	17.82	100.66	65.22	69.74
	2	30.83	16.4	130.32	68.95	63.62
	3	20.87	20.95	128.33	77.76	75.72
	4	37.85	25.03	136.44	63.92	64.03
	5	31.31	11.51	121.04	66.01	64.59
Phase2	6	57.08	17.06			
	7	101.05	20.27			
	8	15.44	20.95			
	9	23.53	15.71			
	10	29.54	18.54			
	11	24.71	18.97			
	12	35.84	20.98			
	13	43.97	19.34			
	14	46.1	17.46			
	15	45.31	19.21			
	16	40.12	20.34			
	17	44.36				

Test5						
	Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI
Phase1	1	56.98	7.33	129.12	123.83	101.29
	2	36.73	18.21	397.67	149.27	153.84
	3	136.628	79.78	134.57	129.32	135.77
	4	26.608	13.18	133.186	116.18	136.21
	5	52.99	20.07	119.735	128.72	136.83
Phase2	6	30.51	32.23			
	7	92.73	23.43			
	8	39.57	29.62			
	9	97.61	21.09			
	10	36.86	26.19			
	11	37.14	22.49			
	12	47.31	25.94			
	13	26.71	36.16			
	14	52.17	40.61			
	15	59.31	60.1			
	16	55.16	30.16			
	17	49.16				

Test6						
	Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI
Phase1	1	25.71	17.43	106.49	72.01	70.55
	2	35.61	29.93	162.46	78.8	64.84
	3	23.76	14.89	122.79	83.52	70.26
	4	25.86	19.83	113.267	63.96	79.75
	5	26.67	14.07	120.35	72.81	63.66
Phase2	6	56.38	24.06			
	7	41.87	10.18			
	8	30.16	20.74			
	9	45.03	19.05			
	10	27.93	16.89			
	11	47.47	17.68			
	12	44.97	21.75			
	13	43.12	16.3			
	14	41.73	19.43			
	15	51.13	19.41			
	16	45.13	21.36			
	17	55.1				

Test7						
	Test Runs	3D Touch	HOMER-S	Hybrid	IVI	MOD IVI
Phase1	1	20.59	8.24	104.71	36.27	30.97
	2	22.57	9.71	113.03	30.56	30.53
	3	23.95	10.15	115.15	38.64	33.77
	4	23.659	11.54	127.7	33.17	25.95
	5	16.23	7.05	111.46	39.22	24.22
Phase2	6	14.12	16.64			
	7	20.74	13.45			
	8	11.16	11.42			
	9	56.41	10.96			
	10	39.87	12.31			
	11	18.58	14.84			
	12	21.04	9.64			
	13	25.71	13.64			
	14	19.16	10.47			
	15	18.13	9.51			
	16	19.65	12.36			
	17	24.13				

APPENDIX C

Raw data of user questionnaire feedback

		3D Touch										
Tester #	Run #	Q1	Q2	Q3-1	Q3-2	Q3-3	Q4-1	Q4-2	Q4-3	Q5-1	Q5-2	Q5-3
2,2	4	7	7	6	4	5	5	5	4	7	7	7
4	7	4	6	4	3	4	4	6	4	7	6	7
5	9	7	6	5	4	7	6	4	3	5	3	7
6,2	12	7	2	2	2	5	3	2	1	6	5	7
7	13	7	6	3	2	2	4	3	3	6	4	6
12,2	24	7	7	7	4	7	6	7	3	7	7	7
13	25	6	3	5	4	5	5	6	5	6	7	5
15,2	30	4	6	5	3	7	6	6	4	6	4	6
18,2	36	4	6	6	3	6	6	6	4	6	7	5
20,2	40	7	7	7	3	6	7	7	4	7	6	6
21	41	5	5	6	4	4	4	4	4	5	6	6
23,2	46	7	7	6	5	6	6	5	4	6	7	7
26	51	6	6	5	4	7	4	5	3	6	6	6
27	53	7	7	4	2	6	6	4	4	7	7	7
29	57	6	6	3	4	6	6	6	3	5	6	7
32,2	64	7	7	5	3	5	6	5	2	6	7	7
33,2	66	6	6	5	4	6	6	4	4	6	6	6

		HOMER-S										
Tester #	Run #	Q1	Q2	Q3-1	Q3-2	Q3-3	Q4-1	Q4-2	Q4-3	Q5-1	Q5-2	Q5-3
2	3	7	7	6	6	6	6	5	6	6	4	5
5,2	10	6	7	6	5	7	7	7	3	7	6	7
7,2	14	7	7	6	7	7	7	7	7	7	7	7
10	19	4	5	5	6	6	6	4	5	5	6	6
11,2	22	4	7	7	7	7	7	7	7	7	6	7
14,2	28	4	7	7	7	7	7	7	7	7	6	7
16	31	7	7	6	7	6	4	3	1	7	7	6
17,2	34	7	7	5	6	6	6	4	4	4	7	7
19,2	38	7	7	6	6	6	5	4	5	3	7	6
22	43	7	7	6	5	7	6	4	1	6	7	6
24	47	6	7	5	5	5	7	3	2	7	7	7
25	49	6	7	7	7	7	5	4	4	6	7	6
28,2	56	7	7	5	6	5	6	3	3	5	6	7
30,2	60	7	7	6	5	7	5	4	3	6	7	7
31,2	62	6	7	5	7	6	7	3	4	5	7	6
34	67	7	7	6	5	6	5	4	2	6	7	7

		HYBRID										
Tester #	Run #	Q1	Q2	Q3-1	Q3-2	Q3-3	Q4-1	Q4-2	Q4-3	Q5-1	Q5-2	Q5-3
1	1	2	6	3	3	3	4	3	1	7	6	6
3,2	6	2	7	2	4	4	2	3	3	6	6	7
4,2	8	2	7	2	3	2	3	3	2	7	6	7
8	15	3	6	3	3	3	3	3	3	5	5	6
9,2	18	1	7	2	3	3	2	3	2	7	7	6

		IVI										
Tester #	Run #	Q1	Q2	Q3-1	Q3-2	Q3-3	Q4-1	Q4-2	Q4-3	Q5-1	Q5-2	Q5-3
1,2	2	7	6	7	7	7	7	7	6	7	6	7
8,2	16	7	5	6	6	7	7	6	6	6	6	5
9	17	7	7	6	6	6	6	6	6	7	7	6
10,2	20	7	6	7	7	7	7	6	7	7	7	7
14	27	7	7	7	7	6	6	6	6	7	6	7
15	29	7	5	6	7	6	5	6	6	6	7	7
16,2	32	7	7	7	5	7	7	7	5	7	7	7
18	35	6	7	6	7	7	6	6	6	6	6	7
22,2	44	7	7	6	6	7	6	6	7	6	7	6
23	45	7	7	7	6	7	7	6	7	6	6	7
25,2	50	7	7	6	6	6	6	7	6	6	7	6
28	55	7	7	7	6	6	7	6	7	7	7	7
30	59	7	7	6	7	7	6	7	7	7	7	6
32	63	7	6	7	6	7	7	6	7	7	7	6
34,2	68	7	6	7	7	7	6	7	6	7	7	6

		MOD IVI										
Tester #	Run #	Q1	Q2	Q3-1	Q3-2	Q3-3	Q4-1	Q4-2	Q4-3	Q5-1	Q5-2	Q5-3
3	5	7	7	6	7	6	7	7	7	6	6	7
6	11	7	7	7	6	6	7	5	6	7	6	7
11	21	7	7	7	7	6	7	5	7	7	6	7
12	23	7	7	7	7	6	7	7	7	7	7	7
13,2	26	7	6	6	6	6	6	6	6	6	6	6
17	33	7	7	7	7	7	7	7	7	5	7	7
19	37	7	7	6	6	6	6	7	7	3	7	6
20	39	7	7	7	7	7	7	6	6	7	6	6
21,2	42	6	6	6	6	6	7	7	7	5	6	6
24,2	48	7	7	6	6	6	6	6	7	5	7	6
26,2	52	6	6	7	6	7	7	7	6	6	6	7
27,2	54	7	7	7	6	6	7	6	7	5	7	6
29,2	58	6	6	6	7	6	7	6	6	5	6	7
31	61	7	7	7	7	7	7	6	7	6	7	6
33	65	6	7	6	7	7	6	7	6	7	7	7