# Evaluating the Need for Display-Specific and Device-Specific 3D Interaction Techniques

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**Abstract.** There are many visual display devices and input devices available to designers of immersive virtual environment (VE) applications. Most 3D interaction techniques, however, were designed using a particular combination of devices. The effects of migrating these techniques to different displays and input devices are not known. In this paper, we report on a series of studies designed to determine these effects. The studies show that while 3D interaction techniques are quite robust under some conditions, migration to different displays and input devices can cause serious usability problems in others. This implies that display-specific and/or device-specific versions of these techniques are necessary. In addition to the studies, we describe our display- and device-specific designs for two common 3D manipulation techniques.

**Keywords:** Virtual environments, display devices, input devices, 3D interaction techniques, migration, specificity.

## 1 Introduction

The number of different devices available for use in virtual environment (VE) systems is staggering [1]. Visual display devices include head-mounted displays (HMDs) and surround-screen, tabletop, and volumetric displays, just to name a few. Input devices include wands, pens, data gloves, pinch gloves, flying mice, gaming devices, PDAs, desktop 3D devices, and a whole host of home-brewed devices and research prototypes. Moreover, there is no standard set of devices for VEs.

This poses an interesting problem for designers and practitioners in the area of 3D user interfaces. Most well-known 3D interaction techniques (see [2]) were designed, implemented, and evaluated using only one set of devices. We call this the "native implementation" of the technique. For example, the native implementation of the Go-Go technique [3] uses an HMD and a tracked wand. While the characteristics of these devices may not have been explicitly considered in its design, the designer was no doubt influenced by the physical devices at his disposal. What is not known is how changes in displays or input devices will affect the usability of a technique.

Therefore, we are evaluating the effects of *migrating* 3D interaction techniques among display and input devices. If there are significant usability issues that arise due to migration, then the techniques might need to be redesigned for the new set of devices; we call these *display-specific* and *device-specific* techniques. Our research in

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this area is part of a larger research program into the use of *specificity* in 3D user interfaces in general [4]. We have also considered *domain-specific* 3D UIs [5].

In this paper, we describe our investigation of migration, which has addressed two research questions: 1) Can we demonstrate a *need* for display-specific and/or device-specific 3D interaction techniques, and 2) If the answer to the first question is yes, can we *design* display-specific and/or device-specific techniques with acceptable usability and performance? We describe three empirical studies addressing the first of these questions. The first two studies are described in detail in [6]; we only summarize them here. We also present two display- and device-specific techniques based on the results of the third study, and give preliminary results supporting their usability.

## 2 Related Work

Many authors have noted the importance of studying the differences between displays and the effects of displays on users, applications, and tasks [e.g., 7, 8]. Few, however, have provided empirical evidence of these effects.

A small number of studies have looked at the effects of particular display characteristics on interaction performance or usability. For example, Arthur [9] studied the effect of field of view in an HMD on performance in searching and walking tasks. Closer to our own work, Kjeldskov [10] reports an ambitious study on the usability of 40 common 3D interaction techniques in a semi-immersive curved display and a fully-immersive surround-screen display. He found qualitative differences in the usability of particular techniques between displays, but no quantitative data was collected. Our prior work [11] demonstrated a statistically significant difference in users' behavior between an HMD and a CAVE during a navigation task.

There have also been few studies that have explicitly addressed the impact of input devices on usability and performance in 3D interaction. The experiments of Zhai [12] and Hinckley [13] are notable exceptions. Still, we know little about the most appropriate mappings between input devices and 3D interaction techniques.

Finally, we note that there are certainly some examples of display-specific or device-specific 3D interaction techniques in the literature. LaViola's step-WIM [14], for example, is a CAVE-specific version of the World-in-Miniature technique [15]. Prior research has not, however, demonstrated the benefits of display- or device-specificity, and the topic of migration of 3D interaction techniques has not been studied systematically.

## 3 Displays, Devices, and 3D Interaction Techniques

In this section, we briefly introduce the VE displays, input devices, and 3D interaction techniques we have studied, and consider mappings among these components.

### 3.1 VE Displays

We have studied perhaps the two most common immersive visual displays: the CAVE [16] and HMD. Although these displays are well-known, it is useful to reflect on their characteristics that might have an effect on interaction. Table 1 summarizes a few of the differences that we have studied or encountered in our work (for more discussion of these issues, see [2]). Note that we are assuming a four-sided CAVE (three walls and a floor), currently the most common configuration.

**Table 1.** Selected differences between common CAVEs and HMDs

| *Characteristic* | *4-sided CAVE* | *HMD* |
|---|---|---|
| Field of view (FOV) | Wide | Narrow |
| Field of regard (FOR) | ~270° horizontal<br>~180° vertical | 360° horizontal and vertical |
| Occlusion issues | Incorrect occlusions possible | Correct occlusions |
| Visual quality | Variable (floor) | Variable (edges) |

A display's "field of view" (FOV) refers to the maximum number of degrees of visual angle that a user can see instantaneously, while "field of regard" (FOR) refers to the amount of the physical space surrounding the user (also measured in degrees of visual angle) in which visual images are displayed [2]. The CAVE has a wide FOV because a user can typically see between 90 and 180 degrees of the display at any time (depending on the stereo glasses that are used); HMDs typically have a narrow FOV between 30 and 60 degrees. On the other hand, tracked HMDs provide a 360-degree FOR because the user sees the VE no matter which direction he looks; a four-sided CAVE has a smaller FOR because of the missing back and top display surfaces.

Another difference between HMDs and CAVEs is the physical location of the display surfaces. In HMDs, the screens are fixed to the user's eyes, while in CAVEs, the screens are fixed in the environment. This leads to the issue of proper occlusion cues. In a CAVE, a virtual object that is "near" to the user can be occluded by a physical object (such as the user's hand) that is farther away, since all virtual objects are actually projected on the physical screens. This problem does not occur in HMDs.

Both CAVEs and HMDs may lack homogeneity in their visual quality. In 4-sided CAVEs, the floor is typically front-projected (i.e. from above). This means that users will cast shadows on the floor. In addition, the floor is often not made of high-quality screen material, and can get dirty. In HMDs, the visual quality is usually lower on the edges of the display, because of distortion caused by the device's optics.

### 3.2 3D Input Devices

We have evaluated two common VE input devices: tracked wands and Pinch Gloves. The tracked wand is perhaps the most common 3D input device used in VEs. It consists of a six-degree-of-freedom tracker embedded in a handheld device, which typically has several buttons, and in many cases a small joystick. Pinch Gloves are worn on the hands and have conductive cloth on the fingertips. "Pinching" two or more fingertips together generates a unique signal that identifies which fingers are touching. The gloves are often combined with six-degree-of-freedom trackers.

Both wands and tracked Pinch Gloves allow the user to provide continuous 3D input (e.g. for pointing, touching, or manipulating) as well as discrete input events (e.g. for selecting, grasping, or releasing). However, they also provide very different affordances to the user. Table 2 summarizes a few of these differences, focusing on those that may significantly affect 3D interaction.

**Table 2.** Selected advantages of wands and Pinch Gloves

| *Advantages of wands* | *Advantages of Pinch Gloves [17]* |
|---|---|
| Physical buttons minimize unintended triggering of events | The gloves are worn, leaving the hands free to do other tasks if needed |
| A single size fits most users' hands | Many more unique input events are possible |
| The device defines a unique orientation (e.g., pointing direction) | Gloves are light and flexible, reducing fatigue, and users can keep their hands in a comfortable posture |
| | Gloves afford two-handed input |

### 3.3 3D Interaction Techniques

Our studies have focused solely on 3D interaction techniques for the task of manipulation, since this is a fundamental yet highly interactive task in 3D user interfaces. Here we briefly describe the four techniques we have considered; we refer the reader to the cited references for more information.

The Go-Go technique [3] allows object manipulation at-a-distance by defining a non-linear mapping between the motion of the user's physical and virtual hands. In a small area surrounding the user, the virtual hand follows the physical hand, but outside this area, the virtual arm extends at a non-linear rate relative to the physical arm. This allows the user to select and manipulate objects both nearby and faraway.

HOMER [18] also addresses manipulation at-a-distance, and also provides scaled virtual hand movements to allow long-distance object manipulation. However, selection of objects in HOMER is done via ray-casting (pointing), which is typically faster and more accurate than selecting objects directly with the virtual hand.

The World-in-Miniature (WIM) technique [15] provides flexible object manipulation by allowing the user to work on small copies of the objects in the VE, rather than the objects themselves. The user holds a small copy of the entire VE in one hand, and selects and manipulates objects in the WIM with the other hand. These actions are reflected in the full-scale world.

Voodoo Dolls [19] is an extension of the WIM that provides more precision. Rather than always working at the scale of the entire VE, the user selects a "context" and is provided with a miniature of that context to hold in one hand, and then can manipulate other objects relative to the context with the other hand.

### 3.4 Mappings

The problem of mapping among displays, devices, and interaction techniques is not trivial. Clearly, not all combinations of these components will provide equivalent usability or task performance, and some combinations may not work at all. Ideally, designers would be able to choose one component and then use guidelines to make appropriate choices of the other components. For instance, many VE developers are constrained to a single visual display type. It would be quite useful to know which combinations of input devices and interaction techniques work well with that display. But as we have noted, the space of devices and techniques is very large.

Considering just the devices and techniques described above, there are 16 possible combinations, all of which would be candidates for a VE developer who needed to provide object manipulation in his/her application. However, each interaction technique has a native implementation. Go-Go, HOMER, and WIM were all originally designed for HMDs and wand-like input devices. Voodoo Dolls was also developed with an HMD, but used tracked Pinch Gloves as the input device.

## 4 Experiment I: Effect of Display Type on General 3D Manipulation Tasks

Our goal in this first experiment was to demonstrate that the properties of the visual display could have a tangible effect on 3D interaction tasks.

Our hypotheses were drawn from the comparison of the CAVE and HMD presented above. We imagined how these differences might affect the usability of 3D interaction tasks. The four hypotheses were:

1. Because of the limited vertical FOR in the CAVE (missing top screen), users will find the HMD more usable for selecting and manipulating objects at a height.
2. Because of the limited horizontal FOR in the CAVE (missing back screen), users will find the HMD more usable for placing objects behind them.
3. Because of the limited FOV in the HMD, users will find the CAVE more usable for tasks requiring interaction on both sides of their bodies.
4. Because of the issue of occlusion in the CAVE, users will find the HMD more usable for tasks requiring object placement very near to their bodies.

We designed a simple user study to test these four hypotheses using 3D selection/manipulation tasks in the CAVE and HMD. Using the Go-Go technique, subjects performed four “construction” tasks in both displays, and we recorded comments and subjective difficulty ratings for each task.

The results of the study strongly supported hypotheses 1 and 2. The missing sides in our four-screen CAVE indeed negatively impacted usability on tasks involving manipulation above and behind the user (requiring the user to change his/her view). Hypothesis 3 was also supported, although less strongly. The fourth hypothesis was not supported; occlusion was not an issue for the manipulation tasks we studied.

Overall, this study showed that display characteristics could significantly affect the perceived usability of 3D interaction tasks. However, these effects seemed to be general, rather than due to the specific interaction technique we used.

For details on the experimental design and results, we refer the reader to [6].

# 5 Experiment II: Effect of Display Type on Usability of a Specific 3D Manipulation Technique

Next, we wanted to show that the usability of a *particular* 3D interaction technique might depend on the display type. Specifically, this second experiment was intended to investigate what happens when a 3D interaction technique designed for one display type is used with a different display type. Our hypothesis was that we would find a significant decrease in usability when an interaction technique designed for one display is evaluated in another. To test this hypothesis, we chose to evaluate the WIM technique [15] in the HMD (its native display) and the CAVE, using the same WIM implementation in both displays.

Subjects performed 32 positioning trials in each display. Unlike experiment I, we gathered quantitative performance data in this experiment for the purpose of demonstrating a statistically significant difference between the two displays.

Results showed that selection time and errors were similar in both display types, but that manipulation time was significantly higher in the CAVE. While this supported our hypothesis that the non-native display would result in degraded performance, this result was less than satisfactory for two reasons. First, the absolute difference in performance was still relatively small. Second, the focus on quantitative performance produced results that were not helpful in terms of producing a CAVE-specific WIM technique. Further work was needed to demonstrate that overall usability suffers when migrating away from the native implementation, and that techniques could then be redesigned in a display-specific or device-specific manner.

For complete details on experiment II, we refer the reader to [6].

# 6 Experiment III: Effects of Display and Device Type on Usability of Specific 3D Manipulation Techniques

The goal of experiment III was to extend our previous results. We wanted to demonstrate that migration could cause significant usability problems for specific 3D interaction techniques. Furthermore, we wanted to study the effect of input device migration as well as display migration.

We chose to evaluate two displays (HMD and CAVE), two input devices (wand and Pinch Gloves), and three manipulation techniques (Go-Go, HOMER, and Voodoo Dolls), as described in section 3. The native implementations of the three interaction techniques use different input devices, although all of them were originally designed for the HMD. Unfortunately, there are very few well-known 3D interaction techniques that were developed for CAVEs originally.

## 6.1 Design

The three independent variables in the study were display device and input device (within-subjects), and interaction technique (between-subjects). Thus, each participant experienced four conditions.

A variety of measures were used to ensure that we were obtaining a good overall picture of usability. We asked participants to provide ratings of frustration, fatigue, difficulty, perceived speed, and perceived accuracy after each set of tasks. We also collected a think-aloud protocol for most of the tasks, in which participants verbalize their thought process and experience in performing a task; interviews were used following each condition to collect similar information. Observation by the experimenter provided another source of usability information. Finally, we measured actual performance on a few tasks, although this was not the focus of the experiment.

Six subjects, with an average age of 20, participated in the experiment. There was one female subject, and all subjects reported themselves to be novice users of VEs. Two participants were assigned to each of the three interaction techniques.

### 6.2 Equipment and Software

The HMD used in the experiment (and in the previous experiments) was a Virtual Research V8, with 640x480 resolution and a 60-degree horizontal field of view. The CAVE was a four-screen Fakespace CAVE of 10x10x9 feet. CRT projectors and active shutter glasses were used to provide stereoscopic graphics in the CAVE. Both displays and all input devices were tracked by an Intersense IS-900 VET tracker. The wand used in the experiment was the standard Intersense IS-900 wand, while the Pinch Glove conditions used a pair of Fakespace Pinch Gloves to which trackers could be attached. Finally, we used a tracked wireless mouse in the non-dominant hand for the Wand-Voodoo Dolls conditions, since the Voodoo Dolls technique requires two input devices (we did not have access to two wands).

The VE software was built on CHASM [20] and SVE [21], while tracker data was handled by DTK [22]. The same reference implementations of the three interaction techniques were used for all combinations of displays and devices.

### 6.3 Procedure

We designed a simple room environment for the study. The room contained a variety of realistic objects (tables, pictures, flowers, etc.) and was large enough to require manipulation at-a-distance. After a period of practice with the first assigned technique, display, and device, subjects were given a series of tasks to perform in this room. Tasks covered a range of difficulty levels, and included both near-space and far-space manipulations. Subjects repeated this set of tasks for each combination of displays and devices for their assigned interaction technique.

### 6.4 Results

The results of this study are quite rich due to the variety of measures that we used, and analysis is still ongoing. We have already identified several salient outcomes, however.

First, our overall conclusion is that naïve migration of these interaction techniques to different displays and input devices was largely successful. None of the techniques completely broke down or became unusable when used with non-native displays and devices. This was surprising, and might be used to argue that display- and device-specific techniques are not needed after all. We did find, however, several key usability problems for the migrated techniques, and we claim that these problems are significant enough to pursue further.

The native implementation of Voodoo Dolls uses the HMD and Pinch Gloves. Migrating this implementation to the CAVE did not result in serious usability problems. Using the wand with either display, however, we found that subjects reported much greater frustration and difficulty in completing certain tasks. We observed that users often bumped the two trackers into one another, lost tracking because one device was covering the other, or found their hands in odd positions when trying to rotate the context or place an object on the left side of the context. These problems were due to the bulkiness of the devices, the natural hand positions of users when holding the devices, and the fact that the reference implementation of Voodoo Dolls assumes that the user is holding the context object at its center.

For HOMER and Go-Go, recall that the native implementation uses the HMD and wand. We found that the HMD-Pinch Gloves and CAVE-wand combinations were still highly usable, but that the CAVE-Pinch Glove combination caused problems for the participants. Because of the missing back wall of the CAVE, most CAVE interfaces must provide a method to allow the user to rotate the environment around its vertical axis. This was required for our manipulation tasks, since users needed to be able to select and manipulate objects in the entire virtual room. In the CAVE-wand condition, this was not a problem, since the joystick on the wand could be used to rotate the environment, and users could even simultaneously manipulate an object (by holding a button) and rotate the environment by using two hands on the wand. In the CAVE-Pinch Glove condition, however, this was not the case. We provided object selection and release with one pinch gesture, and left and right rotations with two other pinches. It was difficult, if not impossible, for users to simultaneously hold a virtual object and rotate the environment. Interestingly, this problem did not occur until we had migrated the technique to both a new display and a new device.

## 7 Designing Display- and Device-Specific Techniques

With the need for display- and device-specific techniques established by our series of studies, the next step was to demonstrate successful technique redesigns for specific displays or devices. Based on the results of experiment II (section 5), we attempted to design a CAVE-specific WIM technique, but we lacked design guidance due to the performance-focused nature of the experiment. The redesigned technique did not improve the WIM's performance in the CAVE. We focus here on two redesigned techniques that were developed as a result of experiment III.

### 7.1 Wand-Specific Voodoo Dolls

To address the usability issues caused by migrating Voodoo Dolls to the wand input device, we designed a device-specific version of the technique. The redesigned technique has several key features:

- the side of the context doll, rather than its center, is attached to the non-dominant hand,
- the interaction positions are offset slightly away from the tracking devices, and
- the visual representations of the user's hands have the same shape and size as the tracking devices.

These changes were intended to reduce the occurrence of trackers colliding with one another, awkward hand positions, and tracker blockage. Although our follow-up usability study is still ongoing, preliminary results do indicate that these changes are having the desired effect and improving usability.

### 7.2 CAVE- and Pinch-Glove-Specific HOMER

The combination of a new display (the CAVE) and a new device (Pinch Gloves) caused usability problems for the HOMER and Go-Go techniques. Since the problems were the same for both techniques, we chose to implement a redesign for only one of them (HOMER). This display- and device-specific version of HOMER simply adds a second Pinch Glove on the user's non-dominant hand. This allows for many different combinations of pinches to indicate selections, releases, and world rotations. We have chosen to use the dominant hand to specify object selection and release, and two pinch gestures on the non-dominant hand to specify rotation of the VE. This allows users to manipulate objects and rotate the environment simultaneously with no fatigue and no conflicts. Early results indicate that this redesign is also quite successful.

## 8 Conclusions and Future Work

With the plethora of VE displays, input devices, and interaction techniques, finding appropriate combinations leading to usable 3D interaction is difficult. We have shown in this work that migration of 3D interaction techniques away from their native displays and devices can sometimes lead to significant usability issues. Although not always needed, in some cases display- and device-specific techniques can be designed to address these problems.

We are currently completing our study of the redesigned Voodoo Dolls and HOMER techniques, and expect to find that their usability greatly exceeds that of the unmodified versions. An open question, however, is whether the usability of the display- and device-specific techniques is equivalent to (or better than) the usability of the original, native implementations. In the future, we also plan to generalize our results into guidelines of two types: first, guidelines to help designers choose appropriate combinations of displays, devices, and techniques, and second, guidelines for managing the migration of techniques to new displays and devices.

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