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TITLE

RESEARCH ON GAZE-CONTINGENT DISPLAYS: PHASE 4 - SUBJECTIVE AND PERFORMANCE EVALUATION OF EDGE-BLENDED GAZE-CONTINGENT WINDOWS

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Research on Gaze-Contingent Displays:

Phase 4 – Subjective and Performance Evaluation of Edge-Blended Gaze-Contingent Windows

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1. Abstract

Gaze-contingent displays with a high-resolution AOI window on a lower-resolution background can supply both fine detail and wide field of view. In previous reports, we investigated high-resolution insert windows with abrupt boundaries. New technology has allowed the evaluation of windows where the transition from high to low resolution is gradual. Two experiments were performed to evaluate the subjective and performance effects of the blended gaze-contingent window.

The first experiment investigated the conditions under which the blending eliminates the subject's awareness of the window, determining the system delay (between an eye movement and the corresponding shift in window position) at which subject become unaware of the window. For blended windows, the maximum permissible delay depend on the level of detail in the background area. For moderate levels of detail, as much as 30 msec of delay could be present without the window being detectable.

The second experiment used objective measures of the effect of the blended window on visual search. Background detail, window size and distance of the target from search start (the central fixation target) were manipulated. Using the measure of latency of the first eye movement to the target, the blended and sharp-edged windows did not differ, even though the first experiment showed that the subjects were unaware of the window. Therefore the blend-edge window's effect is largely subjective in this task, and the effect on performance seems to depend on the difference in information content inside and outside the window.

The results are discussed in the contest of real-world AOI systems, where the practical limitations of system delay, resolution, and artifacts from camera misregistration and tracking errors may make it impossible to hide the window from the operator. Indeed, it may be advantageous to make the window more visible, as this may reduce the impact of tracking errors and may not impact performance. In this case the blending may still be useful to reduce window-edge artifacts.

2. Introduction

A general problem with the most demanding display and imaging applications is high resource requirements for resolution, field of view, and frame rates. The total resource requirements is proportional to the product of these factors, and usually not all can be met simultaneously. One solution is to monitor where the display's viewer is concentrating their attention, and to supply higher resolution and greater image transfer or generation resources to this area. This area is called the AOI (Area Of Interest) or point of gaze.

Gaze-contingent displays integrate a system for tracking viewer gaze position (by combined eye and head tracking) with a display that can be modified in real time at the gaze location. If a high-resolution AOI window on a lower-resolution background is used, such a display can supply both fine detail and wide field of view with reasonable display, data channel, and image source requirements.

Each AOI display system must be optimized for its application. The model chosen for this study was the WACISS (Wide Angle Coverage Infrared Surveillance System). This is a proposed FLIR (Forward Looking InfraRed) camera system designed for aerial search-and-rescue (SAR) tasks (Chevrette and Fortin, 1995).

A wide-angle peripheral FOV of at least 60° is required for scanning by SAR observers, but the low resolution of current IRFPA (Infrared Focal Plane Array) cameras, typically 256 by 256 pixels, would result resolution too low for adequate target detection. The WACISS concept proposes a gaze-contingent method to combine low and high resolution cameras to achieve the required resolution.

3. Background

In two previous reports, we reported on and evaluated gaze-contingent display systems, and performed research into their effect on task performance by subjects.

3.1 Previous Research

In the first report (Stampe and Reingold, 1995) short clips of full-motion color video were used, with digital video sources and special hardware used to generate a windowed display on a VGA monitor. Subjects found and followed a moving target. Results showed that the presence of a window (clear video inside, blurred video outside) slowed the subject's initial motion to the target.

The research carried out in the second report (Stampe and Reingold, 1997) used monochrome, stationary images. This removed the complications in performance analysis caused by the motion and constantly changing nature of the scene, and more closely matched the stimulus qualities of the target FLIR system. The windowed display was generated entirely in software, with extremely fast display update rate (120 or 155 Hz) to minimize system delay (from eye movement to displaying the new window position) to as little as 15 milliseconds.

Research using stationary images allowed investigation of the effects of window size, level of detail outside the window, and system delay on subject performance in searching for a small target. This study confirmed the results of the first report, in that any window changes subject performance. In this case, the image of the target outside the window was degraded enough that it did not aid in the search: indeed, removing the image outside the window speeded the search. This illustrates the importance of matching the low-resolution image outside the window to the search requirements. This will certainly be an issue for FLIR, where "hot" targets tend to be small points, and using wide-angle lenses to capture the low-resolution image severely reduces target contrast. In this case, the area outside the window would simply serve to orient the observer during search.

3.2 Blend Window

Further developments in computing power and software led to the capability to display windows with a "blend region", with the high-resolution area inside the window fading into the low-resolution background over several degrees. This produces a striking improvement in perceived image quality. In many cases, subject cannot detect the window at all.

The blend window consists of a central region with the high-resolution image, and blend region where a linearly changing mix of high- and low-resolution images are displayed, as in Figure 1.

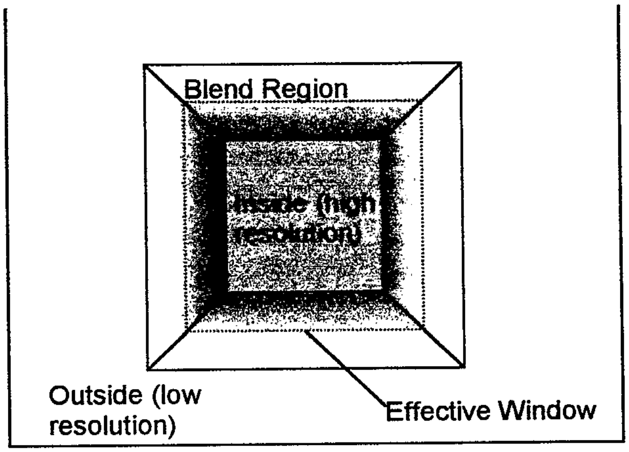
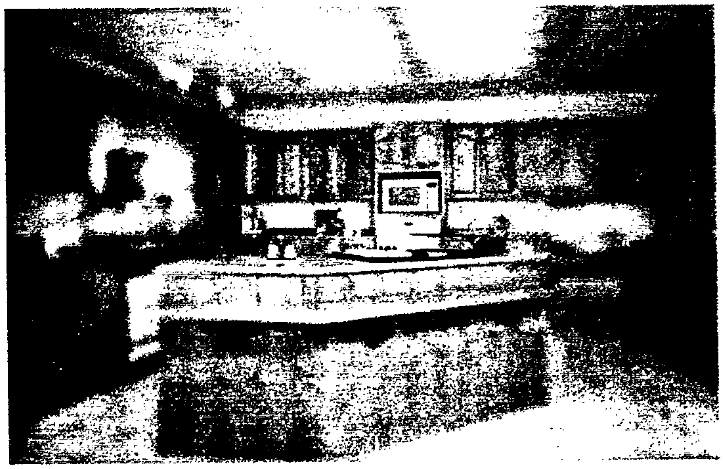
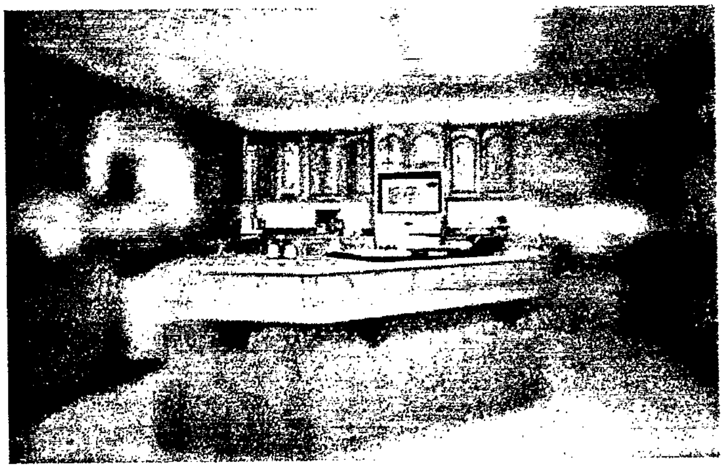


Figure 1: Blend Window. Mixture of Foreground and Background images varies linearly within blend region. Effective window area is set to center of blend region.

The area outside the window contains a lower-resolution version of the image. For these experiments, this was produced by applying a Gaussian low-pass filter to the image to blur it. It is important to note that the amount of blurring used in these studies reduces resolution outside the window well below that of the human eye at the same offset from the center of gaze. Therefore the resolution of the background and size of the window will influence the subject's perception of the display and performance. However, most subjects are unable to see the blend window when moderate blurring of the background image (1.0 cycles per degree Gaussian low-pass filter) and nominal system delay (15 milliseconds) are used. They are aware that parts of the image are degraded, but are unable to explain why.



12° window, 1.0 cycles/degree blur



12° window, 0.5 cycles/degree blur

Figure 2: Blend windows (12° windows shown for visibility).

During initial testing, it was found that the blended window became visible as system delay was increased. Delay of the window motion from eye movements causes the window boundary to move closer to the center of gaze during rapid eye movements. Even if the resolution at the window boundaries did match the resolution profile of the human eye, this effect of delay would still make the window noticeable at times.

4. Experiments

Two studies were carried out to study the gaze-contingent window with blending. The first experiment measured the amount of system delay required to make the blend window visible, with different window sizes and levels of background resolution. The second experiment compared the blend window to the regular sharp-edged window, using a measure of visual processing speed that has been found in previous studies (Stampe and Reingold, 1995; Stampe and Reingold, 1997) to be sensitive to windowing effects in visual search.

4.1 Detection and Delay Experiment

In this experiment, the subjective detectibility of the blend window was investigated. Since the blend window is more visible when the window motion is substantially delayed from eye movements, this delay was varied to change the detectability of the window. This also allowed the maximum system delay for which the window could not be detected to be determined.

4.1.1 Apparatus

The display system and eyetracker were as described in Stampe and Reingold (1997), using an EyeLink eye tracker with a sampling rate of 250 Hz, a PC to generate images, and a 17" Viewsonic monitor. A custom display driver was used for a refresh rate of 120 Hz, to minimize system delay (eye movement to change in the display), which was an average of 15 milliseconds. New window display software was used which could produce a linear blend region at the edges of the window.

4.1.2 Stimuli

The images used were 72 images of residential interiors, selected from the same image set as used in the previous study (Stampe and Reingold, 1997). The image size was 360 by 240 pixels, and the display subtended 30° by 22.5°, for resolutions of 12 pixels per degree horizontally and 10.7 pixels per degree vertically.

As the goal of this experiment was subjective evaluation, no targets were added to the images. During viewing, a window (8° or 12° square) was moved to remain centered on the subject's point of gaze. Within the window, the image was seen clearly. Outside the window, the image was reduced in resolution, using Gaussian blurs of 1.0 cycles/degree and 0.5 cycle/degree. A blending function was used at the edges of the window to mix background and foreground images, with the ratio changing linearly. The blend region width was 2° for the 8° window, and 3° for the 12° window. For example, moving outwards from the subject's point of gaze with the 8° window, the image was full resolution up to 3° from the subject's point of gaze, was a 50% mix of full-resolution and blurred images at 4°, and was completely blurred past 5°.

The window moved to remain centered on the subject's gaze position as measured by the EyeLink tracker. The minimum possible system delay (eye movement to update of the display) was 15 milliseconds, with a variable delay added determined by the subject's past responses. The window was removed during blinks, as gaze position was not known.

4.1.3 Experimental Design

Two independent variables (background blur and window size) were fully crossed, for 4 design cells. The 4 conditions were presented in random order, with each of the 72 images presented once in each condition.

In each cell, an adaptive threshold paradigm was used to measure how much delay between eye motion and window motion was required for subjects to be aware of the window. The initial delay between eye motion and window motion was set to 63 msec (48 msec plus the 15 msec minimum system delay). Subjects examined each image for up to 4 seconds, then pressed a red button if they were not aware of the window's presence, and a green button if they noticed the window. (The window was actually present in all images). If the window was detected, the delay was lowered by 4 msec. If the window was not detected, the delay was increased by 4 msec. Over many trials, the delay converges to the perception threshold.

4.1.4 Subjects

11 subjects were run in the experiment. Eyeglasses or contact lenses were worn by 8 of the subjects, and all had normal or corrected-to-normal vision. All subjects were naive as to the purpose of the experiment.

4.1.5 Procedure

The subjects were seated in a stable chair in front of the monitor, and the EyeLink headgear fitted and the cameras set up. A calibration was performed, and the accuracy of gaze calculation tested. Calibration was repeated if required until an average error of less than 0.5° was achieved. Before each trial, the subject fixated a fixation target and pressed a button to correct for errors in gaze tracking. The picture was then displayed, and subjects examined it in any way they chose for up to 4 seconds. They pressed one of two buttons at any time to indicate whether they thought the window was present.

4.1.6 Results

Custom analysis software was used to process the eye movement data files. In this study, only the system delay (eye motion to display update) data was analyzed. This was averaged over the last 10 trials in each condition to determine the threshold of detection for the window. A threshold of less than 18 msec meant the window was always detected, as the subject would be see delays of 15 msec (the minimum possible) and 19 msec.

The data were analyzed by 2-way repeated-measures ANOVA. Table 1 summarizes the main effects found in the experiment. The degree of blurring of the background image was the only manipulation that had a significant effect on the detectability of the window: with a 0.5 cycle per degree Gaussian low-pass filter, the window was always detected, while 16 msec of additional delay had to be added before the window became detectable with a 1.0 cycle per degree filter.

Variable	**Level**	**Threshold Delay (msec)**
Blur	1.0 c/°	33.2 *
	0.5 c/°	17.6 * (always detected)
Window Size	8°	23.6 (n.s.)
	12°	27.2 (n.s.)

** p<.001 * p<.01 † p<.05

Table 1: Summary of Means and Significance of Main Effects

Table 2 gives the mean of subject's delay thresholds for each combination of window size and background blur. Note that the window is always detected when the heaviest blur is used, but size of the window affects its detectability for the lighter blur. This effect does not reach significance for the small number of subjects in this study (n=11, p=.071).

		Window Size	
		8°	12°
Blur	1.0 c/°	29.6	36.8
	0.5 c/°	17.5	17.7

Table 2: Mean delay threshold for window detection, by Window size and Blur

The thresholds for the 11 subjects are plotted in Figure 3. Two subjects was able to detect the window in all conditions, but all other subjects required additional delay to detect the window when the lighter blur was used. The median delay for light blur was 30.6 msec for both window sizes.

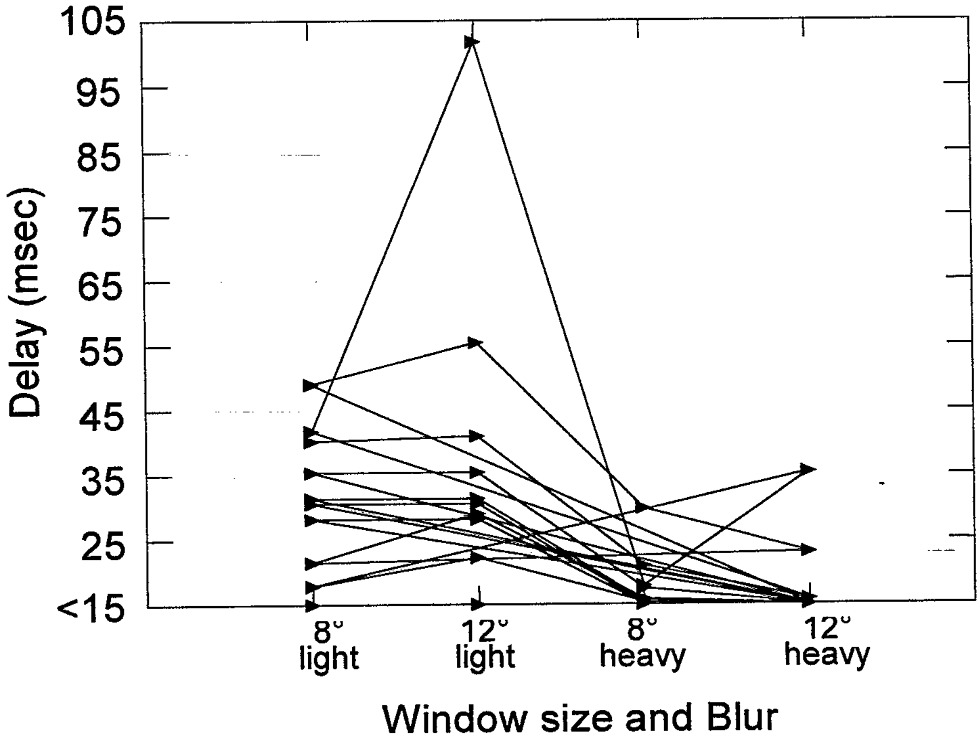


Figure 3: Delays required for detection for all subjects

4.2 Visual Search Performance Experiment

In the second experiment, the effect of the blend window on performance of a visual search task is measured. In previous studies a long visual search was used (Stampe and Reingold, 1997) with a target that was difficult to find in the blurred background image. In this study, subjects were presented with a target that is clearly visible outside the window. The latency from image presentation until the subject's gaze moves towards the target is used as a measure of visual processing speed. Previous studies have shown this measure is an indication of the effect of the window on visual processing of the image, and thus predicts visual search performance.

4.2.1 Apparatus

The display system, software and eyetracker were as described in the previous experiment. No extra delay was added, so the system delay was 15 msec.

4.2.2 Stimuli

The images used were the same 72 images of residential interiors as used in the previous experiment. The image size was 360 by 240 pixels, and the display subtended 30° by 22.5°, for resolutions of 12 pixels per degree horizontally and 10.7 pixels per degree vertically.

One target was added to each image: a 7 by 7 pixel (about 0.6°) white cross with a black border. These targets were added to both the foreground (unblurred) and background (blurred) images. Targets were placed on one of the four diagonals, at distances of 8°, 12°, or 16° from the center fixation point.

During viewing, a 8° square window was moved to remain centered on the subject's point of gaze. Within the window, the image was seen clearly. Outside the window, the image was reduced in resolution, using a Gaussian low-pass filter of 1.0 cycles/degree or 0.5 cycle/degree to blur the image. Three window display conditions were used: no window (all of image blurred), an 8° window with sharp edges on the window (no blend), or an 8° window with a 2° wide blending region as described for the previous experiment.

4.2.3 Experimental Design

Three independent variables (window type, background blur and target distance from fixation point) were fully crossed, for 18 design cells. For each of the 12 blocks, the 72 clips were randomly assigned with four per cell. Each clip in the cell was assigned one of the four target locations. The order of presentation was randomized in each block.

4.2.4 Subjects

66 subjects were run in the experiment. Eyeglasses or contact lenses were worn by 35 of the subjects, and all had normal or corrected-to-normal vision. All subjects were naive as to the purpose of the experiment.

4.2.5 Procedure

The subjects were seated in a stable chair in front of the monitor, and the EyeLink headgear fitted and the cameras set up. A calibration was performed, and the accuracy of gaze calculation tested. Calibration was repeated if required until an average error of less than 0.5° was achieved.

For each trial, the subject first fixated a fixation target and pressed a button to correct for errors in gaze tracking. The picture with the target was then displayed, and subjects were asked to look at the target as quickly as possible, and press a button while fixating the target to end the trial.

4.2.6 Results

Custom analysis software was used to process the eye movement data files. Trials were rejected for anticipation if the subject made a substantial (more than 2°) saccade or a blink before the picture was presented, or less than 70 msec after its appearance. Trials were also rejected if first saccade made by the subject was less than 3° in magnitude, or if its direction was not aimed within 45° of the target. Acquisition of the target occurred when the subject made a saccade to within 3° of the target. A total of 13 subjects were excluded because more than 50% of their trials were rejected.

The measure of visual processing speed used was the latency of the first saccade made after the picture appeared. This is a measure of the time required to process the image, extract the target location, and program a saccade to it. Visual search is a sequence of these processing and saccade steps.

The data were analyzed by 3-way repeated-measures ANOVA. Table 3 summarizes the main effects found in the experiment. As blur increases, there are less distractors to mask the target and the saccadic latency decreases. Latency also increases as the target's distance from the point of gaze increases.

The most important results are those for window type. Under all combinations of target distance and blur, the no-window condition differed from both types of window, but the sharp and blended-edge windows did not differ significantly from each other. This implies that adding blending to the window does improve visual processing, under the conditions used in this study.

Variable	**Level**	**Latency of First Saccade (msec)**
Blur	1.0 c/°	204 **
	0.5 c/°	197 **
Target Distance	8°	193 **
	12°	197 **
	16°	212 **
Window Type	None	191 **
	Sharp	205 **
	Blend	205 **

** p<.001 * p<.01 † p<.05

Table 3: Summary of Means and Significance of Main Effects

4.3 Discussion

In the studies presented in this report, the resolution outside the window was always substantially less than that detectable by the human at the window's border. Even so, a gaze-contingent window with a blending region can be undetectable with low delays and light blurs, as shown in the first study. In contrast, a sharp-edged window (Stampe and Reingold, 1997) will always be visible with the same window size and for the same image resolution outside the window.

The effect of window size and delay may be explained by comparing the motion of gaze and the window during saccades. The window boundary is clearly visible when viewing a stationary window, because this allows the highest-resolution area of the subject's vision to be brought to bear on it. With delay, the subject's gaze moves close to the window's boundaries before the window starts to move away. This allows the subject to view the window more clearly. With heavy blur, the boundary is visible even with low delay, and thus without examining it closely. With lighter blur, parts of the visual field with higher resolution are required to detect the difference between the central high-resolution part of the image and the blurred area outside the image.

This model implies that large windows and less salient transitions between high and low resolution images will allow longer system delays without perception of the window, but only to a point. When long saccades are made, gaze can move at over 400 degrees per second. Gaze can be kept from approaching window edges only by enlarging the window or by keeping system delays low. With the range of resolutions and window sizes for realizable displays, delays of greater than 40 msec probably will make the window visible.

In contrast to the clear subjective advantage of blending, there did not appear to be a performance advantage for blended versus sharp window edges in the second study. Visual processing was slower in both window conditions compared to the non-window condition. This slowing is produced by the difference in information content inside and outside the window. It is known that details at the center of the visual field can mask (interfere with perception) of more peripheral imagery. In the case of both windows, the center of the window contained much more fine detail than the area outside the window, where the target was located. The target was never blurred, so only the information content of the image can account for the slowing. Because the blend and sharp-edged windows were affected equally, it is unlikely that the window edges themselves contributed to this effect.

5. Conclusions

It is possible to hide the presence of the gaze-contingent window from the user of a display system with a high-resolution insert and low-resolution background. When the resolution of the background image is well below the resolving power of the retina at the eccentricity of the window's edge from the center of gaze, the window may become visible. Blending can mask this transition if the resolution mismatch is not too large.

System delay must be kept low to prevent the subject's gaze from approaching the edge of the window during rapid eye movements, as this will cause the window to become visible. Translating the findings in this report into design numbers, the high-resolution insert should not be less than 8° square, which requires a total of 10° of high-resolution imagery available to produce a 2° blending region. Total system delay should be kept below 33 msec, not an easy task as the eye tracker, high-resolution camera steering mirrors and display refresh rate all contribute to this delay.

Adding a blending region did not improve visual search performance in this simple task. It did improve the viewing esthetics of the gaze-contingent window display, which may be important for some applications. Blending is often "free" in optical projection systems, requiring simply a defocused projector aperture. In more unstructured search tasks, the window's abrupt edge might also create distortions and false search targets.

Masking the high-resolution window may even be disadvantageous in practice, especially since it does not appear to produce any performance gain. It may also be desirable to let the operator know what the high-resolution camera's field of view in the image. Most practical gaze-contingent systems using mirror-steered cameras or projection display have undesired but unavoidable tracking problems, including small (0.1° to 1.0°) offsets between high- and low-resolution images, slow peak velocities, and settling artifacts.

Using our system to simulate these types of errors, we observed that the use of a blending window will produce double images, and sharp-edged windows produce discontinuities that are confusing to the viewer. By making the window location clear these problems are reduced. In our initial tests, we changed the brightness or color of the high-resolution insert compared to the background. The blend window may still be useful in this condition, as it reduces artifact created by the brightness or color transition.

6. References

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