Virtual Rear Projection: A Comparison Study of Projection Technologies for Large Interactive Displays

Jay Summet, Gregory D. Abowd, Gregory M. Corso†, James M. Rehg

College of Computing & GVU Center, School of Psychology†
Georgia Institute of Technology
Atlanta, GA 30332-0170
{summetj, abowd, rehg}@cc.gatech.edu, Gregory.Corso@psych.gatech.edu †

Abstract. Rear projection of large-scale upright displays is often preferred over front projection because of the elimination of shadows that occlude the projected image. However, rear projection is not always a feasible option for space and cost reasons. Recent research suggests that many of the desirable features of rear projection, in particular shadow elimination, can be reproduced using new front projection techniques. We report on an empirical study to determine how two of these new projection techniques compare with traditional rear projection and front projection, with the hope of motivating the continued advance of improved virtual rear projection techniques.

1 Introduction

The traditional vision of pervasive computing assumes that computer displays are liberally scattered throughout the environment in a variety of form factors. Large scale interactive displays are an important form factor which have just recently started to leave the laboratory. Commercial products such as the LiveBoard[8] and SmartBoard[11] deliver on the promise of Weiser's yard scale displays. The Everywhere Displays projector[10] greatly increases the ubiquity of displays by allowing interactive foot to yard scale displays to be front projected onto arbitrary planar surfaces. Recent research on the Stanford Interactive Mural has developed interaction and screen management techniques[3] for such large interactive surfaces, while work on electronic whiteboards[9], digital tape drawing[1], and focus plus context displays[2] have demonstrated potential application areas suited for a single user, large interactive display.

When investigating large interactive displays, the traditional implementation method has been rear projection. While rear projected displays can be larger than plasma or LCD displays they are costly from a space, display material, and installation standpoint. In some situations it would be beneficial to replace rear projected displays with a front projected solution. Doing so requires that problems with shadows and occlusions, inherent to front projection displays, be addressed. For example, focus plus context displays that use a front projector for their context area have been "tilted slightly" so the projector can be ceiling mounted to "keep the [sitting] user from casting a shadow on the projection screen" [2].

Researchers have been working to resolve the occlusion problem by filling in the technological space between standard front projection and true rear projection (See Section 2). Projectors have become inexpensive enough so that having redundant coverage of an area is now practical, and work has begun to solve the occlusion problem by actively adjusting the output of multiple, redundant projectors. We use the term *virtual rear projection* to describe the use of multiple redundant passive or active projectors to eliminate shadows.

Although these virtual rear projection techniques have had some success, it is still possible to visually detect the difference between them and a true rear projected surface. Additionally, the active systems exhibit some possibly distracting visual artifacts such as “halos” which follow occluded areas (See Figure 5)[13]. While developing such techniques for large scale interactive displays, we began to wonder just how much of a problem occlusions and shadows posed and how advanced the technology would have to become to be useful. Specifically, we wondered if it was necessary to dynamically compensate for shadows caused by the users. Simply providing redundant illumination (passive virtual rear projection - resulting in “half shadows”) without actively attempting to compensate for occlusions might be sufficient for users to operate effectively.

Although it is our intuition that occlusions and shadows pose a problem to users of vertical front projected displays (possibly explaining why many large scale interactive displays have been implemented using rear projection) we were unable to locate work that quantified the problem. This paper presents the first empirical end-user study of virtual rear projection. The study described in this paper is designed to: 1) Determine the extent to which shadows on a front projected surface affect user task performance. 2) Investigate user strategies for coping with imperfect display technology (which allows occlusions). 3) Evaluate two of the new projection technologies introduced in Section 2 in comparison to standard **Front Projection (FP)** and true **Rear Projection (RP)** in terms of human performance and preference.

In Section 2 we introduce a taxonomy of projection technologies that extend from front projection to true rear projection and motivate the use of virtual rear projection technologies. In Section 3 we explain the setup of the first empirical end-user study of virtual rear projection. We present the results in Section 4 and a followup study in Section 5. We then discuss the findings of our study and present recommendations about when to use each of the technologies in Section 6 and discuss future work in Section 7, followed by our conclusion.

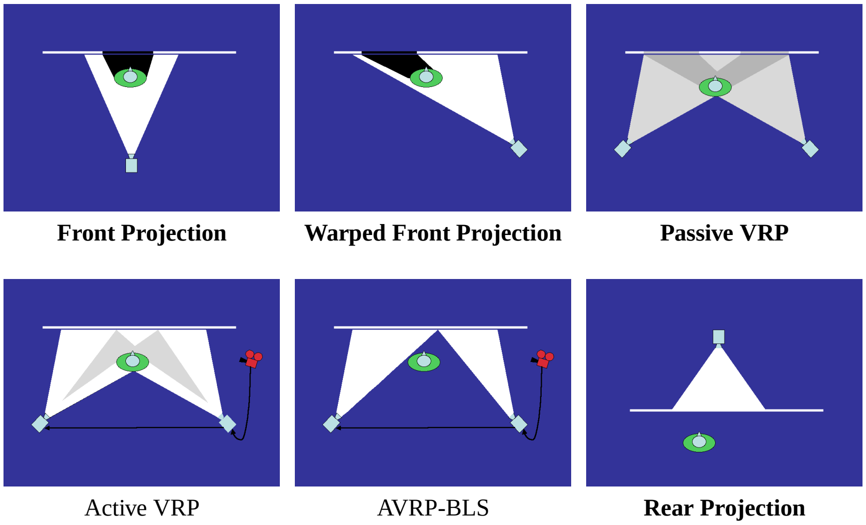
2 Motivating Virtual Rear Projection Technologies

Figure 1 illustrates the emerging continuum of projection technologies (we studied bold entries):

- ***Front Projection (FP)*** - A single front projector is mounted along the normal axis of the screen. Users standing between the projector and the screen will produce shadows on the screen. This is a setup similar to most ceiling mounted projectors in conference rooms.
- ***Warped Front Projection (WFP)*** - A single front projector is mounted off of the normal axis of the projection screen, in an attempt to minimize occlusion of the beam by the user. The output is warped to provide a corrected display on the screen. Examples are new projectors with on-board warping functions, such as used by the

3M IdeaBoard[5], or the Everywhere Displays Projector[10]. Additionally, the latest version of the nVidia video card drivers includes a “keystoning” function which allows any computer running Microsoft Windows to project a warped display.

- ***Passive Virtual Rear Projection (PVRP)*** - Two front projectors are mounted on opposite sides of the normal axis to redundantly illuminate the screen. Output from each projector is warped (as with WFP) to correctly overlap on the display screen. This reduces the number, size and frequency of occlusions. Users standing very close to the screen may still completely occlude portions of the output but usually only occlude the output of one of the projectors, resulting in “half-shadows” where the output is still visible at a lower level of contrast.



Front Projection **Warped Front Projection** **Passive VRP**

Active VRP AVRP-BLS **Rear Projection**

Fig. 1. Projection Technologies (Our four study conditions are presented in **bold**.)

- *Active Virtual Rear Projection (AVRP)* - Similar to PVRP, AVRP adds a camera or other sensor which determines when one of the projectors is occluded. The system then attempts to compensate for this occlusion by boosting output power from the other projector(s) to increase contrast in the “half-shadow” area(s)[7,12].
- *AVRP with Blinding Light Suppression (AVRP-BLS)* - Similar to AVRP, AVRP-BLS adds the ability to detect and turn off projector output that is shining on an object other than the screen, such as an intervening user. This blinding light suppression allows users to comfortably face the projectors without blinding light or distracting graphics being projected into their eyes or onto their bodies[12].
- ***Rear Projection (RP)*** - By using a single projector mounted behind the screen, a rear projection solution prevents occlusions and shadows completely, but requires extra, dedicated space for the beam path.

Our research has focused on developing passive and active virtual rear projection technologies. Competitors to virtual rear projection fall into two general categories, rear projected displays and physical displays. Physical displays include technology such as plasma screens and LCDs which produce an image directly, and must physically be as large as the display area. Currently, it is uneconomical to produce these screens at the size needed for wall scale displays. Plasma screens reach a diagonal measurement of sixty to seventy inches, while LCDs larger than twenty-three inches are rare. In general, making a rigid display surface without flaws increases in difficulty as the size of the display surface increases. Emerging and future technology such as digital wallpaper [4,6] or nanotech paint may eventually solve this problem[1], but for the immediate future, projection is the solution of choice for implementing large scale interactive surfaces.

While rear projection allows large wall sized displays, it requires a significant amount of space behind the display surface. This can become a problem when retrofitting a large interactive surface into a classroom or existing office space. In addition, it can be politicly difficult to annex space for a rear projection display in an existing building. Even if the space is available, installation of a new wall with a rear projection screen is a costly undertaking. The process of installing a new wall into a building is much more disruptive and irreversible than mounting a few projectors to the ceiling and hanging a front projection screen. If a user desires to place wall sized interactive displays on multiple sides of a room, the space, material and installation costs can grow prohibitively expensive.

Even in new construction, rear projection is an expensive option. The average cost to build a square foot of office space in the United States is $77 USD [14]. A five foot (1.52m) wide rear-projection surface will require a clearance of about three feet (0.91m) behind the screen, even when using a space saving twin mirror design. This fifteen square foot (1.39 m^2) area behind the screen will cost $1155 USD, approximately the cost of a cheap projector. Currently, the total cost of a rear projection system is similar to that of a virtual rear projection system with dual projectors. If current trends continue, projector prices will continue to decline, while building costs will continue to increase. Hence, we expect virtual rear projection systems to decrease in price as projectors and computing power continue to grow cheaper, while rear projection costs are more directly tied to display material, space and labor costs. Soon, the cost of a virtual rear projection system will become significantly cheaper than a comparably sized rear projection system. If the technology can be made indistinguishable from true rear projection, virtual rear projection will become a viable option for implementing wall sized interactive displays quickly and flexibly.

At the time we performed this study, we had developed warped front projection and passive virtual rear projection technologies to a point where we felt they were ready to be evaluated by end users. We wanted to determine if one of these technologies would

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[1] Current eInk manufacturing processes use conventional TFT arrays to drive the front plane laminate, limiting the size of such displays to that obtainable by conventional TFT/LCD manufacturing processes. If printed driver electronics can be developed, eInk technology could potentially be used to produce wall sized displays. Currently, nanotech paint is a purely conceptual concept.

be sufficient to replace true rear projection, and if not, use the results to inform our development of active virtual rear projection technologies.

3 Study Setup

The study evaluated the effects of four different projection technologies on a *single user* working with a large scale interactive surface. Participants were asked to perform interactive tasks on a SmartBoard which utilized a contact sensitive film (touch screen) on the display surface for input. Our study presented participants with four counterbalanced conditions**: Front Projection (FP), Warped Front Projection (WFP), Passive Virtual Rear Projection (PVRP),** and **Rear Projection (RP).**

3.1 Equipment Setup

Care was taken to adjust all conditions so that the intensity and resolution of the output was equal. Intensity was measured by a Sekonic Twinmate L-208 light meter to equalize light levels for all conditions and the output resolution was adjusted to provide an apparent resolution of 512x512, covering the entire SmartBoard screen, which measures 58” (1.47m) diagonally. For the front projection conditions (FP,WFP,PVRP) three matched projectors were mounted 7’1” (2.16m) high on a uni-strut beam 10’ (3.05m) from the SmartBoard. The rear projection (RP) condition used a projector mounted behind the SmartBoard screen. The projector used for WFP was mounted to the user’s right (all participants were right handed) when facing the SmartBoard, 27 degrees off-axis. The pair of projectors used for the PVRP condition had 48 degrees of angular separation as measured from the screen.

Two video cameras were used to document each session. One camera was mounted behind the SmartBoard screen and was used to measure occlusions caused by the user in the front projection cases (FP,WFP,PVRP), while the other camera recorded the participants’ interaction with the display surface. As we did not study active virtual rear projection systems in this study, the cameras were used only to collect data for the study and did not provide feedback to the projector system.

3.2 Study Participants and Tasks

Our study participants were seventeen (17) college students, 9 males and 8 females, mean age of 21.3 (σ=1.77), from the experimental pool of the School of Psychology at our university. To avoid handedness effects, we selected right handed participants who exclusively used their right hand for interacting with the screen. All participants had 20/20 eyesight or wore corrective eye-wear to bring their eyesight to 20/20. A photographic image was used to evaluate subjective image quality, and three tasks were presented to the participants. These tasks exercise the basic searching, selecting, dragging and tracing options that a user performs with an interactive surface to perform such UI interactions as button pushing, slider movement, icon dragging, etc. Although they did not directly simulate the use of real applications, we felt that the tasks are relevant for many standard UI interactions and hence, many applications.

Crosses Task (Accurate Selection) - Twenty crosses were displayed in a grid over the display surface. The user was instructed to tap as close to the center of each cross as possible, taking as much time as necessary. Accuracy measurements (X and Y offset from the actual center) were made for each cross using the SmartBoard touch sensitive surface.

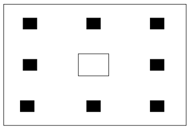

Fig. 2. Center target and the eight possible box starting positions.

Box Task (Fast Search, Selection, and Dragging) - Boxes with 2” sides appeared pseudo-randomly in one of 8 positions around the perimeter of the screen (Figure 2), with a 4” target placed in the center. The user was instructed to drag each box into the target. Each user moved eighty (80) boxes (ten boxes from each of the eight positions) for each projection technology.

For each box, the search/select (acquire) time, drag time, and total time were recorded, as well as the number of drags/touches needed to move it into the target. For analysis of the three front projection conditions (FP,WFP,PVRP), data from the video camera behind the SmartBoard was used to determine if the box was initially visible or occluded. A box which was in a half-shadow (in the PVRP condition), and visible with a lower level of contrast, was considered to be unoccluded.

Spiral Task (Fast Tracing) - An Archimedes’ spiral with three revolutions was presented to the participants to test non-linear dragging as an approximation to activities such as tracing and writing. The participants were instructed to trace the spiral as quickly as possible. While the user’s finger traced sufficiently close to the spiral, it would erase it. If the path deviated significantly from the spiral it would cease to respond (erase) and the user would have to re-trace from their point of deviation. This error metric allowed for fast tracing, but was strict enough to discourage wild gesturing. The time it took the user to complete each spiral was recorded.

4 Results

Tables 1 & 2 summarize our results discussed in the following sections. Table 1 reports on subjective measures of image quality, user preference and acceptance gained from questionnaires while table 2 reports on quantitative results from logged data. We conducted a repeated-measures ANOVA and paired-samples t-tests to determine significance[2].

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[2] *[Image Quality: $F(3,48) = 9.755$, $p < 0.001$; Preference: $F(3,48) = 20.812$, $p < 0.001$; Acceptance: $F(2.156,34.5) = 17.366$, $p < 0.001$]*

Condition	**Image Quality**	**Preference**	**Acceptance**
Front Projection (FP)	4.52	3.35	3.82
Warped Front Projection (WFP)	3.29	*3.18*	*3.47*
Passive Virtual Rear Projection (PVRP)	3.70	***4.65***	*4.88*
Rear Projection (RP)	**5.88**	**6.18**	**6.47**

Table 1. Mean subjective measures from 7 point scales (1 is poor / dislike / unacceptable). RP scores (in **bold**) are significant when compared to all other conditions ($p<0.05$). User preference of PVRP is also significant. The scores of WFP and PVRP (in *italics*) are significant in relation to each other in the user preference and acceptance categories. The other scores report trends in the data that do not fall under the $p<0.05$ significance criteria.

Condition	Box Acquire Time (sec.)	Crosses Error	Spiral Time (sec.)
Front Projection (FP)	1.25 (0.49)	0.0074 (0.0121)	13.75 (4.10)
Warped Front Projection (WFP)	1.12 (0.26)	0.0082 (0.0033)	13.15 (4.00)
Passive Virtual Rear Projection (PVRP)	1.15 (0.28)	0.0084 (0.0088)	13.06 (3.90)
Rear Projection (RP)	1.07 (0.23)	0.0081 (0.0183)	12.27 (3.81)

Table 2. Quantitative measures - Mean (Standard Error)

4.1 Subjective Measures: Image Quality, Preference & Acceptance

Image Quality - As expected, rear projection had the highest reported image quality[3]. To reduce variability we used the SmartBoard's rear projection surface for all conditions. Projecting onto the front of the surface (as FP, WFP, and PVRP do) causes a "ghosting" of the image due to multiple reflections from the front and back faces of the surface and the touch sensitive overlay used for input. WFP and PVRP, which both use off-axis projectors, were at a distinct disadvantage, as the rear projection display surface is specifically manufactured to be used in an on-axis configuration, and off-axis projection results in a visible blurring of the image due to the "across-the-grain" projection. We performed a small follow-up study to test the front projection conditions on a front projection screen (see Section 5). In the post session interview we found that the factor leading to the image quality score was primarily the sharpness (or blurriness) of the image (100%-P: 1-17) with some of the participants citing intensity or color saturation (29%-P: 4,7,8,13,16) and shadows (6%- P: 5) as additional factors. Some participants mentioned multiple factors and were counted in each category for factors leading to their image quality, preference and acceptance rankings.

Preference - Rear projection was prefered over the other projection technologies on the preference question[4] with passive virtual rear projection being prefered over the single

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[3] *"How would you rate the image quality of the display technology? [Poor Quality = 1 2 3 4 5 6 7 = Excellent Quality]"*

[4] *"Please rate the display technology on the following scale for the tasks performed. [Definite dislike = 1 2 3 4 5 6 7 = Liked very much]"*

projector conditions (FP&WFP). When asked to volunteer what factors they considered when making their preference judgments, about half of the participants mentioned image quality (65%-P: 1,3,5,6,7,9,10,12,13,16,17) and an equal number mentioned shadows (65%-P: 2,3,4,5,6,8,10,11,13,14,15) or lack thereof. Users ranked the image quality of PVRP lower than that of FP, yet their preference rankings for PVRP were significantly higher than that of FP. This, combined with the large number of participants who volunteered that shadows were a factor in their preference rankings indicates that PVRP was prefered because of its ability to eliminate virtually all occlusions.

Acceptance - The user acceptance question[5] was designed to determine if users would be willing to use a display technology, even if it was not their first choice (preference). Trends followed the preference rating question with slightly higher differences. When asked to volunteer what factors contributed to their acceptance rating, more than half mentioned image quality (53%-P: 2,3,4,5,6,9,14,16,17), and shadows (53%-P: 4,6,8,9,11,12,13,14,15). Ease of performing the task (P: 6,9), touch-screen problems (P: 7,12), unspecified reasons (P: 10) and “just kind’a a gut reaction” (P: 1) made up the remainder of responses.

4.2 Quantitative Measures: Speed & Accuracy

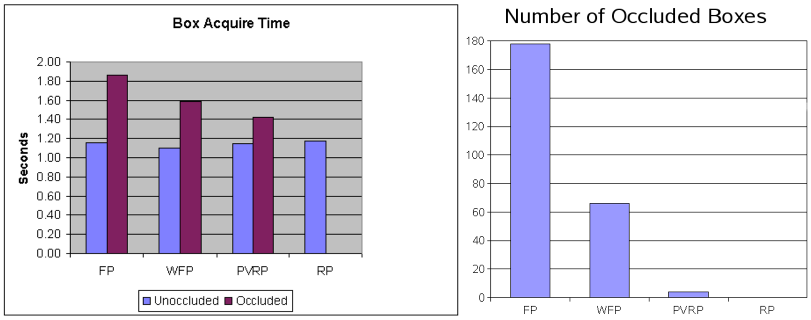

Fig. 3. (a) Acquire time for occluded vs. unoccluded boxes. (b) Number of occluded boxes by condition.

Box Task (Fast Search, Selection, and Dragging) - The Box Task was specifically designed to generate output that would be likely to fall within (and be hidden by) the user’s shadow. We measured the difference in acquire time between occluded and unoccluded boxes and recorded the behaviors participants adopted to compensate for shadows (see Section 4.3). Figure 3a shows the time difference between occluded and unoccluded boxes, demonstrating the performance penalty experienced by users under

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[5] *“Please rate your willingness to use this display technology on the following scale: [Absolutely unacceptable = 1 2 3 4 5 6 7 = Completely acceptable]”*

occluding conditions. WFP (with 66 occluded - 4.9% of all boxes) and PVRP (with 4 - 0.3%) lower the number of occlusions dramatically in comparison to FP (with 178 - 13.1%) (Figure 3b). The majority of occluded boxes fell in the bottom left and bottom center quadrants of the screen because our projectors were mounted near the ceiling and the users were right handed. Additionally, WFP and PVRP reduced the time it took users to acquire an occluded box. This was due to the fact that less of the users' shadow would cover the screen, allowing them to detect the box with less motion.

Crosses & Spiral Task (Accurate Selection & Fast Tracing) - These tasks differed from the Box Task in that the whole task was visually presented at once (a full spiral or all crosses) allowing the participants to plan their motion. In the Crosses Task, participants would generally work from one side of the screen to the other, keeping their shadow away from crosses they were working on. We found no significant difference between the four conditions for accurate selection.

The Spiral Task measured the user's ability to trace a curve quickly, exercising muscle motions similar to free form drawing or writing in a more controlled setting. Users would sway to avoid casting a shadow on the portion of the spiral they were currently tracing. Conditions which eliminated or reduced shadows (RP & PVRP) had slightly faster mean completion times than conditions which did not (FP & WFP), but these trends are not statistically significant.

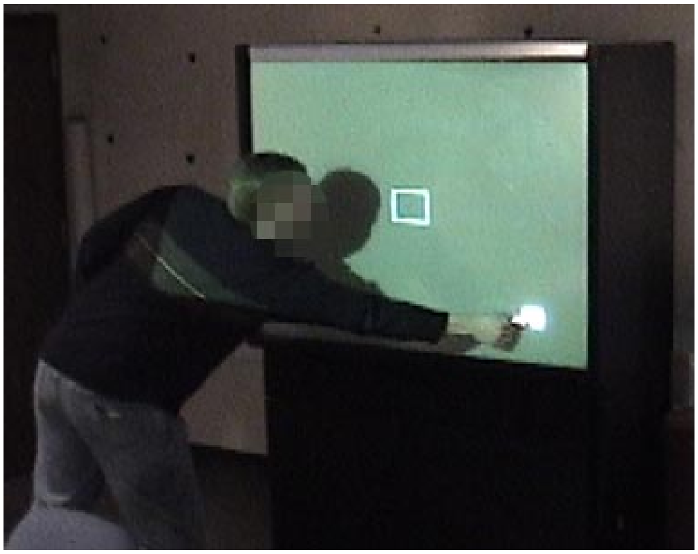

Fig. 4. Participant exhibiting the edge-of-screen coping strategy while working the Box Task in the Front Projection condition.

4.3 Coping Strategies

Occlusion & Shadow Coping Strategies Behavior in the PVRP and RP cases (minimal to no occlusions) were identical for all of the tasks, with almost all participants standing near the center of the screen with feet shoulder-width apart ("A-frame" stance), moving only their arms to reach around the screen.

In the FP and WFP conditions, the participants adopted coping strategies to work around their shadows. For the Crosses Task, most participants would work around their shadows, usually standing to the left of the cross they were currently working on. For the Spiral Task, all participants (other than participant 3, see the "Dead Reckoning" strategy below) would sway their body out of the way of the portion of the spiral they were currently tracing, giving a "tree swaying in the wind" appearance.

Strategies developed for the Box Task, which included randomly appearing targets, were much more involved. Participants generally used one of the following four strategies. Almost all participants settled into a single strategy fairly quickly (within 10 boxes). *Participant 9 changed from the Edge of Screen to the Move on Occlusion strategy half way through the run, and is counted in both.*

- *Edge of Screen* (7 of 17 participants) - Participants stood at the edge of the screen. Participants 2,9,13, and 15 would lean inward to move boxes, immediately returning to their home position to insure that they were not occluding the next box. (See Figure 4.) Participants 1,8, and 14 stood slightly in from the edge, so they would occasionally occlude boxes on the left edge. When unable to find a box, they would sway their upper body from the waist until the box they were occluding became visible.
- *Near Center* (7 of 17 participants) - These participants would stand near the center of the screen (usually with their right shoulder directly above the target). Participants 5, 12 and 16 were short enough to occlude few boxes, while participants 6,7,10, and 17 would occlude boxes and use the above "sway" strategy to find occluded boxes.
- *Move on Occlusion* (3 of 17 participants) - Participants 4, 9, and 11 would move to a new position whenever they occluded a box, and stay there until they occluded another box at which point they would move again.
- *Dead Reckoning* (1 of 17 participants) - Participant 3 stood near the center of the screen so that his shadow would occlude only a single box (position #5, lower left). Whenever he did not see a box, he would blindly select the area in his shadow where the box should be located (with an impressive degree of accuracy) and drag it to the target. (When performing the Spiral Task, participant 3 would "drag through" his shadow along the curve, also with impressive accuracy.)

Participant Awareness of Shadow Coping Strategies & Preference Ratings Factors About half of the participants (47%-P:2,4,6,8,9,13,14,15) volunteered that they developed strategies to cope with occlusions, (*"Were there any specific strategies you used to perform the tasks?"*) while others (47%-P:1,3,7,10,11,12,16,17) only recognized that they had done so when asked by the interviewer (*"Did you have any problems with* *shadows in any of the conditions?" / "How did you deal with them?"*) and one participant (6%-P: 5) who had only occluded 3 boxes (the average participant occluded 14.6 boxes) declared that they had no problems with the shadows.

Interestingly, of the eight participants who volunteered that they had developed strategies to deal with the shadows, seven (P: 2,4,6,8,13,14,15) stated that shadows were a factor in their preference ratings, while one (P: 9) only reported having considered image quality. Of the eight who only recognized their shadow coping behavior after being prompted by the interviewer, three (P: 3,10,11) cited shadows as a factor in their preference ratings, while five reported using image quality exclusively (P: 1,7,12,16,17).

5 Followup Image Quality & Comfort Level Study

We performed a small followup study with ten participants running the image quality task on a front projection screen with the front projected conditions (FP, WFP, and PVRP). The goal of this study was to determine the effects of our primary study's projection surface which was optimized for rear projection, on the image quality scores for the front projection cases. Participants in this secondary study did not perform the performance measurement tasks (Crosses, Box, Spiral). The same photographic image, intensity, resolution, and questionnaire were used to measure subjective image quality. We added the task of reading two cards displayed at the back of the room which forced the participants to face the projectors as if giving a presentation. Participants were then asked to rate the "comfort" level of each condition. ("*Did you find the light from the projector(s) to be annoying? [Annoying = 1 2 3 4 5 6 7 = Unnoticeable]*")

Condition	**Image Quality**	**Comfort**
Front Projection (FP)	4 (1.15)	6.5 (0.53)
Warped Front Projection (WFP)	4.1 (0.99)	5.9 (1.37)
Passive Virtual Rear Projection (PVRP)	3.2 (1.62)	**4.5 (2.07)**

Table 3. Mean (Standard Deviation) subjective measures on a 7 point scale, 1=poor quality/annoying 7=excellent quality/ unnoticeable on image quality and annoyance of projected light on a front projection screen. **Bold** data indicates statistical significance.

Although they can not be directly compared to the primary study, the trends in image quality scores indicate that warped front projection can produce an image quality that rivals that of a front projector, while suggesting that the slight differences in image alignment for passive virtual rear projection produce a lower quality image, even on a front projection surface.

As with the primary study (Section 4), the user was placed in a specific location when performing the image quality task (three feet from the screen, two feet to the left of center). This placement was chosen so that they were *not* blocking the beam path for the front projection (FP) and warped front projection (WFP) conditions, and *were* blocking the beam path of the left projector for the passive virtual rear projection

(PVRP) condition. The location was chosen based upon our observations of projector users, who almost exclusively choose to stand outside of the beam path when possible. We deliberately placed participants in the beam path for the PVRP condition, as it is much harder to avoid a pair of projectors, and the actual deployment of virtual rear projection technologies will likely make it difficult to avoid beam paths. The result of this decision was that neither the FP or WFP conditions beamed light directly into the participants' faces. The comfort scores in Table 3 for FP and WFP are understandably higher than for PVRP, and even with such a limited participant pool the difference between PVRP and the other conditions was significant ($p <= 0.05$). Although obvious, we have empirically confirmed that users notice when they are in the beam path of a projector and find it moderately annoying, motivating the addition of blinding light suppression to active virtual rear projection technologies.

6 Discussion

In our studies, we found that humans are able to adapt to occlusions and shadows from front projection systems via coping behaviors to maintain their level of task performance. Although the front projection acquire times are slightly slower than rear projection (by 0.18 seconds), this difference is not statistically significant. We observed four different types of coping behavior which users developed early and quickly in the front projection sessions. This indicates that at least for simple tasks, a single front projector is sufficient.

However, there are two important qualifications. First, our tasks were quite basic, and we did not measure the amount of cognitive load executing the coping strategies placed on the users. More cognitively challenging tasks may suffer from the use of front projection coping strategies. Secondly, and more importantly, even though performance was comparable, our participants strongly disliked front projection when comparing it to rear projection (subjective rating of 3.35 vs 6.18). There are very few applications where the users' preference does not play a strong role in acceptance and adoption, and these preference scores can not be discounted.

Assuming that a system already has an accelerated 3D graphics card, a warped front projection (WFP) system adds nothing to the hardware cost of a traditional front projection (FP) system, although system software must be designed to use the graphics card to correctly warp the output. Our primary study indicates that such a system reduces occlusions by an average of 62% when compared to a straight front projection system. We believe the low preference score for WFP in our primary study was due to the unfair disadvantage presented by the off-axis projection onto the rear-projection surface. Our followup study on a front-projection surface showed that WFP image quality was virtually identical to a standard front projection system when used on a front projection surface. We recommend warped front projection in situations where only a single projector is available and the application software allows the easy addition of warping code.

Because passive virtual rear projection (PVRP) had the highest user preference scores out of the front projection technologies, eliminated user's coping behavior and virtually eliminated occlusions, we feel it is the correct choice when the user desires a rear projection (RP) solution, but is constrained by the available space. If the space and resources are available, a rear projection system continues to provide the best user experience.

7 Future Work

The studies described in this paper investigated the various projection techniques in relation to the user of an interactive surface but did not investigate the experience of an audience member (in the case of a presentation) or non-driving participant (e.g. in a brainstorming or design session). These experiences may be widely different, especially in the case of warped front projection where the goal of the projection system is to shift the user's shadow to the side. Observers may find that this shifted shadow blocks content of interest or presents a visual distraction that detracts from the experience. Future studies are needed to examine the user experience for non-driving viewers of the display surface.

Virtual rear projection shows promise, and it can be used to deploy large scale interactive surfaces in locations where it is impossible to use rear projection. Virtual rear projection has the potential to become cheaper and easier to deploy than rear projected solutions, but the PVRP we studied is not yet sufficient to replace true rear projection. Because our user study found that users prefered true rear projection to passive virtual rear projection, and that users found the light from front projectors to be annoying, we are continuing to develop active virtual rear projection systems (see Figure 5) with blinding light suppression with the end goal of developing a form of virtual rear projection that is indistinguishable from true rear projection under normal usage. When sufficiently advanced, the active systems will need to be evaluated in a similar study.

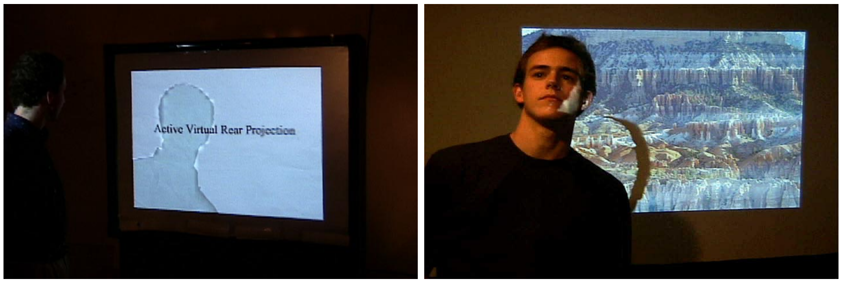

Fig. 5. Active Virtual Rear Projection systems compensating for a moving occluder.

8 Conclusions

In this paper we introduced a taxonomy of projection technologies in the continuum leading from front projection to full rear projection (Section 2) and motivated the development of a *virtual rear projection* replacement for rear projection using multiple front projectors. We performed and reported on an empirical study comparing front projection (FP), warped front projection (WFP), passive virtual rear projection (PVRP), and rear projection (RP) that grounds continued research in the area of virtual rear projection.

We cataloged the occlusion coping strategies that users developed to maintain their level of task performance when using single projector displays (FP, WFP). These coping strategies were not necessary when using passive virtual rear projection or rear projection. Because the users treated PVRP more like RP than the single front projector cases (FP,WFP) we feel that we are on the correct path to duplicating the user experience of rear projection. Additionally, we showed that occlusions could be reduced by 62% simply by re-positioning the projector (WFP) and almost entirely eliminated (0.3% of total boxes were occluded) by using passive virtual rear projection.

The fact that users were able to develop coping strategies to deal with occlusions in the front projection conditions suggests that a front projected display may provide the same task performance as the more expensive options of virtual rear projection and true rear projection. However, users prefered passive virtual rear projection to front projection and warped front projection, ranking it higher in preference and acceptability ratings, second only to true rear projection. Due to these rankings, and the empirical confirmation that users found the light from front projectors to be annoying, we intend to close the gap between front and rear projection by continuing the development of active virtual rear projection with blinding light suppression. Our eventual goal is making virtual rear projection indistinguishable from true rear projection.

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