Virtual Rear Projection: Do Shadows Matter?

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ABSTRACT

Rear projection of large-scale upright displays is often preferred over front projection because of the lack 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 the results of an empirical study comparing two new projection techniques with traditional rear projection and front projection.

AUTHOR KEYWORDS

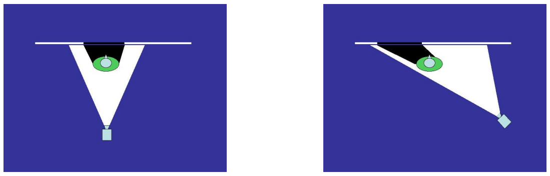
Human performance, user study, display technology, projection, virtual rear projection, interactive surface

ACM CLASSIFICATION KEYWORDS

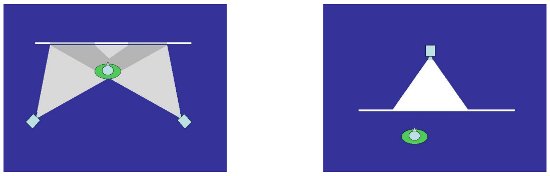
B.4.2 [Input/Output and Data Communications]: Input/Output Devices - Image display; H.5.2 [Information Interfaces and Presentation]: User Interfaces - Graphical user interfaces, Screen design, User-centered design;

INTRODUCTION

Large scale interactive displays are an important form factor which have just recently started to leave the laboratory. Commercial products such as the LiveBoard and SmartBoard and research prototypes [1,5,6] begin to deliver on the promise of Weiser's yard scale displays for single-user, large interactive displays. When investigating large interactive displays, the traditional implementation method has been rear projection. Currently, it is uneconomical to produce plasma and LCD screens at the size needed for wall scale displays. Emerging and future technology such as digital wallpaper [3] or nanotech paint may eventually solve this problem, but for the immediate future, projection is the solution of choice for implementing large scale interactive surfaces. While rear projected displays can be larger than plasma or LCD displays, they also have limitations due to cost and installation requirements. In some situations it would be beneficial to replace rear projected displays with a front projected solution. Using front projection for interactive surfaces requires that the inherent 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" [1]. Pre-emptive shadows [8] eliminate the blinding light from a projector, but are more useful for giving presentations than for interactive displays as they increase the occluded area on the display.



(a) Front Projection (b) Warped Front Projection



(c) Virtual Rear Projection (d) Rear Projection

Figure 1. Taxonomy of Projection Technologies.

Researchers have been working to resolve the occlusion problem by filling in the technological space between standard front projection and true rear projection. A simple solution, called ***Warped Front Projection (WFP)*** uses a single front projector which is mounted off of the normal axis of the projection screen, in an attempt to minimize occlusion of the beam by the user (Figure 1b).

Projectors have become inexpensive enough so that having redundant coverage of an area is now practical. We use the term ***Virtual Rear Projection (VRP)*** to describe the use of multiple redundant projectors to eliminate shadows. Two front projectors are mounted on opposite sides of the normal axis to redundantly illuminate the screen (Figure 1c). After a calibration step using computer vision technology in the GVU PROCAMS Toolkit [9], output from each projector is independently warped (as with WFP) to correctly overlap on the display screen. This reduces the size and frequency of

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occlusions significantly and results in “half-shadows” where the output is still visible at a lower level of contrast.

Although it was our intuition that occlusions and shadows pose a problem to users of upright front projected displays we were unable to locate work that quantified the problem. We designed a study 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); and 3) evaluate two of the new projection technologies **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. We wanted to determine if a passive form of VRP would be sufficient to replace true rear projection, and if not, use the results to inform development of more active virtual rear projection technologies [2, 4].

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 rear projection capable 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.**

Figure 2. Participant during the Box task exhibiting the edge-of-screen coping strategy (FP condition).

Projection intensity was equalized 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 (Figure 2). 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.

Study Participants

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 institute. We selected right-handed participants who exclusively used their right hand for interacting with the screen (without a pen or stylus).

Study Tasks

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, writing, 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.

Box Task (Fast Search, Selection, and Dragging) - Boxes with 2” sides appeared pseudo-randomly in one of 8 potential starting positions around the perimeter of the screen (Figure 3), with a 4” target placed in the center of the screen. The user was instructed to drag each box into the target as quickly as possible.

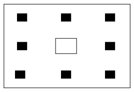


Figure 3. Center target and the eight starting positions.

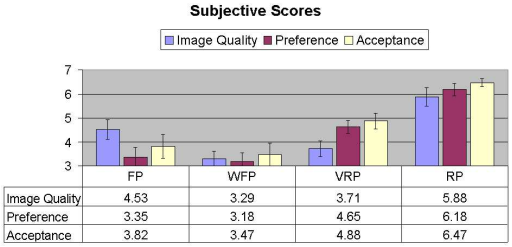
Each user moved ten boxes from each of the eight positions (80 total) for each projection technology. For each box, the search/select (acquire) time, and total time were recorded. For analysis of the three front projection conditions (FP, WFP, VRP), data from a video camera behind the SmartBoard was used to determine if the box was initially visible or occluded.

Crosses Task (Accurate Selection) & Spiral Task (Fast Tracing) - Participants performed two other tasks designed to measure accurate selection (no time pressure) and fast tracing (time pressure) such as used when writing. *The results from these two tasks did not show statistically significant differences between the four conditions and will not be discussed further due to space considerations. Refer to our technical report [7] for more details.*

RESULTS

Figures 4 and 5 summarize our results and present the pairwise T-tests resulting from our statistical analysis. In our within-subjects design, participants experienced each condition in a counter-balanced order. Subjective measures were collected via questionnaire after each condition, while qualitative measures were recorded by the computer administering the tasks. We analyzed the data using a repeated measures ANOVA. To correct for a potential violation of the sphericity assumption we applied a Greenhouse-Geisser correction in all cases. The independent variable was treatment condition (FP,WFP,VRP,RP).

Subjective Measures - A main effect was found for all subjective measures. *[Image Quality: $F(2.224, 35.589) = 9.755$, $p < 0.001$; Preference: $F(2.359, 37.745) = 20.812$, $p < 0.001$; Acceptance: $F(2.156, 34.5) = 17.366$, $p < 0.001$].*



Condition	Compared With:	Image Quality	Preference	Acceptance
FP	WFP	**1.235**	0.176	0.353
	VRP	0.824	**-1.294**	**-1.059**
	RP	**-1.353**	**-2.824**	**-2.647**
WFP	VRP	-0.412	**-1.471**	**-1.412**
	RP	**-2.588**	**-3.000**	**-3.000**
VRP	RP	**-2.176**	**-1.529**	**-1.588**

Figure 4. (Top) Subjective scores from participant questionnaires. (Bottom) Pairwise comparisons of Image Quality, Preference, and Acceptance scores based upon treatment condition. Positive numbers indicate the condition scored higher than the "compared with" condition. Statistically significant differences (p<0.05) are presented in bold.

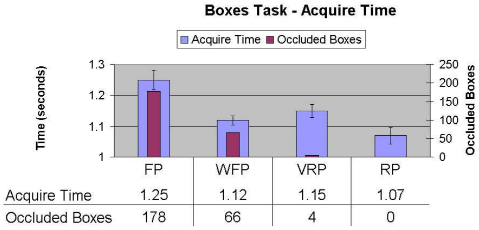
As expected, rear projection had the highest reported image quality. In the post session interview we found that the factor leading to the image quality score was primarily the sharpness (or blurriness) of the image (100%) with some of the participants citing intensity or color saturation (29%) and shadows (6%) as additional factors. We attribute the poor showing of VRP and WFP (leftmost bars in the graph of Figure 4) to using the SmartBoard's display (designed for on-axis projection) for all conditions, which was needed to control for extraneous variables. A followup study has shown that WFP and VRP can perform much better on a surface designed for front projection [7].

Acquisition Time - In the Box task the dependent variables, measured in milliseconds, were (box) Acquire Time and Total Time. A main effect was found based upon the treatment condition for Acquire Time *[Acquire Time: F(2.127,34.036) = 23.940, p <= 0.001]*; no significant difference was found between conditions for the total task completion time. We measured the difference in acquisition time between occluded and unoccluded boxes and categorized the behaviors participants adopted to compensate for shadows. 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%) (Figure 5).

Coping Strategies

Behavior in the VRP 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, participants quickly (within 10 boxes) adopted coping strategies to work around their shadows. Participants generally used one of the following four strategies:

- *Edge of Screen* (7 of 17 participants) - Participants stood at the edge of the screen. Four participants would lean inward to move boxes, immediately returning to their home position to insure that they were not occluding the next box. (See Figure 2.) Three participants 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. Three participants were short enough to occlude few boxes, while the others would "sway" their entire upper body to find occluded boxes.
- *Move on Occlusion* (3 of 17 participants) - Participants 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) - This participant stood so that his shadow would occlude only a single box. Whenever he did not see a box, he would blindly select the area in his shadow where the box should be located and drag it "blindly" to the target.



Condition	Compared With:	Mean Diff. (ms)	Std. Error (ms)	Sig.
FP	**WFP**	**128**	**25.1**	**0.000**
	VRP	**102**	**24.9**	**0.001**
	RP	**185**	**29.2**	**0.000**
WFP	VRP	-25	13.0	0.072
	RP	**57**	**20.8**	**0.014**
VRP	**RP**	**82**	**17.4**	**0.000**

Figure 5. (Top) Acquire times in the Box task with number of occluded boxes in each condition. (Bottom) Pairwise comparisons of Box Acquire Time (in milliseconds) based upon treatment condition. Positive numbers indicate how much slower the "condition" is than the "compared with" condition. All statistically significant differences (p<0.05) are presented in bold.

Blinding Light Followup Study

To statistically confirm that people are annoyed by projected light cast on their faces, we performed a small followup study with 10 participants. In a counter-balanced within-subjects design, we used a single off axis projector to illuminate the users face, or not, as they read a card at the rear of the room. Questionnaire results were analyzed with a paired samples t-test which showed that the difference in subjective comfort level (1.4) between the illuminated (mean=5.9 σ=1.37) and dark (mean=4.5, σ=2.07) conditions was statistically significant (p <= 0.025).

DISCUSSION

We found that humans are able to quickly adapt to occlusions and shadows from front projection systems via coping behaviors to maintain their level of task performance. *This indicates that at least for simple tasks, and only considering efficiency, a single front projector is sufficient.* However, our tasks were quite basic, and 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 (a significant subjective rating difference between 3.35 and 6.18). *There are very few applications where the user's preference does not play a strong role in acceptance and adoption, and these preference scores cannot be discounted.*

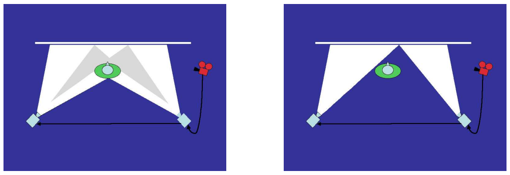
Our study indicates that a warped front projection system reduces occlusions by an average of 62% compared to a front projection system. It can be implemented using a WFP capable projector such as the 3M IdeaBoard or NEC WT600, or in software using a traditional projector with a 3D accelerated graphics card [9]. *We recommend warped front projection in situations where only a single projector is available.*

Of the front projection technologies, virtual rear projection had the highest user preference scores, eliminated user's coping behavior, and virtually eliminated occlusions. *We recommend VRP 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.

The twin facts that 1) users prefered rear projection to our virtual rear projection (VRP), and 2) that they found blinding light annoying, motivate further development of VRP technologies. Although seemingly 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. We expand our taxonomy of projection technologies discussed previously with (Figure 6):

- ***Active Virtual Rear Projection (AVRP)*** - Similar to passive 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), effectively eliminating them [2,4].
- ***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 [2].

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. Our initial AVRP-BLS prototype (Figure 7) updates the display 10 times a second, demonstrating the feasibility but still requiring engineering work to reach the imperceptible threshold.



AVRP AVRP-BLS

Figure 6. Additions to projection technologies taxonomy.

Figure 7. Active Virtual Rear Projection system with Blinding Light Suppression, with a moving user.

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