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Perceived Rendering Thresholds for High-Fidelity Graphics on Small Screen Devices

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Abstract

Small screen devices, also known as small-form-factor (SFF) devices including mobile phones and ultra mobile PCs are increasingly ubiquitous. Their uses includes gaming, navigation and interactive visualisation. SFF devices are, however, inherently limited by their physical characteristics for perception as well as limited processing and battery power. High-fidelity graphic systems have significant computational requirements which can be reduced through use of perceptually-based rendering techniques. In order to exploit these techniques on SFF devices a sound understanding of the perceptual characteristics of the display device is needed. This paper investigates the perceived rendering threshold specific for SFF devices in comparison to traditional display devices. We show that the threshold for SFF systems differs significantly from typical displays indicating substantial savings in rendering quality and thus computational resources can be achieved for SFF devices.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism

1. Introduction

Over the past few years a huge growth in the number of owners of small-form-factor (SFF) devices such as PDAs and mobile phones has taken place. These devices are beginning to play a significant role for *"in the field"* applications, delivering key visual information to the user. Applications including interactive exhibit exploration, navigational tools and multi-user mobile games exploit mobile technology. A drawback to these devices is their current limited ability to provide high fidelity 3D graphics at interactive frame rates, which derives from their physical and technical properties.

High-fidelity graphics makes use of rendering algorithms based on physical interactions that occurs in real life. The use of such global illumination algorithms are capable of producing results that are based on accurate physical measures which are hard to achieve with traditional rasterised graphics. Techniques based primarily on ray tracing methods, which make it possible to simulate the propagation of photons around an environment, are potentially more suitable for global illumination. Recent advances in this field have made it possible to ray trace non-complex scenes at interactive rates on a single desktop PC [WPS*03].

Within high fidelity graphics systems, it is common to produce greater detail than it is physically possible to perceive. This can be a result of several factors including scene complexity, visual acuity and attention. The cost of producing this additional detail is not always insignificant, so by minimising the required computation it is possible to maintain image fidelity at a reduced cost.

By taking into account the effect of human visual perception, it is possible to remove imperceptible details or focus on perceptible errors in a 3D rendering system allowing us to optimise rendering performance [YPG01, CCW03, SDC05]. This would allow us to reduce the rendering effort and produce images which are perceived as high fidelity. Perceptual models can be used to help direct the rendering effort away from areas which would otherwise have been wasted [YPG01, CCW03, SDC05, LDC05].

We believe that by exploiting visual perception and inter-

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active high-fidelity graphic techniques it will be possible in the future to generate high-fidelity images for SFF devices. This paper is concerned with identification of the threshold at which rendering degradation fails to be perceivable. Through analysing the perceived threshold for mobile devices, this can be used to optimise selective rendering techniques to suit the unique perceptual characteristics of SFF devices, and thus reduce the cost of rendering on these devices without noticable fidelity loss.

This paper is divided as follows. Section 2 presents related work in the fields of selective rendering, visual perception and SFF devices. Section 3 provides details of the experimentation, with the results and conclusions in Section 4 and 5 respectively.

2. Background

Realistic image synthesis has for some time been a central concept of computer graphics, including [FPSG96, GTS*97]. Perceptually high fidelity rendering is the process of synthesising physically accurate images, as perceived by a human viewer [MCTG00, MTAS01, PFFG98, RPG99]. A multitude of applications incorporating entertainment (computer games, films and special effects), lighting planning and architectural design make use of high fidelity results we are now capable of generating. The computational cost of rendering these scenes is significant, particularly on a system with limited resources such as a SFF device.

2.1. Hardware

Although complex graphic simulations can now be run on high-performance PCs, there is also a strong market for similar performance on SFF devices. Due to the nature of these devices, constraints on available processing power and battery consumption require novel algorithms in order to optimise usage [PLM*04, MCD*03, ILMR03]. Computationally intensive applications, especially high-fidelity graphics are suitable candidates for optimisation.

The physical characteristics of SFF devices are intrinsically different from traditional display devices. Perception of spatially limited screens and the mode of interaction are fundamental differences to traditional systems. A typical high-end SFF device has a display size of 3.5" and 320×240 resolution.

Through research into the *human visual system* (HVS) and *visual perception* it is possible to optimise the necessary rendering effort whilst maintaining perceptual fidelity.

2.2. Visual Perception and Attention

Visual perception consists of the ability to detect and decipher light signals. It is based on the theory that the image of the world we see is not “presented”, but constructed, in other words we are not solely passive viewers in the world, but actively interpret what we see.

Attention is a cognitive process which involves selective concentration. There are many different theories as to how attention functions, many of which believe that attention is location-specific. The main model used for visual attention specifically in computer graphics was developed by William James in 1890 [Jam90]. This theory uses a model of attention that functions similar to a spotlight, with a sweeping region capable of providing greater clarity, which is believed to correlate with the central foveal region of the retina. The fovea is the region of highest chromatic and spatial visual acuity and covers a region of approximately 2°.

Inattentional blindness is the theory that our brain is unable to process all information that is present, as a result only details attended upon are comprehended, whilst items outside this range can go unnoticed [MR98]. In terms of visual perception, it is believed that attention falls within a region governed by the foveal. Cater *et al.* [CCL02] demonstrated how conspicuous objects within a scene are ignored if they are not relevant to the task being undertaken. For the prediction of the affect on attention of low-level features, Itti *et al.* developed a computer model to produce two-dimensional *saliency maps* which describe where users attention will be attracted [IKN98]. An experiment by Sundstedt *et al.* [SDC05] investigated the threshold for perceiveable supersampling for traditional displays.

Based on these ideas, it is possible to re-target the necessary computation in light of understanding that it will be a human viewing the images. In order to make use of perceptual analysis for computational optimisation, we require computer systems that are capable of predicting how a human may perceive visual stimulus. One such system was developed by Daly [Dal93], the Visual Difference Predictor(VDP) as discussed in Section 4.3.

Work by McNamara investigated the comparison of synthetic graphical scenes against real life equivalents [MCTR98]. Results from her latest work has proved that parameter settings for extensive computation do not necessarily improve perceived results [McN05].

2.3. Selective Rendering

By taking into account the HVS, it is possible to focus the rendering effort in order to reduce the cost of rendering without compromising the perceived quality [SDL*05]. In order to improve rendering quality, ray tracers supersample the scene by casting multiple rays per pixel. The act of tracing multiple rays is at significant additional computational cost.

One of the first rendering systems to exploit the HVS was by Mitchell [Mit87], which directed sampling density by predicting regions where noise may be perceiveable. Myszkowski [MTAS01] used the VDP to determine when to stop rendering for their progressive global illumination renderers. Luebke and Hallen [LH01] presented perceptual-based rendering for interactive rendering using level of detail. Yee *et al.* [YPG01] presented a selective rendering algorithm that modified the search radius of the irradiance cache algorithm depending on the saliency of each pixel. The saliency value was derived from a perceptual oracle calculated by a combination of the Itti et al. saliency map [IKN98] and motion perception. Cater *et al.* [CCW03] used the concept of task distractors in a ray per pixel selective renderer. Sundstedt *et al.* [SDL*05] combined the notions of the saliency map and task map together into an importance map for their selective renderer. Mastoropolou *et al.* [MDCT05] extended the concept of on-screen distractors to sound-emitting objects for their selective renderer. A complete review of similar graphic techniques based on perception was presented by O'Sullivan *et al.* [OHM*04].

In order to develop novel rendering systems it is important to carry out psychophysical studies to understand the nature of perception specific to the target system.

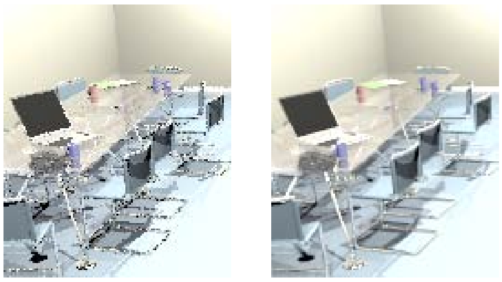
3. Experimental Method

This research is concerned with analysis of the limits of perception for SFF devices relating to our visual acuity of such devices. It will enable us to develop an understanding the underlying perceptual characteristics of SFF devices, in this case the quality of the rendering threshold. This threshold is the level at which sampling additional rays per pixel produces inperceptible benefit. Our method is based on the experiment developed by Sundstedt *et al.* [SDC05] for traditional displays.

Perceptual analysis of the rendering threshold was carried by conducting a psychophysical experiment on static scenes. The selected scenes were similar to those designed and used in the similar experiment by Sundstedt *et al.* [SDC05], with the addition of one further scene, the Office, as part of our future research. The scenes differed from the original experiment in resolution, in order to maximise coverage of the target device display. Five of the chosen scenes were composed of realistic environments, with a Checkerboard scene for analysis of high spatial frequencies. The perceptive boundary was determined by varying the number of rays shot for each pixel, see Figure 1.

3.1. Procedure

Twenty participants took part in the experiment, all of whom had normal or corrected to normal vision, ranging in age from 20-30 (16 men and 4 women). All participants had technical knowledge of computer graphics. Participants were presented with pairs of images and were asked to perform a two-alternative forced-choice (2AFC) for which they believed contained the superior rendering quality. For each



1 ray-per-pixel 25 rays-per-pixel

Figure 1: *Variation of sampling.*

pair, one of the images was the *gold standard* 25 ray-per-pixel scenes, whilst the other was from the set of $\{n^2 : 1 \leq n \leq 5\}$ where n^2 is the number of rays shot per pixel. A gold standard of 25 rays-per-pixel was chosen as it seemed to provide a high fidelity of rendering across most scenes. The order images were displayed was randomised in order to remove any bias. Each image was displayed for five seconds. Experimentation was carried out in a dark room to limit the effect of ambient lighting, see Figure 2.

Figure 2: *Participant undertaking physchophysic experiment.*

The major difference in our work from the work by Sundstedt *et al.* [SDC05], apart from analysing SFF devices, is that a variable viewing distance was used. Subjects before hand were shown a sample image and asked to hold the device at a distance that they felt maximised their viewing ability. For each participant distances from the eyes to the devices were recorded.

3.2. Experimental Hardware

The experiment was carried out on the GP2X, a Linux-based handheld game console and media player, which enabled viewing applications to be customised and developed, see Figure 3. The device used has a 3.5" TFT LCD display, capable of presenting a resolution of 320×240 with 24bit colour, which compares favourably with other highend SFF devices.

Figure 3: *The GP2X Linux-based handheld game console and media player.*

3.3. Rendering

Since the final goal of this work is to identify the perceived rendering thresholds to be used in a selective renderer, we make use of the selective renderer `srpict` [LLC03] to render the images. `srpict` is based on the *Radiance* [War94] lighting simulation package and is a modified version of the *Radiance* renderer `rpict` and selectively renderers images based on the contents of a saliency map by varying rays per pixel using a stratified jittered sampling strategy. For these experiments `srpict`'s ray per pixel setting was fixed to a given constant throughout each frame.

Scenes were rendered at 320×240 to fulfil the entire viewing area of the display device. The time taken to render the scenes can be seen in Table 1. These were carried out on an Intel Pentium 4 2.4GHz with 3Gb RAM.

4. Results

Analysis of the results was carried out in three components: *statistical analysis* for analysis of perceivable differentiation, *comparison using VDP* computer model of perception, and *analysis of perceived resolution*.

4.1. Perceived Size

Acuity limits of the HVS are constrained as a result of the finite number of rods and cones which make up the retina, and the connection of these to neurons. Humans have a 180 degree forward-facing field of view. One degree of a field of vision is typically projected across 288 microns (millionths of a metre) of the retina, which is on average equal to 120 cones. Since each cone is connected to one neuron, the normal limitation of the HVS is 120 components across a single degree field, any more than this will not be perceived as discrete elements [SB94].

In Figure 4, it can be shown how to calculate the resolution at a distance $\underline{\mathbf{d}}$ from the eye. The angle Θ is equal to 1/60th of a degree, by dividing the area subtended from the eye to the projection plane the distance **X/2** can be calculated:

$$\Theta/2 = tan(\mathbf{X}/2\underline{\mathbf{d}}) \qquad (1)$$

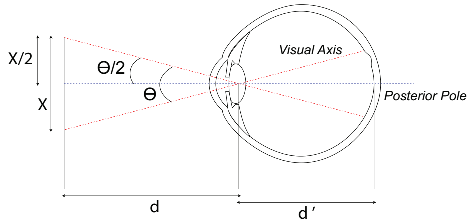


Figure 4: *Calculation of the resolution projected to the eye.*

During the experiment it was found that the device was held within a distance of 35-60cm from the eyes. Using Equation 1 we calculated the relative angle subtended from the display to the eye. For the SFF device we found that the angle was between 6.8-11.6° compared to 16° for the 17" monitor used in the experiment by Sundstedt *et al.* [SDC05]. This corresponds to approximately 813-1391 and 1926 cones respectively, which relates to 2.5-4.3 and 1.5 cones per pixel.

This indicates that for both the SFF device and the monitor the 2° foveal region is completely encompassed within the projected resolution of the displays. Due to the higher number of cones per pixel for the SFF device it can also be hypothesised that the rendering threshold for the SFF may be higher than that of the monitor since more neurons are engaged per pixel because each cone is connected to one neuron. It should however be noted that the brain may also analyse input from these receptors at a higher level, taking into account several inputs.

4.2. Statistical Analysis

Analysis of our experiment results was carried out using *Chi-square*. This is a non-parametric test for calculating the degree of confidence of an hypothesis. It tests for statistical significance for bivariate tables. Analysis allowed us to determine a statistically significant preference for each pair. The null hypothesis ideal for each pair is an equal preference. In theory, assuming no bias, it was expected that this should be produced for the 25 v 25 rays-per-pixel scenario. Table 2 and Figure 5 contain the computed Chi-square values.

Analysis using Chi-square with a probability bound greater than 0.05 for significant results indicates that for all scenes noise effects can be perceived in all scenes with less

No. of Rays	Art Gallery	Checkerboard	Corridor	Kalabsha	Library	Office
1	4.003	2.625	34.881	4.974	45.301	47.503
4	14.516	9.018	153.173	12.573	162.364	191.069
9	32.110	19.636	343.214	26.973	373.449	430.734
16	56.732	34.543	599.502	67.321	570.727	786.811
25	88.896	53.513	790.539	78.003	792.939	1,380.559

Table 1: *Time taken to trace scenes in seconds.*

	Art Gallery		Checkerboard		Corridor		Kalabsha		Library		Office	
No. of Rays	x^2	p	x^2	p	x^2	p	x^2	p	x^2	p	x^2	p
1	1.758	0.200	**15.172**	**0.001**	**7.025**	**0.010**	**10.989**	**0.001**	**6.144**	**0.025**	**10.989**	**0.001**
4	0.416	1.000	**7.033**	**0.010**	0.107	1.000	0.902	1.000	0.417	1.000	**5.013**	**0.050**
9	0.102	1.000	2.558	0.200	0.000	1.000	0.404	1.000	0.417	1.000	2.506	0.200
16	0.100	1.000	0.000	1.000	0.404	1.000	2.506	0.200	0.400	1.000	0.102	1.000
25	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000

Table 2: *Chi-Square Analysis (df=1; critical value 3.841 at 0.05 level of significance). Significant results in bold.*

than four rays-per-pixel apart from the Art Gallery. For the Office and Checkerboard scenes this threshold increased to include 4 rays. The difference for the Office scene may be a result of the extreme contrast between the foreground and background. It was expected that the high spatial frequency of the Checkerboard scene would enable noise effects to be highly pronounced. It must be noted that the accuracy of these statistical tests is limited by the number of participants used in the experiment. In general the results decrease monotonically with an increase of rays-per-pixel, exceptions to these as in the case of Kalabsha and Corridor may be a result of the study size.

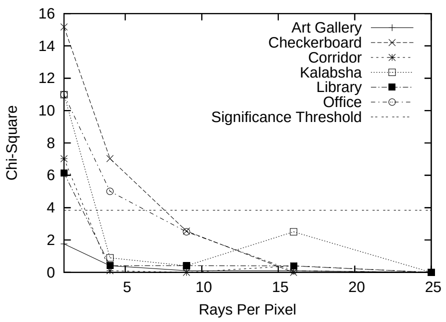


Figure 5: *A graph of statistical signficance levels of scenes.*

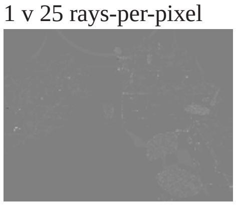
4.3. Comparison using VDP

Daly's VDP can be used within computer graphics to forecast whether difference between pairs of images are perceivable to the HVS [Dal93]. VDP is designed to highlight effects at or above the Just-Noticeable-Difference (JND) level of the HVS. However, VDP does however not take into account visual attention, therefore errors detected by VDP may be identified in areas that were not attended to by the participant within the permissible viewing time.

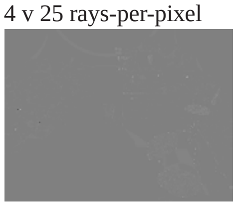
Output from the VDP system is a detection map, which establishes the probability of difference detection between the images as well as measurements of the degree of differentiation. Identical images will produce a probability of 0 for a difference being detected, and 1 for disparate pairs. VDP was used to compare our statistical result with those predicted using VDP. A Table of error measurements are included in 3. Image results from the Office scene can be seen in Figure 6.

1 v 25 rays-per-pixel

4 v 25 rays-per-pixel



9 v 25 rays-per-pixel



16 v 25 rays-per-pixel

Figure 6: *VDP maps visualising perceptual error. Variation of rays-per-pixel comparison against 25 rays-per-pixel "gold standard".*

When considering a perceptual VDP error of 1% difference only the Art Gallery for all cases and Kalabsha for 4 rays-per-pixel does not conform to our experimental valida-

	Art Gallery		Checkerboard		Corridor		Kalabsha		Library		Office	
No. of Rays	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n	$\bar{x}$	n
1	2.195	4.577	**5.026**	**13.242**	**0.851**	**1.333**	**2.003**	**5.055**	**1.863**	**4.266**	**2.305**	**6.371**
4	1.058	1.070	**1.579**	**3.413**	0.266	0.311	1.774	3.053	0.839	1.044	**1.145**	**1.803**
9	0.576	0.449	0.806	1.427	0.184	0.165	1.648	2.214	0.435	0.521	0.491	0.482
16	0.441	0.275	0.348	0.592	0.169	0.186	1.356	2.009	0.184	0.336	0.359	0.221

Table 3: *VDP error calculations against 25 rays-per-pixel "gold standard". $\bar{x}$ = average VDP error (%), n = number of pixels in error (%). Bold indicates significance from Chi-Square analysis.*

tion. This may be due to attention of the viewers which is not taken into account by VDP.

5. Conclusions and Future Work

The results from the original experiment on traditional displays [SDC05] indicated that for all scenes at 4 rays-per-pixel a clear difference was noticed in comparison to the gold standard, for the Checkerboard scene this increased to include upto 16 rays-per-pixel. Although no concrete conclusions can be drawn from this and the original experiment due to differences in methods, there was a difference in the perceived thresholds.

From our results we can conclude that we can reduce sampling compared to traditional displays. These results are especially significant when considering that participants had the option of personally selecting their optimal viewing distance. The results also suggest that SFF devices cannot be assumed to be perceived as purely small versions of traditional displays, especially since the results contradict the initial hypothesis based on calculations of perceived size, see Section 4.1. The perceived quality is likely to additionally be a function of how much information is presented. A smaller resolution render of the same scene will contain less information since there are fewer pixels. In terms of high-fidelity rendering this is very valuable since ray tracing's complexity increases with the number of rays shot and increases only logarithmically with the complexity of the scene [WBWS01]. For SFF devices our result indicates that we can get away with tracing a lower number of rays than on traditional displays, making ray tracing potentially more viable on SFF devices. As an example of this efficiency, using the selective renderer `srpict` modulating between our calculated threshold of four rays per pixel and a minimum value of one ray every four pixels, with 59,980 rays (just 3% of our gold standard of 25 rays per pixel and 20% of four rays per pixel image) we renderered an image of the Corridor scene which has a VDP error of only 0.45% on average and merely 0.35% of the pixels were in error compared to the gold standard making it perceptually indistinguishable from the highest quality image. It must be noted that although we have demonstrated that a reduction in necessary computation for SFF devices is possible, basic ray tracing with multiple rays-per-pixel can still produce artefacts on SFF displays.

As part of our future work will we examine the physiology of the HVS further to see if we can exploit it's limitation for viewing SFF devices. The findings of this research will form the basis for a perceptually adaptive rendering solution for SFF devices. We believe that through exploiting the novel perceptual characteristics for such devices it will be possible to even further optimise specific rendering parameters to reduce necessary computation and power consumption without affecting overall perception of the images.

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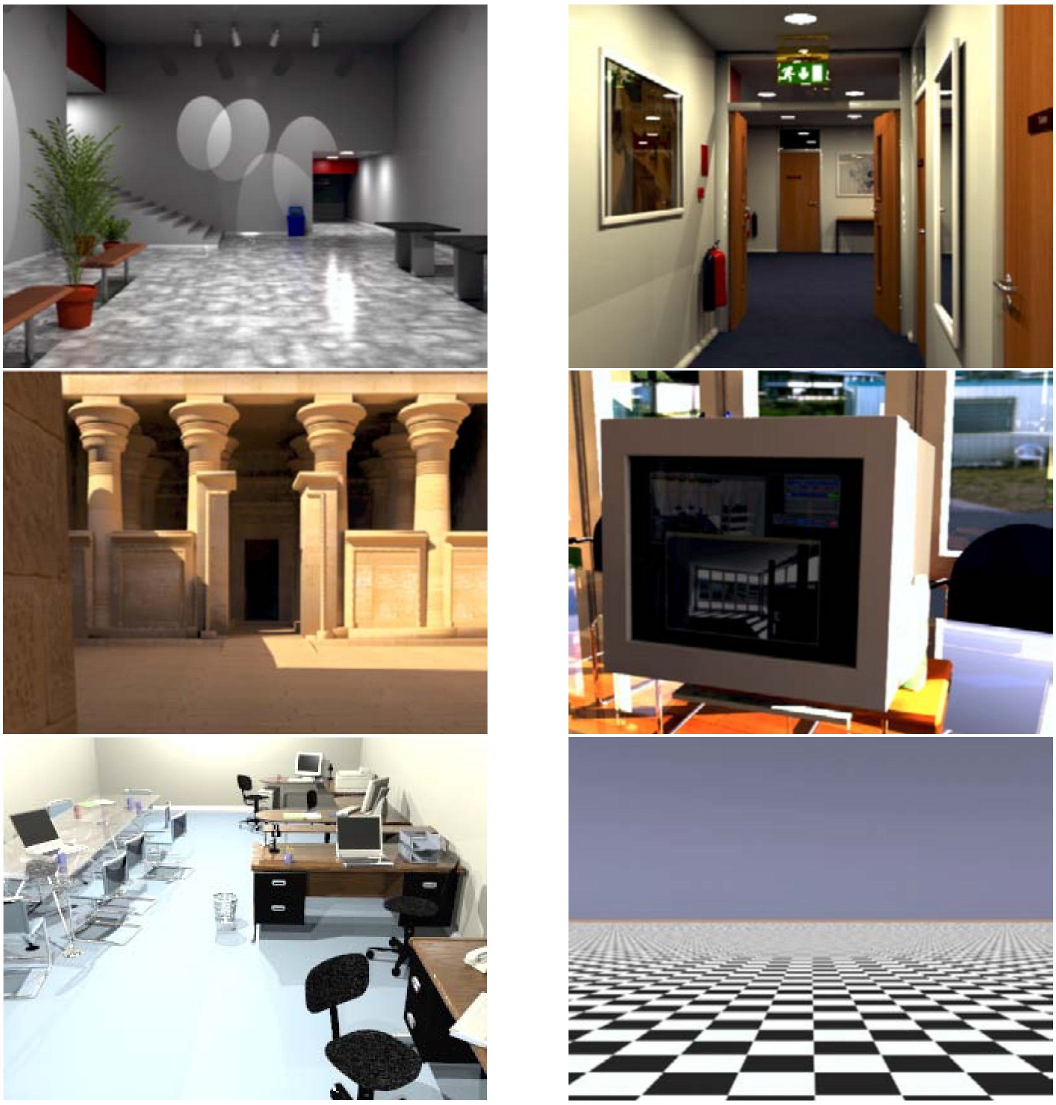

Figure 7: *High quality rendererings of experimental scenes (top left-bottom right): Art Gallery, Corridor, Kalabsha, Library, Office, and Checkerboard*