HOW LATE CAN YOU UPDATE? DETECTING BLUR AND TRANSIENTS IN GAZE-CONTINGENT MULTI-RESOLUTIONAL DISPLAYS

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This study investigated perceptual disruptions in gaze-contingent multi-resolutional displays (GCMRDs) due to delays in updating the image after an eye movement. GCMRDs can be used to save processing resources and transmission bandwidth in many single-user display applications such as virtual reality, simulators, video-telephony, remote piloting, and teleoperation. The current study found that image update delays after an eye movement could be as long as 60 ms without significantly increasing the detectability of image degradation and/or transients due to the update. This is good news for designers of GCMRD applications, since it is ample time to update their displays after an eye movement without disrupting perception.

Users of virtual reality, simulators, video-telephony, remote piloting, teleoperation, and other single-user applications often need large, high-resolution displays exceeding limits on transmission bandwidth and/or computation resources. One way around these limitations is to eliminate detail that users cannot resolve in the visual periphery. Gaze-contingent multi-resolutional displays (GCMRDs) do just that, by dynamically displaying high resolution where the user is looking, as indicated by a gaze-tracker, and lower resolution elsewhere (Reingold *et al.*, 2003). Human factors research on GCMRDs has primarily focused on the limits of peripheral resolution, and the effects of going below them (Loschky & McConkie, 2002; Loschky *et al.*, in press). Fewer studies have investigated the perception of blur and image motion caused by updating the image whenever the eyes move, and particularly how early in each fixation the updating must occur to be imperceptible or, at least, to avoid interfering with visual tasks.

The top panel of Figure 1 schematically represents the image update process that must occur at the end of each saccade. In top panel A, an eye indicates the user’s gaze position on the screen, the white circle around it represents the region of highest resolution, the surrounding gray area represents the lower-resolution over the rest of the image, and the arrow indicates an eye movement into that area. Top panel B shows the eye at the new gaze location, before the update. After some delay, the high resolution area is updated to the new gaze location, as shown in top panel C. The question investigated here concerns the effects of delays in this updating process. While ideally one would update the display immediately at the end of each saccade, this is impossible in practice because it takes time 1) to identify when a saccade has ended and where the eyes are, 2) to render the new multi-resolutional image, 3) to transmit it, and 4) to display it. Rendering the image, alone, can take 25-150 ms (Reingold et al., 2003).

Such delays between the end of the saccade and the time of updating the image, referred to here as *update delays*, can cause perceptual difficulties in two ways. First, when a new fixation begins, the fixated region still has reduced resolution, which may hinder perception. Second, when the update occurs, the change in resolution may be perceived as motion, which may disrupt perception. However, saccadic suppression raises perceptual thresholds just before, during, and after each saccade (Ross *et al.*, 2001), which may help reduce sensitivity to these transients. Still, simulator studies show that image update delays impair perception and task performance (Grunwald & Kohn, 1994; Turner, 1984) and sometimes cause simulator sickness (Draper *et al.*, 2001; Frank *et al.*, 1988). A recent study of the detection of post-saccadic image resolution changes indicates that delays greater than 5 ms can be detected (McConkie & Loschky, 2002). However, the relevance of that study to answering our questions regarding the effects of GCMRD update delays on perception is unclear, since it did not involve a GCMRD. More recently, Loschky and McConkie (in preparation), used a GCMRD with update delays of 5, 15 and 45 ms, and found that a 45 ms delay did not reduce search performance but did increase fixation durations.

The current study directly measures image update delay effects on conscious perception, by having viewers detect image blur or motion transients in a GCMRD, while factorially varying delay and image filtering levels. The study uses a relatively wide range of update delays (5-80 ms) and a range of image filtering levels that bracket the blur detection threshold, in order to determine whether update delays can push otherwise undetectable image blur above threshold.

METHOD

Participants

Twelve paid undergraduate and graduate students participated. All had 20/30 or better uncorrected vision.

Stimuli

Stimuli were 24 monochrome photographic scene images (18º x 12º, 768 x 512 pixels), with varied subject matter and much visual detail.

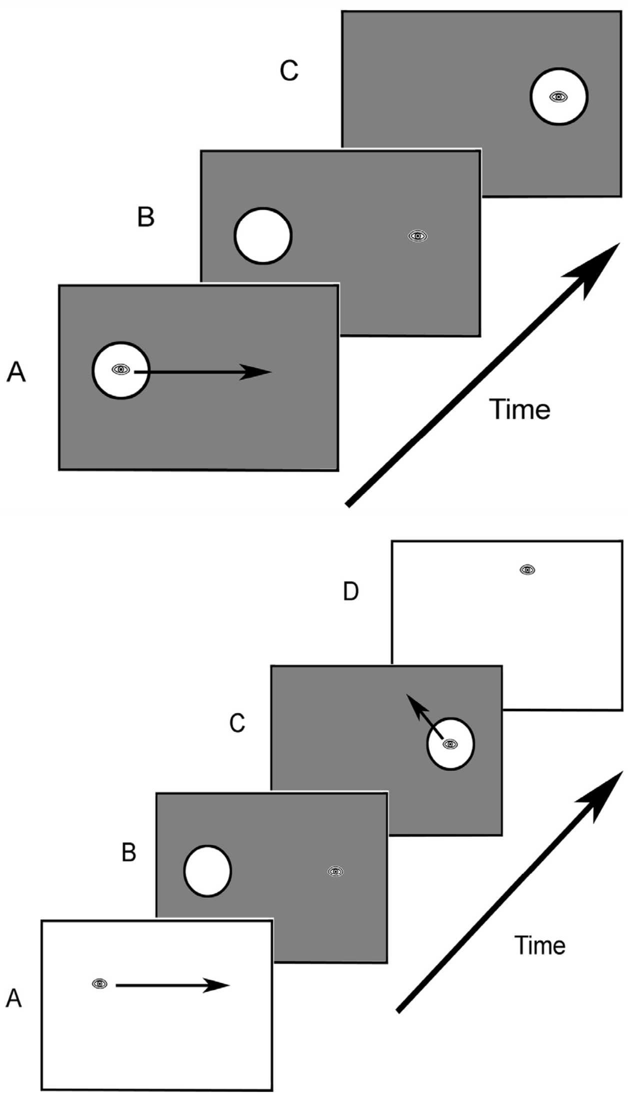

Figure 1. Top: Schematic of a GCMRD over time. Bottom: Same for a delayed occasional GCMRD.

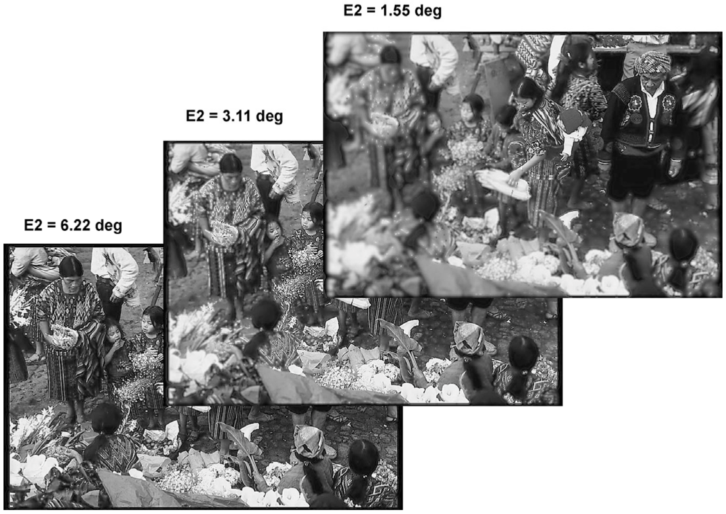

Figure 2. A set of 3 example images for filtering levels E2 = 6.22º, 3.11º, and 1.55º.

The images were filtered using an algorithm developed at Eastman Kodak Company. The algorithm is a modified version of Geisler and Perry's (1998) foveated multi-resolution pyramid. In the Geisler and Perry approach, different levels of the pyramid are circularly truncated based on the estimated spatial frequency cut-offs of the visual system at different eccentricities. The reconstructed image from the zone-limited pyramid contains fine structure at the point to which the gaze is directed, and becomes increasingly more blurred towards the peripheral retina. In the modified method, one computes a contrast threshold map based on the peak frequency of the pyramid level, and uses the contrast threshold map to threshold (i.e., reduce to zero contrast) the image content. Whenever the image contrast of a specific frequency band is below the corresponding visual contrast threshold/cut-off, the image contrast is thresholded. All other image content is kept unchanged. In this way, the foveated zones are not circular, but have somewhat irregular boundaries, thus avoiding the hard boundaries that are inherent in the Geisler and Perry approach. As shown in Figure 2, the algorithm produces a continuous resolution drop-off, rather than the discrete resolution drop-off suggested by the simplified schematic in Figure 1. We used three levels of image filtering to bracket the updating detection threshold. We varied filtering using a parameter corresponding to E2 for grating resolution (the eccentricity at which resolution drops to half maximum). The filtering E2 values were 6.22º, 3.11º, and 1.55º (Figure 2). Previous research (Loschky et al., in press) using a 5 ms update deadline, found that the predicted blur detection threshold, E2 = 3.11º, was almost never detected, one octave greater filtering, E2 = 1.55º, was often detected (60%), and filtering one octave below the predicted threshold, E2 = 6.22º, was never detected. Filtering conditions were counterbalanced across images and participants.

Apparatus

We used an eye-tracker with high spatial accuracy (Dual Purkinje Image Generation 5), and a system designed to minimize image-update delays. Eye position was sampled at 1000 Hz, providing high temporal resolution for identifying the ends of saccades. We avoided on-line image generation time by pre-computing 330 versions of each image (in a 22 x 15 imaginary grid over the image) and storing them in a 2 GB randomly accessible image memory and display controller. Thus, wherever viewers' eyes were directed on critical fixations when a modified image was presented, there was an image version whose center of highest resolution was within 0.41º of gaze position. Our 60 Hz monitor could be updated at any point during the refresh cycle, so updates were completed within 17 ms of initiation.

Procedures

In order to examine conscious perception of the visual artifacts produced by update delays in a GCMRD, we combined elements of the delayed window paradigm used in

Loschky and McConkie (in preparation) and the occasional window detection paradigm used in Loschky, et al. (in press). The current paradigm is shown schematically in the bottom panel of Figure 1. On most fixations, viewers saw an all high-resolution image, represented schematically by white space (Figure 1, bottom panel A). However, at the onset of occasional critical saccades, ranging from the 9th to the 11th, the high-resolution image was replaced with a multi-resolutional image, whose center of highest resolution was put at the preceding gaze location (fixation n-1). Thus, when the eyes landed at the new gaze location, they were usually in a lower-resolution region (bottom panel B), as in a normal GCMRD before updating of the image (c.f., top panel B). Then, after a delay of 5, 20, 40, 60, or 80 ms, the point of highest-resolution was put at the new center of gaze (bottom panel C; c.f., top panel C). Finally, as soon as the next saccade was initiated, the constant high-resolution image was returned to the screen (bottom panel D).

The viewer's task was to detect the blur or update-related motion (bottom panels B and C) that occurred for only a single critical fixation. Subjects indicated their detection by pressing a button as soon as they detected blur or a transient (with all responses occurring within ≤ 7 fixations of the critical fixation). After another 9 to 11 saccades, the next critical fixation occurred, and this pattern continued for the duration of each 30 second trial. (Subjects were not told about these contingencies.)

As a control condition to measure subjects' false alarm rates, we included "no-change" display changes in which the high-resolution image was replaced by a copy of itself after the same update delays and filtering conditions as the real changes.

We also attempted to replicate the finding that a display change made only 5 ms after the start of a fixation is undetectable (McConkie & Loschky, 2002). We did this by including a special condition in which the first multi-resolutional image (Figure 1, bottom panel B) was replaced by the constant high-resolution image (bottom panel D) 5 ms after the start of a critical fixation.

To motivate participants to carefully look at the images, we asked them to do several picture memory-related orienting tasks: 24 trials each of "short-term learning," "short-term test," "long-term learning," and "blur/transient detection only." Detection data were combined across tasks.

RESULTS

We examined the effects both of image filtering levels and of image updating delays on the detection of image updating in GCMRDs. We first cleaned the data by excluding blinks, extreme outlying reaction times (top and bottom 1%), extremely short fixation durations and saccade length (bottom 1%), and errors in positioning the center of highest resolution ≥2º on either fixation n or fixation n-1.

Perceptibility of updates as a function of filtering level. As expected based on the results of Loschky, et al. (in press), we found a significant effect of filtering level on detection, *F* (1.66, 18.26, Geisser-Greenhouse adjusted) = 138.21, $p < .001$. As shown in Figure 3, subjects essentially never false alarmed, nor detected filtering level E2 = 6.22º, rarely detected filtering level E2 = 3.11º, and frequently detected filtering level E2 = 1.55º.

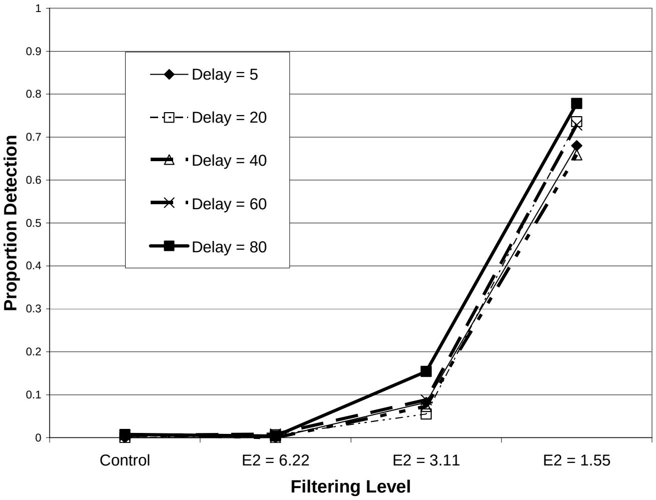

Figure 3. Proportion detection of occasionally presented gaze-contingent multi-resolutional images as a function of filtering level (control, E2 = 6.22º, 3.11º, and 1.55º) and update delay (5, 20, 40, 60, and 80 ms).

Perceptibility of updates as a function of delay. We were able to replicate McConkie and Loschky (2002) using a GCMRD, by showing that viewers *never* detected a change from the first multi-resolutional image to an all high-resolution image 5 ms after the start of a fixation. This supports the claim that our 5 ms delay condition serves as a no-delay baseline condition.

Figure 3 shows that update delays significantly increased detection, *F* (4, 44) = 5.68, $p = .001$, and interacted with filtering level, *F* (12, 132) =1.83, $p = .048$. This interaction is because updates have no effect when image blur is completely undetectable (filtering level E2 = 6.22º). Nevertheless, while blur in level E2 = 3.11º was very rarely detected, an 80 ms update delay significantly increased detection relative to the 5 ms baseline (*F* (1, 11) = 6.67, $p = .025$), though no shorter delays did so. The same was true for the more detectable filtering level E2 = 1.55º (80 ms vs. 5 ms, *F* (1, 11) = 4.94, $p = .048$, all other comparisons n.s.).

Perceptibility of updates as a function of saccade length. Analysis of our data showed that detection increased with saccade length. In the most detectable condition (E2 = 1.55º), with data pooled across all delays, we found that detection increased from saccades of ≤ 1º (59%) to saccades of 5º (72%), beyond which the detection rate remained fairly stable. Similar trends were shown in each delay condition separately. However, when the data pool was divided by 3 filtering conditions x 5 delays x 5 saccade lengths (1º, 3º, 5º, 7º, and 9º), the results became less stable.

DISCUSSION

The current study has provided a test of the effect of update delays on the detectability of image blur and/or motion transients in GCMRDs. Update delays had a relatively small but significant impact on conscious perception of image degradation. As predicted, long update delays (80 ms) significantly increased detection of a filtering level (E2 = 3.11º) that was otherwise almost never detected. However, for update delays ≤ 80 ms, and filtering levels bracketing the blur detection threshold, the effect of update delay was much less than that of filtering level, and for filtering levels well below the blur detection threshold, delays had no impact. Interestingly, the current study did not find significantly increased detection relative to the 5 ms delay baseline for update delays ≤ 60 ms, though our previous research found increased fixation durations for 45 ms delays (Loschky & McConkie, in preparation). This difference was likely due to using more detectable blur and a discrete resolution drop-off GCRMD in the previous study, though it is also possibly due to differences between eye movements and conscious detection processes.

The relatively small effect of update delays we have found can be explained by considering a characteristic of this type of GCMRD. As noted above, detection of updates increased with saccade length. This is because a longer saccade takes the eyes further from the center of highest resolution, thus increasing the degree of blur that will be present in foveal vision (Figure 1, top and bottom panels A and B) . After the update delay, the change is made to produce highest resolution in the foveal area (Figure 1, top and bottom panel C). Thus, the longer the saccade, the greater the initial blur and the greater the amount of stimulus change at the fovea. When a short saccade is made, the increase in the level of filtering at the fovea is quite small; in the case of very short saccades, no change may occur at all. In the current study, with the stimuli and display conditions used, saccades tended to be rather short: the modal saccade length was 0.75º, the median was 2.25º, and the mean was 2.94º (SD = 2.54º). These values are typical of eye movements made in both picture viewing (Henderson & Hollingworth, 1998) and real world perception (Bahill *et al.*, 1975). Thus, with a preponderance of short saccades, on average fairly small blur increases tend to occur at the fovea prior to the update, and fairly small changes occur across the image due to the update, producing low levels of perceptual disruption. The amount of disruption caused by update delays would be greater in situations where longer saccades tend to be made.

It should also be noted that the low detection rates in this study were due in large part to the fact that we used levels of image filtering near the detection threshold, and we excluded cases from our analyses having poor accuracy in aligning the center of highest resolution with the fovea. Thus, GCMRD applications using more detectable filtering levels, and/or having lower spatial accuracy in aligning the center of highest resolution, would result in greater perceptual disruptions due to update delays than we have shown here. Nevertheless, the fact that delays in our study as long as 60 ms did not significantly increase detection is very good news for designers of GCMRDs for single-user applications, because it is ample time to update their displays after each eye movement without causing perceptual difficulties.

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