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Saliency of Peripheral Targets in Gaze-contingent Multi-resolutional Displays

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Abstract

The three experiments reported document a slowing of peripheral target acquisition associated with the presence of a gaze-contingent window. This window effect was shown for displays using either moving video or still images. The window effect was similar across a resolution-defined window condition and a luminance-defined window condition suggesting that peripheral image degradation is not a prerequisite of this effect. The window effect was also unaffected by the type of window boundary used (sharp or blended). These results are interpreted in terms of an attentional bias resulting in a reduced saliency of peripheral targets due to increased competition from items within the window. We discuss the implications of the window effect for investigating the perceptual processes involved in natural scenes and for gaze-contingent multi-resolutional displays (GCMRDs) that have been proposed to solve the processing and bandwidth bottleneck in many single-user displays, by dynamically placing high-resolution in a *window* at the center of gaze, with lower resolution everywhere else.

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Saliency of Peripheral Targets in Gaze-contingent Multi-resolutional Displays

Many new or proposed display technologies place tremendous demands on limited processing resources and transmission bandwidth. Such demands often involve various combinations of high image resolution, a large field of view, fast update rates, and low bandwidth communication channels. Example applications include flight, driving, or medical simulators, immersive virtual reality (VR), remote piloting or driving, teleoperation, and video-telephony. Meeting the combined needs of such applications necessitates a reduction of processing resources and bandwidth. However, because all of the above-listed applications are single-user displays, a possible solution is to place high image resolution only at the point of gaze, and lower resolution everywhere else. This requires dynamic updating of the high-resolution display area of interest, or window, whenever the gaze moves. The most natural method of achieving this is to use gaze-tracking technology. We will therefore refer to such displays as gaze-contingent multi-resolutional displays (GCMRDs) (for a review see (Reingold, Loschky, McConkie, & Stampe, Accepted). While much work has been put into developing multi-resolutional displays (often called variable-resolution, spatially-variant resolution, area of interest, or region of interest displays) far less work has been done to examine the effects that such displays have on the perception and performance of their users (but see references cited below; see also (Watson, Walker, Hodges, & Worden, 1997) for work using head-contingent multi-resolutional displays).

The current study is particularly concerned with the perceptual effects of GCMRDs. Previous research in this area has essentially taken two forms. The first line of research has been to find the set of display parameters that results in an imperceptible GCMRD, i.e., indistinguishable from a constant high-resolution display (Loschky, McConkie, Yang, & Miller, 2001). However, such a display may not always be feasible, or even needed, for most applications. Thus, most GCMRD human factors research investigates the perception and performance effects produced by perceptible GCMRDs (i.e., displays with abnormalities that are quite perceptible to the user). This second line of work may therefore contribute to our understanding of the operation of the human visual system while laying the groundwork for selecting GCMRD system design characteristics to achieve specified human performance goals.

This latter line of research has consistently found, for example, that "degrading" the visual periphery in GCMRDs results in shorter saccades (Loschky & McConkie, 2000; Loschky & McConkie, in press; Loschky et al., 2001; Shioiri & Ikeda, 1989; van Diepen & Wampers, 1998), and longer search times (Loschky & McConkie, 2000; Loschky & McConkie, in press; Parkhurst, Culurciello, & Neibur, 2000; van Diepen & Wampers, 1998). Loschky, McConkie, and colleagues (Loschky & McConkie, in press; Loschky et al., 2001) have shown that the shorter saccade lengths were due to a tendency to fixate more locations in the high-resolution area and fewer in the degraded area. They explained this as being due to a reduction in the salience of degraded peripheral saccade and search targets.

The present study was designed to further explore this hypothesis of reduced saliency for peripheral targets (i.e., for targets outside the window). In three experiments we documented an interference effect hindering peripheral target acquisition in GCMRDs employing moving video (Experiments 1 and 2) or still images (Experiment 3).

Experiment 1

This experiment employed a GCMRD with full-motion video and had observers search for a moving ring target. The present study posed the following question: If degraded objects in the visual periphery are less salient than those in the high-resolution window, will viewing a scene completely in low-resolution make it easier to locate a salient peripheral target? Though counterintuitive, this might occur if objects in the high-resolution window competed for attention with the peripheral target, which would be less likely to happen when both the foveal and peripheral regions were degraded. In order to test this hypothesis, we compared four display conditions: 1) all lower resolution, 2) a small window, 3) a large window, and 4) all higher resolution. The dependent variables of interest were initial saccadic latency and total target acquisition time.

Method

Participants

Participants were 18 undergraduate students at the University of Toronto, who were paid for participating. All had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Stimuli & Design

Stimuli were full-color video clips shot from a helicopter flying over landscapes (desert and canyon) containing a target moving against a moving background. The clips were approximately 3 sec long each, shown at a rate of 30 fps at 320 x 240 pixels. The average luminance was about 60 fL. There were two versions of each clip: filtered and unfiltered. The unfiltered video clips had an effective resolution of about 11 arc min/line pair, and an average luminance of about 60 fL. The filtered video clips were produced using a process equivalent to a Gaussian filter (0.5 cycles/deg) to filter both the target and the background. The effective resolution of the filtered video clips was about 85 arc min/line pair using a -6 dB criterion, and the luminance was unchanged. In the filtered images, the target was also filtered, but still discriminable from the background, though sometimes only by target motion.

Resolution-defined windows were created by combining filtered and unfiltered versions of the same clip, running simultaneously and synchronized in time. The unfiltered version of the video clip was displayed inside the window, and the blurred version of the video clip was displayed outside the window. We manipulated the size of the high-resolution circular window, with all other regions being blurred. There were four display conditions: (a) Filtered No-window, (b) Filtered Small Window (1.5° radius), (c) Filtered Large Window (3° radius), and 4) Unfiltered No-window (i.e., all higher resolution). Note that in the two window conditions, the level of low-pass filtering (0.5 cycles/deg) removes a large amount of higher spatial frequency information that would otherwise be perceptible in much of the visual periphery (e.g., at eccentricities > 40° (Yang, Coia, & Miller, 2001)), though the filtering begins at 1.5° and 3° eccentricity. Thus, the filtering should produce highly noticeable image degradation. All windows were centered at the participant's gaze position, as measured by the EyeLink gaze tracking system (described below). The edges of the window remained sharp; there was no blending region between the window and the background.

The target, a 1° ring, moved in a straight line at a constant velocity of approximately 8°/sec from the beginning to the end of the video clip. The color of the target was selected by averaging the color of the background on which it appeared, and the target's luminance was raised by 40 to 80% relative to the background. This coloring technique was designed to make target search dependent on the motion of the target (i.e., it would be difficult to discriminate the target from the background in a static scene). There were four directions of target motion: vertically down the left side, vertically down the right side, diagonally down and to the left, and diagonally down and to the right. The backgrounds were 16 video clips of mountainous and desert terrains shot from a moving helicopter, some from a forward-looking vantage point, which contained optic flow cues for forward self-motion, and some from directly above looking down. All background motion was from the top to the bottom of the screen, but never the in the same direction and speed as the target motion.

Apparatus

The SR Research Ltd. EyeLink eye tracking system used in this research has high spatial resolution (0.01°) and a sampling rate of 250 Hz (4 ms temporal resolution). The three cameras on the EyeLink headband allow simultaneous tracking of both eyes and of head position, computing true gaze position with unrestrained head motion. Only the participant's dominant eye was tracked in these studies. The EyeLink system uses an Ethernet link between the eye tracker and display computers to supply real-time gaze position and saccade event data. The on-line saccade detector of the eye tracker was set to detect saccades with an amplitude of 0.5° or greater, using an acceleration threshold of $9500°/sec^2$ and a velocity threshold of 30°/sec. Two additional computers, 66 MHz 486-DX PC compatibles, were used to concurrently play the processed (filtered or high luminance) and unprocessed video clips, respectively, and feed the video to the display computer. The display computer, a 100 MHz 486-DX PC compatible, controlled stimulus presentation, integrated incoming video signals, and displayed one channel as background imagery and part of the other channel as a window at the participant's point of gaze on a 17" ViewSonic 17PS monitor. The display was positioned at a viewing distance of 60 cm so that the total field of view was 30° (horizontal) x 24° (vertical). The total system throughput delay (time it takes from the eye movement to a change in the display) was 21 ms.

Procedures

The task for the participants was to acquire (i.e., look directly at) a target as rapidly as possible, and track it until the video clip ended. No other response was needed. A trial sequence began with a fixation dot on a blank screen. The participant fixated the dot, and the experimenter initiated the trial when the gaze cursor stabilized. The fixation dot disappeared, and after approximately 0.5 sec the video clip started. When the video clip ended, the fixation dot reappeared, and the next trial began. Participants received a practice block of 8 trials, followed by 4 experimental blocks of 16 trials each, for a total of 64 trials per subject. Each block contained 4 trials for each of the 4 display conditions (Filtered No-window, Small window, Large window, Unfiltered). In addition to measuring target acquisition time, participants' subjective impressions of image quality were collected.

A 9-point calibration was performed at the start of the experiment followed by a 9-point calibration accuracy test. Calibration was repeated if the error at any point was more than 1°, or if the average error for all points was greater than 0.5°. Before each trial, a black fixation target was presented at the center of the display. The participant fixated this target and the gaze position measured during this fixation was used to correct any post-calibration drift errors. Throughout each trial, the experimenter was able to view on a separate monitor the target path, overlaid with a cursor corresponding to real-time gaze position. If the experimenter judged that gaze-tracking accuracy had declined, the experimenter initiated a full calibration before the next trial. However, this occurred very infrequently.

Results and discussion

Subjectively, participants reported that the filtering produced very noticeable peripheral image degradation. We used 2 dependent measures to quantify performance: (a) initial saccadic latency, defined as the time from the start of the video clip until the first eye movement (i.e., saccade); (b) target acquisition time, defined as the time until gaze position was within 2° of the target; and For the purposes of the analyses, a saccade was defined as any eye movement with a peak velocity over a threshold of 25°/sec, and an amplitude of at least 1°. The latency to first saccade was the time from video onset to the first saccade (in any direction). The latency to acquisition was the time from the start of the video clip (video onset) to the acquisition of the target, defined as the first full 20-ms period in which the gaze position kept within 2° of the target. Not included in the analyses were: (a) trials containing a blink during the period beginning 100 ms. prior to video onset and ending 80 ms. following target acquisition; (b) trials in which acquisition occurred more than 2 sec. following video onset; (c) trials in which error was greater than 3° in the first 100 ms. after acquisition; (d) trials in which the average error was greater than 2° after acquisition; and (e) trials in which anticipatory saccades were made, i.e., any saccades made within 100 ms. before or 60 ms. after video onset. In total, 6.1% of the trials were excluded.

As shown in Figure 1, for both dependent measures, while performance in the Unfiltered No-Window condition was clearly the best (all ts > 9.71, $p < .001$), the Filtered No-window condition resulted in better performance than either of the Filtered window conditions (all ts >

3.37, $p < .01$). Performance did not significantly differ across the two window conditions (all ts < 1).

The results of the experiment were rather counter-intuitive as more visual information resulted in poorer target detection performance. Specifically, it is clear that the bi-resolutional displays (i.e., gaze contingent window conditions) led to inferior performance compared to the Filtered No-Window (i.e., all low-pass filtered, low resolution) condition. Longer initial saccadic latencies in the window conditions were observed, and this initial slowing was likely responsible for the longer total target acquisition times. This is the case because the magnitude of the window effects on initial latencies and acquisition times were similar. These findings are consistent with the hypothesis of a reduction in the saliency of the peripheral target in the window conditions.

A counter-argument, however, is that the above effects were simply due to the fact that the periphery was lower resolution than the window, with the worse performance having been due to the lower resolution of the peripheral image. For example, one could easily explain the better performance in the Unfiltered No-window control condition than in any of the filtered conditions by arguing that the target was harder to detect due to the filtering. However, such an argument would *not* account for the superior performance in the Filtered No-window condition compared to the window conditions. Nevertheless, it might be argued that these differences do not reflect variations in saliency, per se, but, instead, some artifact due to having filtered the images and targets.

In order to rule out such *filtering artifact* arguments, it is important to distinguish between the effects of filtering and of windowing. In order to accomplish that in the next experiment we introduced a gaze-contingent window condition that did not involve degrading the image outside the window. This would allow for the possibility of showing an effect of a gaze-contingent window on the detection of peripheral targets in the absence of peripheral image filtering. If such a display produced the same effects on target detection as found in Experiment 1, this would rule out the filtering artifact account.

Experiment 2

In this experiment, two types of window were used: the standard resolution-defined window, with higher resolution in the window and a low-pass filtered periphery, and a luminance-defined window condition in which the luminance *inside* the window was increased by 20% and luminance *outside* the window was *unchanged*. Note that in luminance-defined window condition a window was present, but the quality of the peripheral image was preserved. Two No-window conditions were used as well, one in which the display is uniformly higher resolution, and one in which the display is uniformly low-pass filtered. As in Experiment 1, the task was to detect peripheral target stimuli moving across the screen. It was hypothesized that the presence of both types of the windows, resolution-defined and luminance-defined, would impair performance on this task, indicating that the effect of having a salient window can impair peripheral task performance independently of resolution differences between the two regions. Furthermore, it was hypothesized that the filtering of the periphery in both the window-present and window-absent conditions would impair performance, indicating that the degraded quality of the peripheral imagery also impairs detection performance.

Method

Participants

Participants were 60 undergraduate students at the University of Toronto who received credit in an introductory psychology course for participation. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Design

A 2 x 2 (Filtering x Windowing) design was used. There were two levels of Filtering, filtered or unfiltered, and two levels of Windowing, window and no-window, for a total of four conditions. The Filtered Window condition was the previously described *resolution-defined window*, while the Unfiltered Window condition was the *luminance-defined window* condition. In the Filtered No-window condition the image was uniformly low-pass filtered, and in the Unfiltered No-window condition, the image was uniformly higher resolution.

The four conditions were counterbalanced with the four types of target motion for a total of 16 combinations. Each combination, and each background scene, appeared in a random sequence four times per block, for a total of 64 trials per block. Three blocks of trials were used in the experiment. Before the experiment began, participants were given a practice block of eight trials.

Stimuli

The stimuli were identical to those used in Experiment 1, with the following exceptions. All windows were roughly circular with a 3° radius. Luminance-defined windows were created by displaying the unfiltered version of the video clip across the entire screen, but selectively increasing the luminance *inside* the window by 20%.

Apparatus & Procedures

The apparatus and procedures were identical to those used in Experiment 1.

Results and discussion

As in Experiment 1, we measured participants' initial saccadic latency and target acquisition latency. We used similar exclusion criteria for the data, and in total, 5.8% of the trials were dropped.

The mean latency to first saccade is shown in Figure 2. A 2 x 2 (Filtering x Windowing) within-subjects analysis of variance of the latency to the 1st saccade revealed main effects of Filtering, $F(1,59) = 245.84$, $p<.001$, and Windowing, $F(1,59) = 138.70$, $p<.001$, with no interaction, $F < 1$. The main effect of Filtering indicated that participants were significantly slower to make their first saccade when the periphery was filtered, and this was true both when a window was present, $t(59) =10.55$, $p<.001$, and when a window was absent, $t(59) =13.11$, $p<.001$. As can be seen in Figure 2, the filtering effect on initial saccadic latency was nearly the same whether a window was present or not (window present filtering effect = Filtered window – Unfiltered Window = 49 ms; window absent filtering effect = Filtered No-window – Unfiltered No-window = 46 ms). The main effect of Windowing indicated that participants were slowed by the presence of a window, and this was true for both the resolution-defined window $t(59) =7.95$, $p<.001$ and the luminance-defined window $t(59) =9.43$, $p<.001$. The slowing of the initial saccade produced by the resolution-defined and luminance-defined windows was about the same (resolution-defined window effect = Filtered window – Filtered No-window = 40 ms; luminance-defined window effect = Unfiltered window – Unfiltered No-window = 37 ms).

As is clearly shown in Figure 2, the latency to acquire the target yielded a similar pattern of results. An analysis of variance of the data showed main effects of Filtering, $F(1,59) = 36.58$, $p<.001$, and Windowing, $F(1,59) = 7.72$, $p<.01$, and no interaction, $F<1$. Thus both the presence of the window and the filtering of the periphery caused a slowing of target acquisition.

The results of this study show that both the presence of a window and low-pass filtering of the peripheral target increase the time taken to initiate the first saccade to a peripheral target and to acquire that target. By distinguishing the effects of windowing and low-pass filtering, we can rule out any explanation of the results of Experiment 1 based purely on filtering the target since the presence of a window clearly plays an important role as well. Indeed, the windowing effect appears to be just as strong using a luminance-defined window as a resolution-defined window. This strengthens the argument that the windowing effect is due to greater relative salience of objects within the window in comparison to those outside it, including the target.

Nevertheless, there is an alternative explanation for the results of both Experiments 1 and 2 and most of the studies showing shorter saccade lengths and longer search times with GCMRDs having highly degraded peripheries (Loschky & McConkie, 2000; Loschky & McConkie, in press; Loschky et al., 2001; Parkhurst et al., 2000; Shioiri & Ikeda, 1989; van Diepen & Wampers, 1998). In all these studies the window conditions employed involved a sharp boundary between the regions inside and outside the window due to the resolution or luminance difference across these display areas (but see (Loschky et al., 2001).

Consequently, the saliency of the window boundary might be able to explain the longer initial saccadic latencies in Experiments 1 and 2. If the window boundary is salient, it might compete with the target for attention when the display initially appears on the screen, thus resulting in longer initial saccadic latencies found in both experiments. Unfortunately, neither Experiment 1 nor Experiment 2 provide any way of distinguishing whether relative to the target in the periphery, it is the objects in the window that are salient, or the window boundary that is salient.

Questions regarding the impact of the window boundary on the perception and performance of observers in GCMRDs are also important for applied reasons. Specifically, when bi-resolutional displays have been used in flight simulators, it has been frequently reported that users prefer larger windows, because with smaller windows, the edges are more visible (e.g., (Turner, 1984). If the findings in Experiments 1 and 2 were shown to be due to the visibility of the boundary of the window, this would add further support to the claim that designers of GCMRD applications should avoid having such boundaries.

Experiment 3

In this experiment, we had two chief goals. First, we wanted to test the hypothesis that a sharp boundary is necessary to produce the *window effect* in Experiments 1 and 2, that is, a slowing of initial saccadic latencies to a salient peripheral target in the bi-resolutional condition relative to an all-low-pass condition. In order to test this hypothesis, we decided to compare window conditions in which there was either a sharp or a smoothed resolution boundary. If we find that initial saccadic latencies are longer in *both* the sharp *and* smooth-boundary window conditions than in an all low-pass filtered condition, as in both Experiments 1 and 2, this would add strength to the argument that visual salience is reduced outside the window. If the window effect disappears when the window boundary is smoothed, this would suggest that sharp boundaries are generally problematic for perception in GCMRDs.

Second, we wanted to see if we could replicate the window effect of Experiments 1 and 2 with a GCMRD using static images. Since both of the above experiments used full-motion video, it is possible that the window effects found in those experiments are limited to moving targets and/or a moving image context. Thus, we decided to use a GCMRD with static images and static targets. If the window effect from the previous two experiments generalizes to the static targets and scene contexts, this would suggest that more general perceptual processes are involved in the effect, and that image motion is not a necessary component of it.

Methods

Participants

Participants were 45 undergraduate students at the University of Toronto, who were paid for participating. All had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Stimuli and Design

The images used were 72 images of residential interiors. The image size was 360 by 240 pixels, and the display subtended 30° by 24°, filling the entire screen, 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. Targets were placed on one of the four diagonals, at a distance of 12° from the central fixation point. For each of the 288 image (72) by target-location (4) combinations, filtered versions were created by using a Gaussian low-pass filter of 1.0 cycles/degree (cpd).

On some trials, a 12° square window was dynamically centered on the participant's point of gaze (i.e., the edge of the window was 6° from the center of vision vertically or horizontally)(see Figure 3). Within the window, the image was relatively high-resolution (i.e., as in the unfiltered image). Outside the window, the image was in lower-resolution (i.e., as in the *filtered* image). Three window display conditions were used: the Filtered No-window condition (all of the image was uniformly low-pass filtered), a 12° window with no blending region (Sharp-boundary Window condition), or a 12° window with a 3° wide blending region (Blended-boundary Window condition). In this latter condition, a blending function was used at the edges of the window to mix periphery (filtered) and foreground (unfiltered) images, with the ratio changing linearly. For example, moving up, down, left or right from the participant's point of gaze, the image was full resolution up to 4.5° from the participant's point of gaze, was a 50% mix of the full-resolution and lower-resolution images at 6°, and was all lower-resolution past 7.5°. It is important to note that, as in Experiments 1 and 2, the degree of low-pass filtering used in this experiment (1 cycle/degree) reduced image resolution outside the window well below the sensitivity limits of the human visual system for much of the visual periphery (Loschky et al., 2001; Yang et al., 2001). Thus, the filtering should have produced very noticeable image degradation. In the blended-boundary window condition, participants reported that they were aware that parts of the image were degraded but were unable to perceive the blend (i.e., they perceived smooth degradation into the periphery). In contrast, in the sharp-boundary window condition, participants reported perceiving the contours of the window as an abrupt change in the quality of the image.

Each participant performed in 12 blocks of 72 trials. Across blocks, each of the 288 image-by-target-location combinations appeared once in each of the 3 window conditions (Filtered No-window, Sharp-boundary Window, and Blended-boundary Window) for a total of 864 trials in the experiment.

Apparatus

The eyetracker and monitor were the same as in Experiments 1 and 2. The display was generated using an S3 VGA card and the frame rate was 120 Hz. The average delay between an eye movement and the update of the gaze-contingent window was 14 ms.

Procedures

The procedures were identical to those in Experiment 1.

Results and discussion

Custom analysis software was used to process the eye movement data files. Trials were rejected for anticipation if the participant made a substantial saccade (more than 2°) or a blink either before the picture was presented, or less than 70 ms. after its appearance. Trials were also rejected if first saccade made by the participant was less than 3° in magnitude, or if its direction was not aimed within the 45° region around the target. These exclusions accounted for 2.2% and 3.4% of the total trials respectively. Analyses were then performed on the remaining trials. The results show that the target was generally quite salient, with the initial saccade endpoint falling within 3° or less of the target on 86% of all trials. Consequently, the best measure of acquisition speed was deemed to be the initial saccadic latency measure.

As shown in Table 1, the all low-pass Filtered No-window condition produced reliably shorter mean initial saccadic latencies to the target than either of the window conditions (No-window vs. Sharp-boundary *T*(44, 7.13, p< .001), No-window vs. Blended-boundary *T*(44, 6.87, p< .001)), while the Sharp- and Blended-boundary windows were identical to each other.

The results of the Experiment 3 suggest that having a gaze-contingent window results in longer initial saccadic latencies than an all low-pass filtered image, but whether the gaze-contingent window boundary is sharply defined or smoothly gradated makes no difference. This allows us to reject the *window boundary artifact* explanation of our results. This strengthens the argument that the objects inside the window become relatively more salient than they otherwise would have been, resulting in increased competition for attention between objects in the high-resolution window and the target in the periphery.

The results of the Experiment 3 also show that the slowing of initial saccadic latencies in windowed conditions is a robust effect and is not dependent on using full-motion video as in Experiments 1 and 2. However, the 14 ms window effect in the present experiment (see Table 1) was smaller than the window effects in Experiments 1 and 2 that were 58 ms and 40 ms respectively. Whether this difference in the size of the window effect was due to the full-motion versus still image factor, or some other difference between these studies (e.g., saliency of the target versus the periphery, color vs. monochrome images, etc.) will need to be determined by further research.

General discussion

In this study, we documented that programming a saccade to a peripheral target can be disrupted by the presence a gaze-contingent window. We demonstrated that this *window effect* was obtained regardless of whether or not peripheral degradation or filtering is used (Experiment 2) and when either sharp or smoothed window boundaries were employed (Experiment 3). This effect appears to be quite general and was obtained with either moving video (Experiments 1 and 2) or still images (Experiment 3).

We propose an account of the window effect in terms of attentional factors. Specifically, we hypothesize a type of attentional capture caused by the gaze-contingent window, reflecting an increase in saliency of objects inside the window, and a relative decrease in saliency for peripheral objects. It is this increased competition between the objects in the window and the peripheral target that causes the window effect we observed.

Our effect is similar to other findings of interference with performance on peripheral detection tasks as a function of increased foveal load (Crundall, Underwood, & Chapman, 1999; Holmes, Cohen, Haith, & Morrison, 1977; Ikeda & Takeuchi, 1975; Mackworth, 1965; Pomplun, Reingold, & Shen, 2001; Williams, 1985; Williams, 1988; Williams, 1989) see (Williams, 1988) for a review). For example, Holmes, Cohen, Haith, and Morrison (1977) demonstrated that the mere presence of a foveal item that subjects were instructed to ignore resulted in poorer peripheral task performance (Ikeda & Takeuchi, 1975; Mackworth, 1965). The authors interpreted this finding as a general interference effect; the foveal item draws the attention of the observer and thus interferes with processing of other stimuli in the visual field. Given that this decline in peripheral task performance was sometimes found to be greater for targets at larger eccentricities (Mackworth, 1965; Williams, 1985), it was argued that the foveal load reduced the useful field of view, leading to the coining of the controversial term *tunnel vision* (see (Williams, 1988).

Regardless of the mechanism responsible for the window effect we documented, this effect has important implications for human factors research related to GCMRDs. Taken together, the window effect and previous findings showing shorter saccade lengths and longer search times in GCMRDs (Loschky & McConkie, 2000; Loschky & McConkie, in press; Loschky et al., 2001; Parkhurst et al., 2000; Shioiri & Ikeda, 1989; van Diepen & Wampers, 1998), clearly point to perception and performance costs that may be associated with the use of GCMRDs. However, the practical implications of such effects should be very different depending on the specific application area. In piloting situations, split second delays in reacting to peripheral stimuli, e.g., a missile flair, can have severe consequences. But there are no important consequences for such a delay in video-telephony, or Internet image download applications.

It is also important to note that evidence of the window effect does *not* mean that GCMRDs *always* produce *worse* performance than a uniform high resolution displays. In fact, it has been shown that it is possible to *substantially* filter the periphery of images in a GCMRD without *any* effect on viewers' perception and performance (Loschky et al., 2001). Thus, the level of peripheral filtering may be critical in determining whether a windowing effect is found with a GCMRD. It is also noteworthy that the current results showed no effect for blending the boundary between levels of resolution. This therefore fails to support to the claim that such blending is important in GCMRDs. However, given the limited nature of the present analyses, it would be premature to make any judgments based on this null result.

Clearly, more research is required in order to investigate the perceptual and attentional factors underlying the window effect documented here. Nevertheless, our preliminary findings indicate that this effect may have important implications for both applied and basic investigations of eye-movements during the performance of complex naturalistic tasks.

References

Crundall, D. E., Underwood, G., & Chapman, P. R. (1999). Driving experience and the functional field of view. Perception, 28, 1075-1087.

Holmes, D. L., Cohen, K. M., Haith, M. M., & Morrison, F. J. (1977). Peripheral visual processing. Perception and Psychophysics, 22, 571-577.

Ikeda, M., & Takeuchi, T. (1975). Influence of foveal load on the functional visual field. Perception & Psychophysics, 18, 255-260.

Loschky, L. C., & McConkie, G. W. (2000). User performance with gaze contingent multiresolutional displays. In A. T. Duchowski (Ed.), Proceedings of the Eye Tracking Research & Applications Symposium 2000 (pp. 97-103). Palm Beach, FL.: ACM.

Loschky, L. C., & McConkie, G. W. (in press). Investigating spatial vision and dynamic attentional selection using a gaze-contingent multi-resolutional display. Journal of Experimental Psychology: Applied.

Loschky, L. C., McConkie, G. W., Yang, J., & Miller, M. E. (2001). The role of spatial frequency on salience in free viewing of complex images. Paper presented at the Poster session presented at the 42nd Annual Meeting of the Psychonomic Society, Orlando, FL, USA.

Mackworth, N. H. (1965). Visual noise causes tunnel vision. Psychonomic Science, 3, 67-68.

Parkhurst, D., Culurciello, E., & Neibur, E. (2000). Evaluating variable resolution displays with visual search: Task performance and eye movements. In A. T. Duchowski (Ed.), Proceedings of the Eye Tracking Research & Applications Symposium 2000 (pp. 105-109). Palm Beach, FL.: ACM.

Pomplun, M., Reingold, E. M., & Shen, J. (2001). Investigating the visual span in comparative search: The effects of task difficulty and divided attention. Cognition, 81(2), B57-B67.

Reingold, E. M., Loschky, L. C., McConkie, G. W., & Stampe, D. M. (Accepted). Gaze-contingent multi-resolutional displays: An integrative review. Human Factors.

Shioiri, S., & Ikeda, M. (1989). Useful resolution for picture perception as a function of eccentricity. Perception, 18, 347-361.

Turner, J. A. (1984). Evaluation of an eye-slaved area-of-interest display for tactical combat simulation, The 6th Interservice/Industry Training Equipment Conference and Exhibition (pp. 75-86).

van Diepen, P. M. J., & Wampers, M. (1998). Scene exploration with Fourier-filtered peripheral information. Perception, 27(10), 1998, 1141-1151.

Watson, B. A., Walker, N., Hodges, L. F., & Worden, A. (1997). Managing level of detail through peripheral degradation: Effects on search performance with a head-mounted display. ACM Transactions on Computer-Human Interaction, 4(4), 323-346.

Williams, L. J. (1985). Tunnel vision induced by a foveal load manipulation. Human Factors, 27, 221-227.

Williams, L. J. (1988). Tunnel vision or general interference? Cognitive load and attentional bias are both important. American Journal of Psychology, 101, 171-191.

Williams, L. J. (1989). Foveal load affects the functional field of view. Human Performance, 2, 1-28.

Yang, J., Coia, T., & Miller, M. (2001). Subjective evaluation of retinal-dependent image degradations, Proceedings of PICS 2001: Image Processing, Image Quality, Image Capture Systems Conference (pp. 142-147): The Society for Imaging Science and Technology.

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Table 1. Effect of Window Type on Mean Initial Saccadic Latency to the Target in Experiment 3.

Window Type	Initial Saccadic Latency (ms)
All low-pass, None	191*
Sharp-boundary	205
Blended-boundary	205

*$p<.001$

Figure Caption

Figure 1. Initial saccadic latency and target acquisition latency in milliseconds (ms) as a function of the four filtering conditions of Experiment 1.

Figure 2. Initial saccadic latency and target acquisition latency in milliseconds (ms) as a function of the windowing and filtering conditions of Experiment 2.

Figure 3: Panel A – a Blended-boundary window: the high-resolution area inside the window fades into the low-resolution background over several degrees. The mixture of foreground and background images varies linearly within the blending region. The effective window area is set to the center of blending region; Panel B - an illustration of a 12° Blended-boundary window (participant's gaze position is at the center of the screen), filtering outside the window was produced by using a Gaussian low-pass filter of 1.0 cycle/degree (cpd).

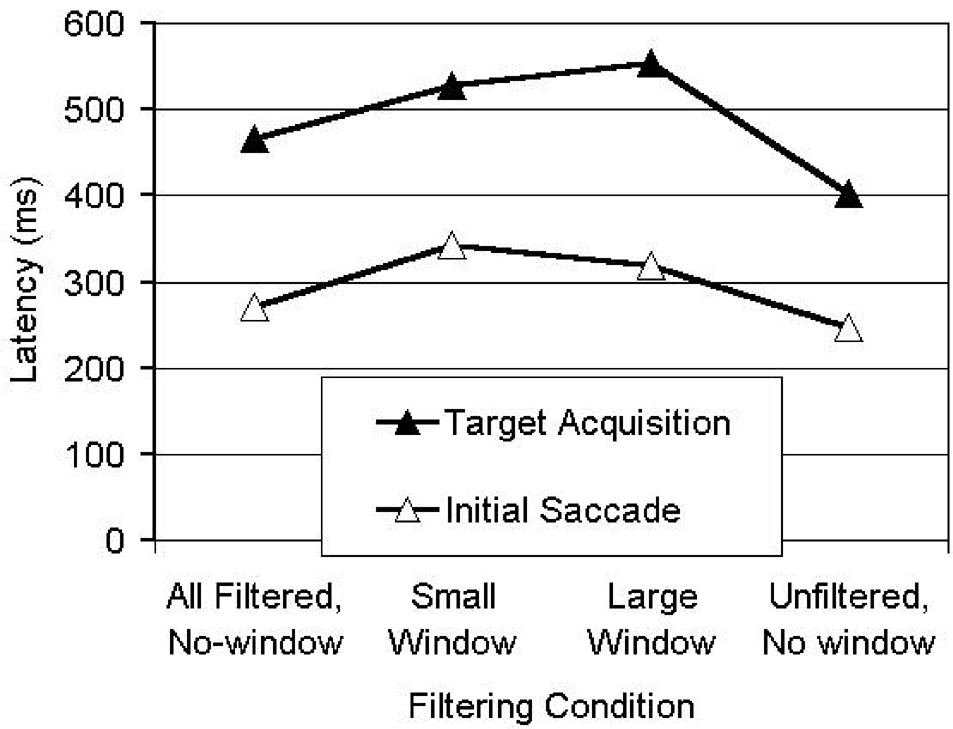

600
500
400
300
200
100
0
Latency (ms)
Target Acquisition
Initial Saccade
All Filtered, No-window
Small Window
Large Window
Unfiltered, No window
Filtering Condition

Figure 1

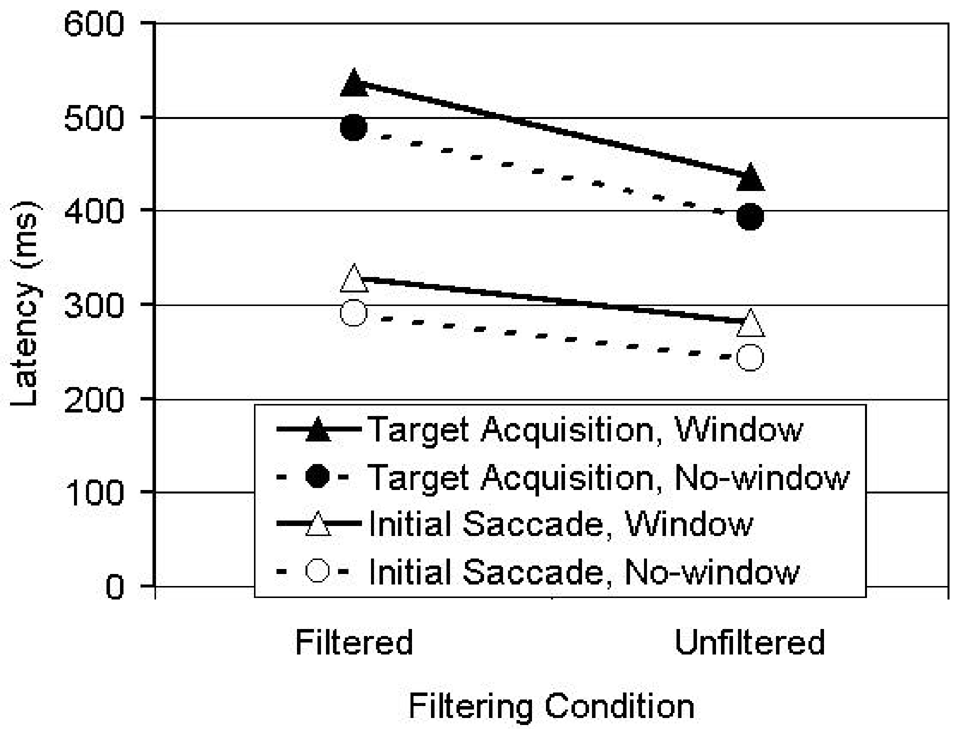
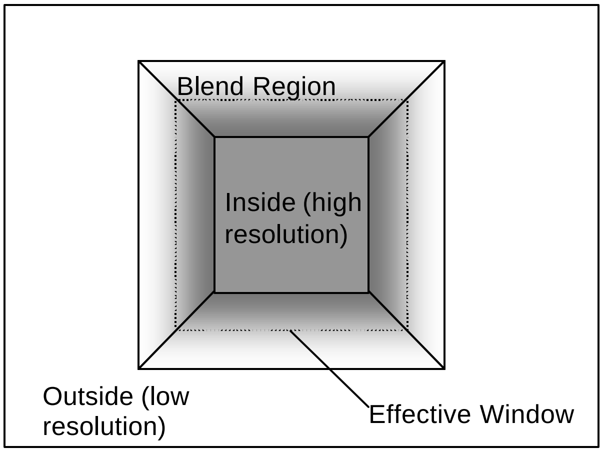

600
500
400
300
200
100
0
Latency (ms)
Target Acquisition, Window
Target Acquisition, No-window
Initial Saccade, Window
Initial Saccade, No-window
Filtered
Unfiltered
Filtering Condition

Figure 2


Blend Region
Inside (high resolution)
Outside (low resolution)
Effective Window

A

B

Figure 3