

P-39: Perceptual Tests of the Temporal Response of a Shuttered LCoS Projector

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Abstract

Perceptual motion blur was studied using imagery presented on an LCoS projector equipped with a mechanical shutter to reduce pixel hold-time. Perceptual measures of image blur were obtained with a simple test stimulus, as well as imagery similar to that used in Air Force flight simulation and training. Measured pixel hold-time was found to accurately predict perceived blur.

1. Introduction

Liquid-crystal displays (LCDs) have relatively high spatial resolution, but their temporal resolution is limited compared to CRTs. This limited temporal resolution often results in the blurring of moving images [1-3]. It was originally believed that moving-image blur was due to the long onset and offset times typical of LCDs, which were often longer than the frame duration. However, the onset and offset times of LCDs have been reduced significantly over the past ten years, and so their limited temporal response seems now to be a consequence of the sample-and-hold property related to both the design of the LCD driver circuitry and the LCD itself [4]. It has been concluded, from temporal resolution measured using a simple moving line stimulus, that a hold-time of approximately 8 msec or less, as opposed to the current 16.7 msec, significantly reduces motion blur [5, 6].

In a previous paper [5], we reported that an LCD projector equipped with a mechanical shutter that reduced pixel hold-time by approximately 33% resulted in a significant reduction in perceived blur. Further, experienced pilots who viewed the resulting imagery rated moving image quality as significantly higher when the shutter was used. In the present paper, we have expanded our previous study by assessing perceived blur for an LCoS projector whose hold-time has been varied over a larger range.

2. Display Characterization

Two displays were evaluated. One display was a prototype LCoS projector that employed a rotating shutter to reduce pixel hold-time. The shutter was synchronized with the activation of the LCoS panels. The second display, which was used for comparison, was a Barco Model 909 CRT projector. This CRT display is similar to displays currently used by the Air Force for flight-simulation and training [7]. A pixel format of 1280 × 1024 was used with both projectors. The native resolution of the LCoS display was 1920 × 1080, thus we did not use the whole LCoS panel. However, a one-to-one correspondence between image generator and display pixels was maintained. All imagery was displayed on a rear-projection screen, and subtended approximately 70° (H) × 58° (V). Because the red, blue, and green LCoS panels were slightly misaligned, we used only the green LCoS panel in order to avoid confusing blur with color misalignment. To match the appearance of the CRT and LCoS as closely as possible, only the green CRT was used. Image size was approximately 52 × 43 inches, and thus was similar to that used in the front window of the Mobile Modular Display for Research and

Training (M2DART) currently used in Air Force flight-simulators [7].

Display spatial resolution was characterized using procedures adopted from accepted measurement standards [8, 9]. Display temporal response was measured for each of the LCoS-display shutter conditions and for the CRT using a photodiode-based circuit and an oscilloscope. The photodiode was directed at a 30 Hz flashing square generated by our test program [5, 6, 10]. A Fluke ScopeMeter was used to record the photodiode response. Luminance and contrast measures were also obtained for each display.

2.1. Results

Figure 1 shows gamma functions for each LCoS shutter condition. The 6% hold-time reduces the light by approximately 93% relative to the 100%, or No-shutter, condition. The horizontal spatial resolution of the LCoS and CRT projectors were approximately equal at 1150 lines and 1200 lines, respectively.

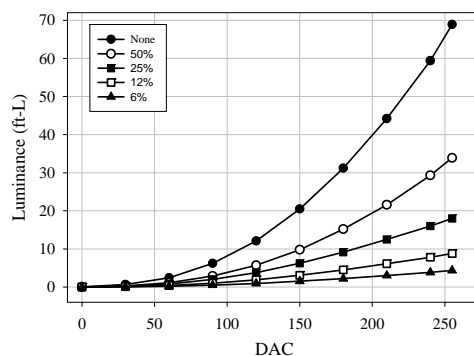


Figure 1. Luminance and gamma measurement for each of the LCoS shutter conditions.

Figure 2 shows the normalized temporal luminance distributions for three of the LCoS hold-times as well as for the CRT projector. Shown in Table 1 are the nominal and measured (at half-amplitude) hold-times for each experimental condition.

3. Experiment 1

3.1. Methods

Observers. Six observers between the ages of 21 and 56 participated in the study. All observers had normal, or corrected to normal, visual acuity. Three of the authors served as observers.

Stimuli and Apparatus. The test stimulus was a pair of vertical lines (20° in length) that moved horizontally across the display, and whose separation could be varied [5-6]. The test-stimulus varied in speed from 100 to 1200 pixels/second (5.6 to 67.5 degrees/sec). The LCoS projector was evaluated for five hold-times corresponding to 100%, 50%, 25%, 12%, and 6% of the 16.7 msec frame duration. In order to equalize the appearance of

the test stimulus, as well as the background, for all hold-times, neutral density filters were used to reduce the luminances associated with the larger hold-times so that they were equal to the luminance for the 6% hold-time. For the CRT, the intensity of the test stimulus and background were adjusted to match the luminance of the 6% LCoS condition.

Procedure. The observers first adapted for 6-8 minutes to the ambient illumination of the experimental room. The moving test stimulus was then presented, and observers were instructed to track the stimulus and adjust the separation of the vertical lines such that the gap between them was minimized, while keeping the width of the two lines equal. Each observer made four adjustments of each of the test-stimulus speeds, which were presented in a random order. The hold-times were tested in separate experimental sessions, and the order in which they were tested was also randomized.

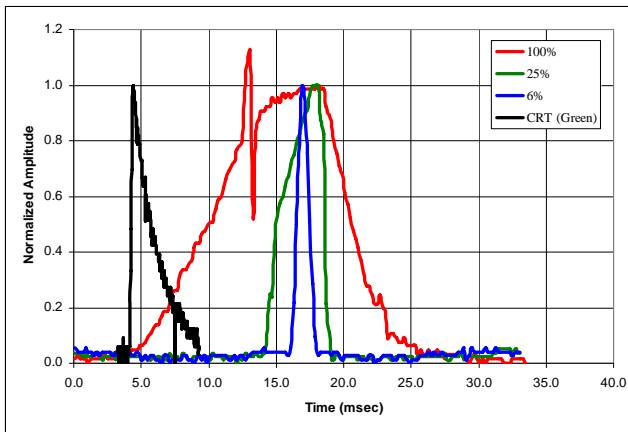


Figure 2. Normalized temporal luminance distributions for three of the five hold-times tested, and for the CRT projector.

Table 1. Nominal and measured (half-amplitude) hold-time for each LCoS shutter condition and for the CRT projector.

Condition	Nominal Hold-time (msec)	Measured Hold-time (msec, half-amplitude)
100%	16.7	10.4
50%	8.4	8.0
25%	4.2	3.8
12%	2.0	1.8
6%	1.0	1.0
CRT	--	1.4

3.2. Results

Shown in Figure 4 are the results of the perceived-blur measurements for each LCoS hold-time and for the CRT projector. Perceived blur, as indicated by the adjusted gap width, clearly increases with increased speed.

A Repeated-Measures Analysis of Variance indicated that the main effects of Speed [$F(6, 30) = 65, p < 0.001$] and Hold-Time [$F(5, 25) = 26, p < 0.01$], as well as the Speed \times Hold-Time interaction [$F(30, 150) = 22.5, p < 0.001$] were all statistically

significant. Further, a set of *a priori* contrasts indicated that the perceived blur associated with the 100% and 50% hold-times were significantly different from those obtained for the CRT. However, the perceived blur associated with the 25%, 12%, and 6% hold-times were not significantly different than those obtained for the CRT.

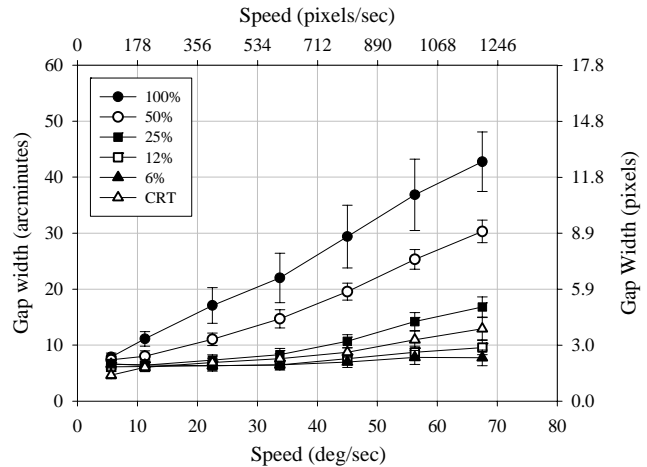


Figure 3. Perceived blur with moving line stimulus in Experiment 1.

4. Experiment 2

4.1. Methods

Observers. Nine observers participated in Experiment 2. Five of the observers were experienced fighter pilots. Three of the authors again served as observers. All observers had normal, or corrected to normal, visual acuity.

Stimuli and Apparatus. The test targets for Experiment 2 were chosen to be more similar to those viewed in Air Force flight simulation and training. The targets were F-16 aircraft that appeared at simulated distances of 200, 400, 800, and 1600 m (corresponding to target sizes of approximately 3.5, 1.75, 0.87, and 0.44 deg) over a terrain-database scene of the Nellis AFB/Las Vegas area. The targets moved from left to right across the display.

Procedure. For the first task, observers viewed the aircraft targets and adjusted their speed in order to produce minimally visible blurring. For the second task, observers viewed the terrain-database scene as it would appear if a simulated aircraft were pitching up and down (similar to a porpoising maneuver). Observers were instructed to adjust the pitch rate until the terrain just appeared blurred. Each of these tasks was performed for the 100% (No-shutter), 50%, and 25% LCoS hold-times. The experienced pilots who participated in these tasks also responded to several questions regarding the acceptability of the perceived blur in the context of Air Force flight training.

4.2. Results

Figure 4 shows the speed at which a target aircraft was judged to just appear blurred for each of the simulated target distances (i.e., sizes) and LCoS hold-times tested. The speed required to just produce blur increased significantly with both simulated distance and hold-time. For the 25% hold-time, observers often reported difficulty tracking the target before they noticed target blur. A

Repeated Measures Analysis of Variance indicated that effect of Hold-Time [$F(2, 16) = 7.14, p < 0.05$] and Simulated Distance [$F(3, 24) = 11.7, p < 0.01$] were significant. A test of *a priori* contrasts indicated that blur speed was significantly higher for the 25% hold-time than for the 100% (No-shutter) hold-time [$F(1, 8) = 8.3, p < 0.05$], but that blur speed was only marginally different for the 50% and 100% hold-times [$F(1, 8) = 5.0, p = 0.055$].

Figure 5 shows the pitch rate required to produce noticeable blurring of the terrain imagery for the three hold-times tested. As shown, the required pitch rate increased with decreased hold-time. Pitch rates encountered in fast-jet simulation are typically limited to about 9 deg/sec. A Repeated-measures Analysis of Variance indicated that the effect of Hold-Time was significant [$F(2,16) = 55.3, p < 0.001$], and *A priori* contrasts indicated that the 100% hold-time and 50% hold-time conditions were significantly different than the 25% hold-time condition [$F(1,8) = 128.6, p < 0.001$; $F(1,8) = 25.9, p = 0.001$].

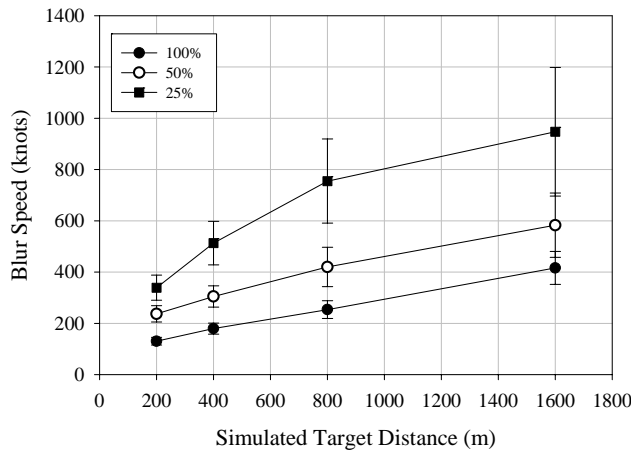


Figure 4. Target aircraft speed required for each shutter condition to produce perceived blur in Experiment 2.

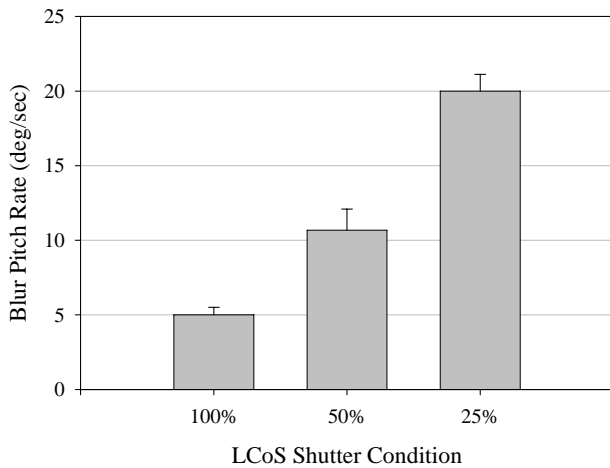


Figure 5. Pitch rate required to produce perceived blur in Experiment 2 for three LCoS shutter conditions.

Follow-up interviews with the experienced pilots who participated in Experiment 2, revealed that all immediately noticed the improvement in moving image quality when LCoS hold-time was reduced, and all indicated a strong preference for the reduced hold-times as compared to the 100% hold-time. For the 25% hold-time, pilots generally noted that the speeds needed to produce blur were generally beyond those that would occur in typical training scenarios. However, opinion varied as to the degree of improvement in temporal resolution that would be required to adequately support flight-simulator training. About half of the pilots reported that the 50% hold-time reduced moving image blur sufficiently to be useful for training; while the other half felt that an additional reduction in blur, such as with the 25% hold-time, was needed.

5. Discussion

The results of Experiment 1, using the simple moving test stimulus, show that a reduction of LCoS hold-time resulted in a significant decrease in the perceived blur of moving targets. This result is similar to that found in our previous study [5]. In the present study however, pixel hold-times were varied over a greater range. The results of Experiment 1 indicated that perceived blur was not statistically different from that of a CRT display when LCoS hold-time was reduced to 3.8 msec (25%) or less. Thus a sample-and-hold display with a hold-time of about 4 msec would appear to be acceptable for applications involving fast moving targets or terrain imagery. As shown in Figure 1, a 3.8 msec (25%) hold-time reduces peak luminance from about 70 ft-L to 20 ft-L. Although this is a substantial reduction in luminance, a luminance of 20 ft-L is similar to that of current CRT displays used for Air Force training, and may therefore be acceptable. The peak luminance of the Barco 909 used in Experiment 1, for example, was approximately 24 ft-L.

The results of Experiment 2, in which imagery much more similar to that encountered in Air Force flight simulation and training, was used, support those of Experiment 1. Observers asked to track fast-moving target aircraft perceived significant blur for the 100% (10.4 msec) hold-time. The 50% (8.0 msec) hold-time resulted in a significant decrease in moving-image blur, but some blur was still evident at speeds that are typical in flight-simulator training. The speeds required to produce perceived target blur for the 25% (3.8 msec) hold-time were generally higher than would typically be encountered in flight-simulator training. Similarly, the aircraft pitch rate required to produce perceptible blur for the 25% hold-time was much higher than would be observed for a fast-jet simulation using typical flight dynamics.

Based upon the comments of the experienced pilots who participated in Experiment 2, the presence of some blurring, particularly if it is noticeable only at higher speeds, would not interfere with Air Force training. Thus, while the 25% hold-time essentially eliminated perceived blur, its use may not be justifiable considering the concomitant loss of scene brightness. A shutter with a 50% hold-time may be adequate for Air Force training purposes. A 50% shutter would result in a peak luminance, for the LCoS projector used here, of about 30 ft-L, which is slightly higher than that of displays currently in use [7]. However, it remains to be determined what effect the presence of moving blur has on important tasks such as the detection of aspect change in high speed air-to-air engagements, or the identification of ground targets during close-air-support (CAS) training. Further, it is likely that there is an interaction between luminance level, and

perceived blur. The results presented here were obtained at a relatively low luminance level in order to equalize luminance relative to the 6% hold-time. Observers may perceive greater blur for the same moving target speeds if luminance levels were increased.

The Air Force has been working towards ultra-high resolution (i.e. eye-limited resolution) displays to support stringent visual requirements needed for air-to-air and air-to-ground flight training. Several of the pilots participating in Experiment 2 noted that high spatial resolution was more important than moving image quality. However, it is important to note that increases in static spatial resolution may be reduced with long hold-time displays when the imagery moves.

The results of Experiments 1 and 2 are highly correlated with the photodiode measurements described above (see Table 1). Figure 6 shows how the average moving-line blur relates to LCoS hold-time. This straight-forward relationship shows that a simple measurement, which we have described here, as well as in previous studies [5, 6, 10], predicts moving-image quality and would allow displays to be selected to suit various temporal-response requirements. A similar method has been described by Teunissen, Li, and Heynderickx [11] and is much simpler than methods such as the Motion Picture Response Time (MPRT), which involve the use of a motion tracking CCD camera, or a CCD camera combined with a tracking mirror [12, 13, 14].

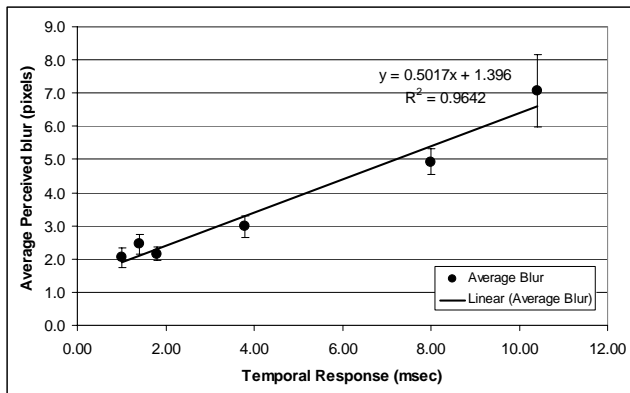


Figure 6. Average perceived moving-line blur as a function of temporal response (hold-time).

6. Conclusion

Sample-and-hold visual displays, such as LCD, LCoS, and DLP projectors, have typically been unacceptable for Air Force simulation and training due to their relatively low temporal response. The results presented here indicate that displays whose hold-times are reduced to about 4 msec (at half amplitude) would be acceptable for fast-jet flight simulation, and that even a hold-time as high as 6 to 8 msec may be adequate. However, these conclusions must be verified at higher luminance levels. Finally, the simple pixel hold-time measurements described here can be used to predict moving image blur.

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