Virtual Rear Projection: An Empirical Study of Shadow Elimination for Large Upright 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, pshupcg@prism.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 ubiquitous 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 begun leaving the laboratory. Commercial products such as the LiveBoard[6] and SmartBoard[9] have began to deliver on the promise of Weiser's yard scale displays. The Everywhere Displays projector[8] allows interactive displays in the foot to yard scale to be (front) projected onto arbitrary planar surfaces, greatly increasing the ubiquity of displays. Recent research on the Stanford Interactive Mural has developed interaction and screen management [3] techniques for such large interactive surfaces, while work on electronic whiteboards[7], 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. Rear projected displays can be larger than plasma or LCD displays and do not suffer from the shadows and occlusions of front projection displays. But, 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 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. Projectors have become cheap 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. The following list illustrates the emerging continuum of projection technologies:

- *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[4], or the Everywhere Displays Projector[8]. Additionally, the latest version of the nVidia video card drivers includes a “keystoning” function which allows any Windows computer to project a warped display.
- *Virtual Rear Projection (VRP)* - 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.
- *Active Virtual Rear Projection (AVRP)* - Similar to VRP, 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)[5,10].
- *AVRP with Blinding Light Suppression (AVRP-BLS)* - Similar to AVRP, AVRP-BLS adds the ability to turn off projector output that is projecting on a user or object. 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[10].
- *Rear Projection (RP)* - Using a single projector mounted behind the screen, so that it is not possible to occlude the projection beam or cause shadows.

Although these techniques have had some success, their results are not yet indistinguishable from a rear projected surface, and exhibit some possibly distracting visual artifacts such as “halos” which follow occluded areas.

While developing such “virtual rear projection” 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. Simply providing redundant illumination (resulting in “half shadows”) without actively attempting to compensate for occlusions might be good enough for users to operate effectively. If this was the case, further development of active virtual rear projection technology would be unnecessary. 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.

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 allow occlusions). 3) Evaluate **Warped Front Projection (WFP)** and **Virtual Rear Projection (VRP)** in comparison to standard **Front Projection (FP)** and true **Rear Projection (RP)** in terms of human performance and preference.

2 Study Design

The study compares the four conditions listed below for 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**: FP, WFP, VRP, RP.**

2.1 Equipment Setup

Care was taken to adjust the output of all projectors so that the intensity on the screen was equal between the different conditions (as measured by a Sekonic Twinmate L-208 light meter). For all conditions 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,VRP) 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 VRP 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,VRP), while the other camera recorded the participants’ interaction with the display surface.

2.2 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 School of Psychology’s experimental pool. Participants were selected to be right-handed, and used their right hand exclusively for interacting with the screen. A photographic image, used to evaluate subjective image quality, and three tasks were presented to the participants. These tasks (especially the second and third) exercise the basic operations (searching, selecting, dragging and tracing) that a user performs with an interactive surface, and are the low level operations needed to perform such UI interactions as button pushing, slider movement, icon dragging, etc. Although they do not directly simulate the use of real applications, we feel that the tasks are relevant for many standard UI interactions and hence, many applications.

Accurate Selection Task (Crosses Task) - 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.

Fast Search, Selection, and Dragging Task (Box Task) - Boxes with 2” sides appeared pseudo-randomly in one of 8 positions around the perimeter of the screen (Figure 1), while a 4” target was placed in the center of the screen. The user was instructed to drag each box into the target. The user moved eighty (80) boxes (ten boxes from each of the eight positions) for each condition.

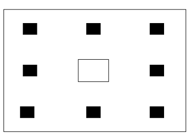

Fig. 1. Target and box starting positions.

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,VRP), 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 VRP condition), and visible with a lower level of contrast, was considered to be unoccluded.

Fast Tracing Task (Spiral Task) - An Archimedes’ spiral with three revolutions ($\theta = 6\pi$), designed to test non-linear dragging as an approximation to activities such as tracing and writing, was presented to the participants who were instructed to trace it as quickly as possible. While the user traced sufficiently close to the spiral, their finger would erase it. If their path deviated significantly from the spiral it would cease to respond (erase) and they would have to re-trace from their point of deviation. The error metric allowed for fast tracing, but was strict enough to discourage wild gesturing.

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

Table 1. Mean subjective measures from 7 point scales. RP scores (in **bold**) are significant when compared to all other conditions ($p<0.05$). User preference of VRP is also significant. The scores of WFP and VRP (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 does not fall under the $p<0.05$ significance criteria.

3 Results

Tables 1 & 2 summarize our results discussed in the following sections. We conducted a repeated-measures ANOVA to analyze our data. To correct for a potential violation of the sphericity assumption in the acceptance case we applied a Greenhouse-Geisser correction. Results from the subjective measures (Table 1) indicate significant differences for all four conditions. *[Image Quality: $F(3,48) = 9.755$, $p < 0.001$; Preference: $F(3,48) = 20.812$, $p < 0.001$; Acceptance: $F(2.156,34.5) = 17.366$, $p < 0.001$]* Post-hoc analysis used paired-samples t-tests.

3.1 Subjective Measures: Image Quality, Preference & Acceptance

Image Quality - As expected, rear projection had the highest reported image quality ("*How would you rate the image quality of the display technology? [Poor Quality = 1 2 3 4 5 6 7 = Excellent Quality]*"). To control independent variables we used the SmartBoard's rear projection surface for all conditions. Projecting onto the front of the surface (as FP, WFP, and VRP 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 VRP, 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. 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 the overall favorite on the preference question *("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]")*. 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.

Acceptance - The user acceptance question (*"Please rate your willingness to use this display technology on the following scale: [Absolutely unacceptable = 1 2 3 4 5 6 7 = Completely acceptable]"*) 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.

3.2 Quantitative Measures: Speed & Accuracy

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

Condition	Box Aquire 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)
Virtual Rear Projection (VRP)	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 Deviation)

time between occluded and unoccluded boxes, as well as observed the behaviors they adopted to compensate for shadows (see section 3.3). Figure 2 shows the time difference between occluded and unoccluded boxes, demonstrating the performance penalty experienced by users under occluding conditions. WFP (with 66 occluded - 4.9% of all boxes) and VRP (with 4 - 0.3%) lower the number of occlusions dramatically in comparison to FP (with 178 - 13.1%). The majority of occluded boxes fell in the bottom left and bottom center quadrants of the screen. However, the number of occluded boxes was insufficient to significantly affect the overall task completion time.

We found no significant difference between the four conditions for accurate selection, as measured by the crosses task.

The Spiral task measured the user's ability to quickly trace a curve, exercising muscle motions similar to free form drawing or writing, in a more controlled setting. Conditions which eliminated or reduced shadows (RP & VRP) had slightly faster mean completion times than conditions which did not (FP & WFP), but these trends are not statistically significant.

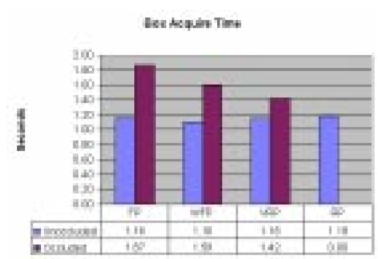

Fig. 2. Acquire time for occluded vs. unoccluded boxes.

3.3 Observations

Occlusion & Shadow Coping Strategies Behavior in the VRP and RP cases (minimal to no occlusions) were identical, 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. When compensating for occlusions in the FP and WFP conditions, participants generally used one of the following four strategies. Almost all participants settled into a single strategy fairly quickly (within 10 boxes).

- *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. 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) - These participants (P4,P9,P11) 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.)

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 P3) 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.

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, (*“Where their any specific strategies you used to perform the tasks?”*) while others (43%-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).

4 Future Work

We are very interested in studying FP, WFP, and VRP techniques when used on a display surface more suitable for front projection, and plan a followup study to confirm that the image quality degradation we found was attributable to the use of a rear projection surface and was not a problem with the WFP or VRP techniques themselves. We plan on integrating this study with an examination of the preference ratings of 3rd party viewers of the display (such as in a meeting or presentation scenario) using a more realistic application such as a presentation viewer.

Finally, the results of this study (specifically, the user preference of RP overall and VRP over other front projection techniques) motivate our work to continue the development of active virtual rear projection technology with blinding light suppression, with an end goal of developing a form of virtual rear projection that is indistinguishable from true rear projection under normal usage.

5 Conclusions

In this paper we introduced the continuum of projection technologies leading from front projection to full rear projection (Section 1) and reported on an empirical study comparing front projection (FP), warped front projection (WFP), virtual rear projection (VRP), and rear projection (RP).

We measured the time it took users to cope with an occluded stimulus when using FP, WFP, and VRP and reported on the decreasing frequency of occlusions as you approach RP. We also reported on the coping strategies used by participants working with single projector front projected displays (FP,WFP) which were not exhibited when using virtual rear projection or rear projection. We feel the fact that users did not use occlusion coping strategies when using virtual rear projection is an important indication of the benefits it provides over FP & WFP.

We found that the effect of occlusions on our tasks were statistically non-significant on measures of overall user performance (speed & accuracy), suggesting 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, a rear projected display was prefered by users, ranking higher in preference and acceptability ratings over the other technologies evaluated. Virtual rear projection, although ranked lower than rear projection, was ranked higher than warped front projection and front projection.

Users prefered rear projection over passive virtual rear projection, indicating that passive VRP is not yet good enough to replace rear projection. We plan to continue developing active virtual rear projection with blinding light suppression to make it more indistinguishable from true rear projection.

References

1. Ravin Balakrishnan, George W. Fitzmaurice, Gordon Kurtenbach, and William Buxton. Digital tape drawing. In *ACM Symposium on User Interface Software and Technology*, pages 161–169, 1999.
2. Patrick Baudisch, Nathaniel Good, and Paul Stewart. Focus plus context screens: combining display technology with visualization techniques. In *Proceedings of the 14th annual ACM symposium on User interface software and technology*, pages 31–40. ACM Press, 2001.
3. F. Guimbretire, M. Stone, and T. Winograd. Fluid interaction with high-resolution wall-size displays, 2001.
4. 3M IdeaBoard. http://www.3m.com/us/office/meetings/product_catalog/wd_ideaboard.jhtml.
5. Christopher Jaynes, Stephen Webb, R. Matt Steele, Michael Brown, and W. Brent Seales. Dynamic shadow removal from front projection displays. In *Proceedings of the conference on Visualization 2001*, pages 175–182. IEEE Press, 2001.
6. Simply LiveWorks. http://www.wearesimply.com/.
7. Elizabeth D. Mynatt, Takeo Igarashi, W. Keith Edwards, and Anthony LaMarca. Flatland: New dimensions in office whiteboards. In *CHI'99 Proceedings*, pages 346–353, 1999.
8. Claudio Pinhanez. The everywhere displays projector: A device to create ubiquitous graphical interfaces. In *Proceedings of Ubiquitous Computing (Ubicomp)*, pages 315–331, 2001.
9. Smart Technologies SmartBoard. http://www.smarttech.com/products/index.asp.
10. T.J. Cham, J. Rehg, G. Sukthankar, R. Sukthankar. Shadow elimination and occluder light suppression for multi-projector displays. In *CVPR Demo Summary*, 2001.