LIQUID-CRYSTAL DISPLAYS AND MOVING-IMAGE QUALITY

Julie Mapes Lindholm
Lockheed Martin Technology Services, 6030 South Kent, Mesa, AZ

Byron J. Pierce
Human Effectiveness Directorate, Air Force Research Laboratory, Mesa, AZ

Angelique A. Scharine
Department of Psychology, Arizona State University, Tempe, AZ

ABSTRACT

It is frequently suggested that liquid crystal displays (LCDs) could be tiled to provide full-field-of-view, high-resolution images for flight simulation. However, even though LCDs can create static images of high quality, moving images often appear blurred and of relatively low contrast. This motion-dependent reduction in image quality is usually ascribed to the temporal properties of LCD pixels. Nonetheless, the problem does not seem to be generally well understood. Here we attempt to clarify the issue. We begin with a comparison of the temporal and corresponding temporal-frequency responses of hypothetical LCD and cathode ray tube (CRT) pixels. We then examine the spatiotemporal-frequency spectra of space-time images formed during simulated flight: the original, continuous image; the digital-image sequence; the display image; the retinal images; and the "perceptual image." In this analysis, we focus on the effects of a pixel's temporal response on the display-image spectrum and the effects of direction-of-gaze motion on a retinal-image spectrum. In the final section, we discuss predicted perceptual effects of display-determined spatiotemporal-frequency attenuation and present data indicating that, during smooth pursuit of a simple stimulus that is successively displaced in accord with a constant velocity, observers' spatial percepts can be accurately predicted.

AUTHORS' BIOGRAPHIES

Julie Mapes Lindholm is a senior scientist with Lockheed Martin Technology Services Group at the Air Force Research Laboratory in Mesa, Arizona. Her research focuses on the mechanisms of form and motion perception, particularly as they pertain to image generation and display technologies. She received the B.A. degree in psychology from the University of Redlands and the M.S. and Ph.D. degrees in experimental psychology from the University of Wisconsin-Madison.

Byron J. Pierce is a senior research psychologist employed by the Air Force Research Laboratory, in Mesa, Arizona, where he is team lead for the visual research and development program. Dr. Pierce is responsible for the planning, management, and conduct of visual R&D activities for flight simulation and training. He was awarded a Ph.D. in experimental psychology from Arizona State University, an M.S. in engineering psychology from the University of Illinois, and a B.S. in psychology from Arizona State University.

Angelique A. Scharine is a graduate student in the Department of Psychology at Arizona State University, where she is working on her Ph.D. in experimental psychology. Her research interests are in the areas of auditory and visual perception. She received the M.S. degree in educational psychology and the B.S. degree in mathematical education from the University of Utah.

LIQUID-CRYSTAL DISPLAYS AND MOVING-IMAGE QUALITY

Julie Mapes Lindholm
Lockheed Martin Technology Services, 6030 South Kent, Mesa, AZ

Byron J. Pierce
Human Effectiveness Directorate, Air Force Research Laboratory, Mesa, AZ

Angelique A. Scharine
Department of Psychology, Arizona State University, Tempe, AZ

INTRODUCTION

In flight simulators, the database, image generator (IG) and pilot's input define a continuous image that is distributed over time and over two dimensions of space (Figure 1). The IG samples this *original image* to create a sequence of two-dimensional, digital images. The display system then converts the *digital-image sequence* into a visible, space-time image. During observation of this *display image*, an image is formed on the retina of each eye. Variation in the observer's direction of gaze affects the spatiotemporal composition of these *retinal images*, and direction-of-gaze-related extraretinal signals modify the *perceptual image* (percept) that results from the retinal signals.
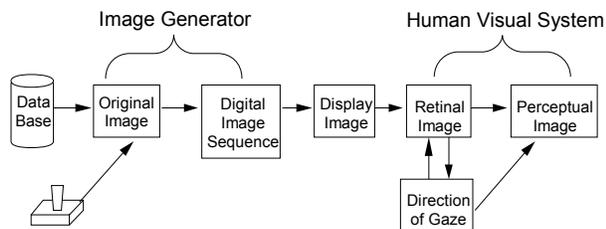

Figure 1. Diagram of image formation during simulated flight.

Most current flight simulators use display technologies based on the cathode ray tube (CRT). It is frequently suggested that lower cost, higher resolution images could be created by tiling liquid crystal display (LCD) projectors. However, even though LCDs can create static images of high quality, moving images often appear blurred and of relatively low contrast. This motion-dependent reduction in image quality is usually attributed to the temporal properties of LCDs (e.g., Parker, 1997; Poynton, 1996). Nonetheless, the problem does not seem to be generally well understood (e.g., Larimer, 1997; Macpherson, 1998). Here we attempt to clarify the issue.

We begin by summarizing the temporal response of an LCD pixel. We then examine the spatiotemporal-frequency spectra of the images formed during simulated flight. In the final section, we discuss the predicted perceptual effects of display-determined spatiotemporal-frequency attenuation

LCD-PIXEL TEMPORAL CHARACTERISTICS

The amount of light reflected or transmitted by an LCD pixel is determined by the orientation of the liquid crystal molecules. These molecules require time to orient to a new position and thus to display a new intensity. The "response time" of a pixel is generally considered to be the sum of the black-to-white and white-to-black transition times (VESA, 1998). However, transition duration depends upon the initial and desired orientations of a pixel: Intermediate gray-scale transitions may be much longer than black-white transitions.

Figure 2 illustrates a generalized version of the VESA procedure for the assessing response time. First, L_{higher} and L_{lower}, the steady-state luminances for the higher and lower input values, are used to compute $L_{difference} = L_{higher} - L_{lower}$; $L_{10} = 0.1 L_{difference} + L_{lower}$; and $L_{90} = 0.9 L_{difference} + L_{lower}$. The corresponding times, $t_{10\text{-rise}}$, $t_{90\text{-rise}}$, $t_{90\text{-fall}}$, and $t_{10\text{-fall}}$ are then used to compute the rise time, t_{rise}, and the fall time, t_{fall}: $t_{rise} = t_{90\text{-rise}} - t_{10\text{-rise}}$ and $t_{fall} = t_{10\text{-fall}} - t_{90\text{-fall}}$. (Note that the measured rise and fall times are less than the times required to complete the respective transitions.)
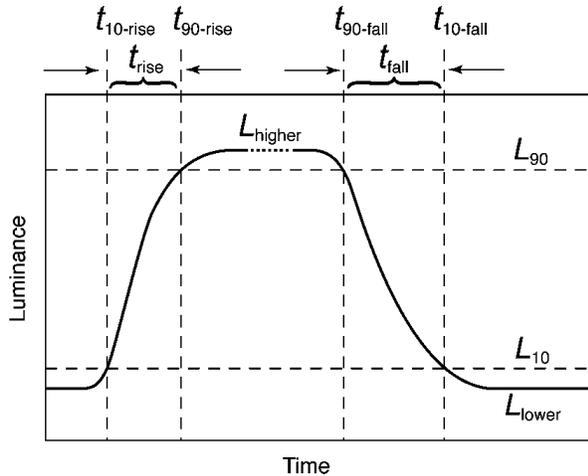
Figure 2. Illustration of an LCD-pixel response to an increase and a decrease in designated gray level.

Figure 3. Hypothetical temporal responses (TR_a, TR_b, TR_c) to a one-frame increment in designated gray level.

their temporal-frequency responses for a display with a 60-Hz refresh rate. Note that although amplitude attenuation increases somewhat with the duration of the response (TR_a > TR_b > TR_c), the first zero occurs at the refresh rate in each case.
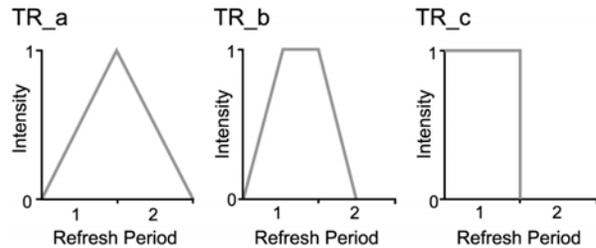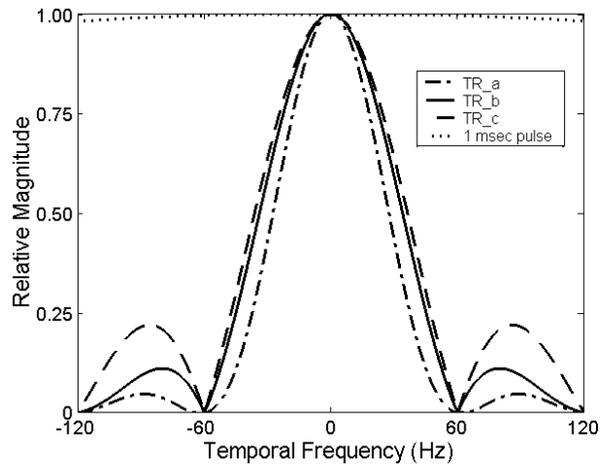

Figure 4. Temporal-frequency responses, to ±120 Hz, of TR_a, TR_b, TR_c (for a 60 Hz display) and a 1-msec square pulse.

It is often stated that the poor quality of moving LCD images is due to the slow response of an LCD pixel. ` The response time is, however, only part of the problem. With current LCD technology, if a given transition time is less than the duration of the refresh period, the designated luminance level is held until the end of the refresh period. The resulting display image depends upon the entire temporal response.

Figure 3 shows three hypothetical temporal responses (TR_a, TR_b, and TR_c) to a 1-frame increment in specified gray level. Each of these responses has several idealized properties: The specified level is reached within a refresh period; the luminance transitions are linear; and the rise and fall times are equal. The responses differ from each other in the durations of their transitions. In TR_a, the rise and fall times are equal to the refresh period. Thus, the luminance of the pixel increases throughout one refresh period and decreases throughout the next. In TR_b, the rise and fall times are equal to half the refresh period. This results in a "hold time" of half the refresh period and a return to the lower intensity halfway through the next period. In TR_c, the transitions are instantaneous, with the higher intensity held throughout the first refresh period.

The temporal response of a pixel serves as a temporal reconstruction filter and is thus an important determinant of the display image that results from a given digital-image sequence. Despite the differences in their transitions times, the three temporal responses have similar filtering characteristics. Figure 4 shows

By comparison, the temporal response of a CRT pixel is typically very brief: Light intensity rises rapidly and then decays to less than 10% of its peak value within about a millisecond (Parker, 1997). A CRT thus passes a very wide band of temporal frequencies. In Figure 4, the temporal-frequency response of a CRT pixel is approximated by that of a 1-msec square pulse. Note that frequencies within ± 120 Hz are minimally attenuated.

To clarify the effects of a pixel's temporal response, we consider the spatiotemporal-frequency spectra of the images formed during flight simulation.

IMAGE SPECTRA

Original-Image Spectrum

The Fourier transform of a space-time image consists of three-dimensional, spatiotemporal-frequency components. In a flight simulator, the spectrum of the original image is likely to include infinitely high spatial frequencies. To limit spatial aliasing, low-pass spatial filters are often applied prior to or during the sampling process.

The temporal frequency of a spatial sinusoid equals the product of its spatial frequency and its velocity. Thus, if an image is static, every spatial frequency will have a temporal frequency of zero. If an image depicts motion, there will be spatiotemporal-frequency components that have a nonzero temporal frequency. During simulated flight, some of these temporal frequencies may exceed half the temporal sampling rate. Nonetheless, with current technology, no attempt is made to limit temporal aliasing—that is, the image is not subjected to a temporal presampling filter.

Digital-Image-Sequence Spectrum

The spectrum of a digital-image sequence consists of the original-image spectrum plus replicas of that spectrum at multiples of the temporal and spatial sampling frequencies. If a spatiotemporal frequency in the original image exceeds half the sampling rate on one or more dimensions, spectral replicas will extend into the frequency space bounded by one-half the sampling frequencies. When this occurs, it is not possible for the display device to accurately reconstruct the original image from the digital-image sequence.

Display-Image Spectrum

The display-image spectrum consists of the digital-image-sequence spectrum after it has been subjected to the spatial and temporal reconstruction filters of the display system. In order for the display system to accurately reconstruct the original image, (a) the spatial and temporal frequencies in the original image would have to be limited to less than half the spatial and temporal sampling rates, respectively, and (b) the spatial and temporal reconstruction filters of the display system would have to pass the spectrum of the original image without attenuation and to remove the

spectral replicas introduced by the sampling process (Rosenfeld & Kak, 1976; Holst, 1998).

If the original image is taken to be that defined by the database, the first condition will generally not be met. However, the IG may be equipped with a spatial antialiasing filter that removes spatial frequencies greater than half the sampling rate. In this case, the spatially low-pass image can be taken as the original image. Then, if all of the image velocities are sufficiently low, the original image will be appropriately band limited and reconstruction accuracy will depend upon the reconstruction filters of the display system.

Although display systems differ somewhat in their spatial reconstruction filters, they generally pass spatial frequencies up to half the sampling rate without undue attenuation while substantially attenuating most of the higher frequencies introduced by the spatial sampling process. In contrast, as we have illustrated, there are large technology-dependent differences in the temporal reconstruction filters of display devices: Specifically, LCDs markedly attenuate many temporal frequencies less than half the temporal-sampling frequency, whereas CRTs pass, with minimal attenuation, temporal frequencies many times greater than half the temporal-sampling frequency.

Because temporal antialiasing filters are not used and image velocities are not consistently low, display-image spectra are likely to contain temporally aliased components—components consisting of an original spatial frequency with an erroneous, lower temporal frequency. CRT image spectra will also contain the original, high-temporal-frequency (> 30 Hz) components. These components will have roughly the same amplitudes as their aliased counterparts. Although an LCD image may also contain most of the original, high-temporal-frequency components, they will be severely attenuated. In our view, it is this difference between CRT and LCD high-temporal-frequency attenuation that accounts for the difference in moving-image quality.

Retinal-Image Spectrum

If the direction of gaze is approximately stationary during observation of a display image, a retinal-image spectrum will approximate a spatially low-pass[*] version of the spectrum of the display image. Under

---

[*] The optics of the eye serve as a low-pass spatial filter.

unconstrained viewing conditions, however, an observer's direction of gaze typically tracks a moving object that is the focus of attention. Moreover, even though pattern motion in a display image is not smooth, the eyes (or eyes and head) tend to move smoothly rather than in discrete jumps. Thus, if a spatial pattern in a display image is successively displaced in accord with velocity $\mathbf{v_O}$, the displacements of the pattern in the retinal image will be in accord with $\mathbf{v_{DIFF}} = \mathbf{v_O} - \mathbf{v_G}$, where $\mathbf{v_G}$ is the direction-of-gaze velocity. The temporal frequencies in the retinal image will shift accordingly (i.e., by the product of the spatial frequency and $\mathbf{v_G}$), thus shearing the image spectrum.

In general, if the direction-of-gaze moves at a constant velocity during observation of a display image, a retinal-image spectrum will be a sheared version of the display-image spectrum. The amplitude of a component will be unaffected by the change in temporal frequency. Thus, if a high-temporal-frequency component in the display image has been severely attenuated by the extended temporal response of an LCD pixel, that component will be attenuated in a retinal image, even though its temporal frequency is low.

Perceptual-Image Spectrum

Retinal images are filtered by higher levels of the human visual system (HVS). Those portions of the retinal-image spectra that fall within the passband of the HVS presumably contribute to the perceptual-image spectrum. Extraretinal signals related to the direction of gaze also provide input to the perceptual system. Thus, our working hypothesis is simply that the effective "perceptual-image spectrum" represents a composite of the two retinal-image spectra, after being filtered by higher levels of the HVS, and extraretinal signals that "replace" the motion that was removed by eye and head motion.

PREDICTED PERCEPTS

For a display with a given temporal response, the temporal frequency of a spatiotemporal-frequency component determines its attenuation in the display image. The perceptual effects of attenuating a given component depend upon its temporal frequency in the retinal image, and thus upon direction-of-gaze motion. If spatiotemporal-frequency components fall within the passband of the HVS, their attenuation is likely to affect the resulting percept.

Constant Direction of Gaze

Static Images. If the original image is static, all of its spatiotemporal frequencies have a temporal frequency of 0 Hz, and the spatiotemporal frequencies introduced by temporal sampling all have a temporal frequency that is an integer multiple of the sampling rate. Although a CRT would pass these spectral replicas with little attenuation, they would be completely removed by an LCD with TR_a, TR_b, or TR_c (see Figure 4). The extended temporal responses of such LCD pixels would thus eliminate the fluctuation in luminance (i.e., flicker) that can sometimes be seen on a 60 Hz CRT.

Low Image Velocities. If the original image is characterized by pattern velocities that result in spatiotemporal-frequency components with temporal frequencies up to, but not greater than, half the temporal sampling rate (e.g., < 30 Hz), the components introduced by temporal sampling will all have temporal frequencies greater than 30 Hz. Most of these components will be severely attenuated by an LCD. In contrast, a CRT will pass many of the temporal-sampling-induced components with little attenuation. Although this difference favors the LCD, it is unlikely to be perceptually significant: Because the HVS is relatively insensitive to most spatiotemporal frequencies with a temporal frequency greater than 30 Hz, few of the sampling-induced frequencies in a CRT image will be visible.

Of greater perceptual importance, an LCD will also attenuate the amplitudes of components in the original-image spectrum. The degree of attenuation will increase with the temporal frequency of a component. For a given velocity, then, attenuation will increase with spatial frequency. Attenuation of the higher spatial frequencies in a pattern causes the pattern to "blur." According to the view developed here, this blur is likely to be perceived.

High Image Velocities. If the original image is characterized by pattern velocities that result in spatiotemporal-frequency components with temporal frequencies greater than 30 Hz (i.e., greater than half the temporal sampling rate), temporal aliasing will occur in the display image (i.e., some temporal-sampling induced components will have temporal frequencies less than 30 Hz). An LCD will significantly attenuate both aliased and nonaliased components that a CRT will pass with negligible attenuation. Attenuation of spatiotemporal frequencies within the passband of the HVS will presumably result in perceived blur. If aliased components are visible,

the perceived motion may be discriminably different from smooth motion (Lindholm, Askins, & Krasnicka, 1993; Watson, Ahumada, & Farrell, 1986)

Smooth Pursuit

When the direction of gaze is constant during observation of a moving pattern, many of the spatial frequencies that are attenuated by an LCD may have temporal frequencies that place them outside the passband of the HVS. If that is the case, their attenuation will not affect the perceptual image. During smooth pursuit, the spatial frequencies that compose the moving pattern typically have relatively low temporal frequencies, placing the spatiotemporal-frequency component within the passband of the HVS.

If a pattern in the display image is displaced in accord with a constant velocity, the attenuation of a spatiotemporal-frequency component in its spectrum is consistent and *predictable*. In the view developed here, if display-image-component attenuation is predictable, the perceptual image during smooth pursuit is predictable.

Such predictions can best be understood by considering, first, the characteristics of a retinal image that would be formed if pursuit were perfectly accurate—that is, if v_{DIFF} = 0. In the frequency domain, as previously discussed, the spatial frequencies that compose the pattern in the original-image spectrum would all have a temporal frequency of 0 Hz. The attenuation of a component would be a function of its temporal frequency in the display image and the temporal response of the display device.

In the space-time domain, during perfectly accurate tracking the pattern would be repetitively painted at the same location on the retina. With an LCD, pattern blur would result from the constant velocity movement of the retina during the extended pixel response. With a CRT, the retina would have little time to move during the brief temporal response, and the pattern would not be blurred.

Tracking is, however, never perfectly accurate. Variability in v_{DIFF} will cause variability in the pattern and in the location of the pattern that is painted on the retina. A corresponding variability will occur in the temporal frequency of a given spatial frequency in the retinal-image spectrum. Nonetheless, v_{DIFF} will usually be small enough to ensure that the components of the original-image spectrum all fall within the passband of the HVS and that the components introduced by temporal sampling all fall outside the passband of the HVS.[♣] Consequently, the *visible* spatial spectrum during moderately accurate tracking is likely to approximate that during perfectly accurate tracking. In the view developed here, the perceived pattern during tracking is therefore likely to approximate that which would be repetitively painted on the retina if tracking were perfectly accurate.[#]

We have predicted the spatial percepts for each of the three hypothetical temporal responses for a variety of luminance patterns and velocities. To do so, we convolved the spatial luminance profile of the pattern with the temporal response to one-frame increase in gray level and then convolved this image with a space-time representation of the velocity. (Lindholm and Scharine, 2000, used a similar approach to predict perceived chromoluminance patterns during tracking of moving patterns in images created by a single-chip Digital Light Processing projection system.)

Figure 5 illustrates the predicted spatial percepts, for TR_a, TR_b, and TR_c, during tracking of a one-pixel-wide white bar moving across a black background in accord with a constant horizontal velocity v (v = 0, 1, 2, and 4 pixels per refresh period). Note that blur increases and contrast decreases as velocity increases, for all three temporal responses. For a CRT with a phosphor persistence of about 1 msec, the predicted percept would be more-or-less independent of velocity.

Figure 6 illustrates the predicted spatial percepts during tracking of a more complex pattern that is displaced 0, 1, 2, or 4 pixels to the right on successive frames of an LCD with TR_b. Note that, with this temporal response, the letters in the pattern are badly blurred at v = 2. The predicted blur would be slightly greater with TR_a and slightly less with TR_c. With a temporal response of about 1 msec, the pattern would be sharp for all four velocities.

[♣] This statement pertains only to the case in which all of the spatial frequencies in the original image moved at the same velocity—not to images in which there is a stationary background or in which multiple patterns are moving at different velocities.

[#] The HVS is not an ideal filter (i.e., it is not equally sensitive to all spatiotemporal frequencies within its passband). Consequently, tracking inaccuracies are likely to have some effect on the spatial percept.
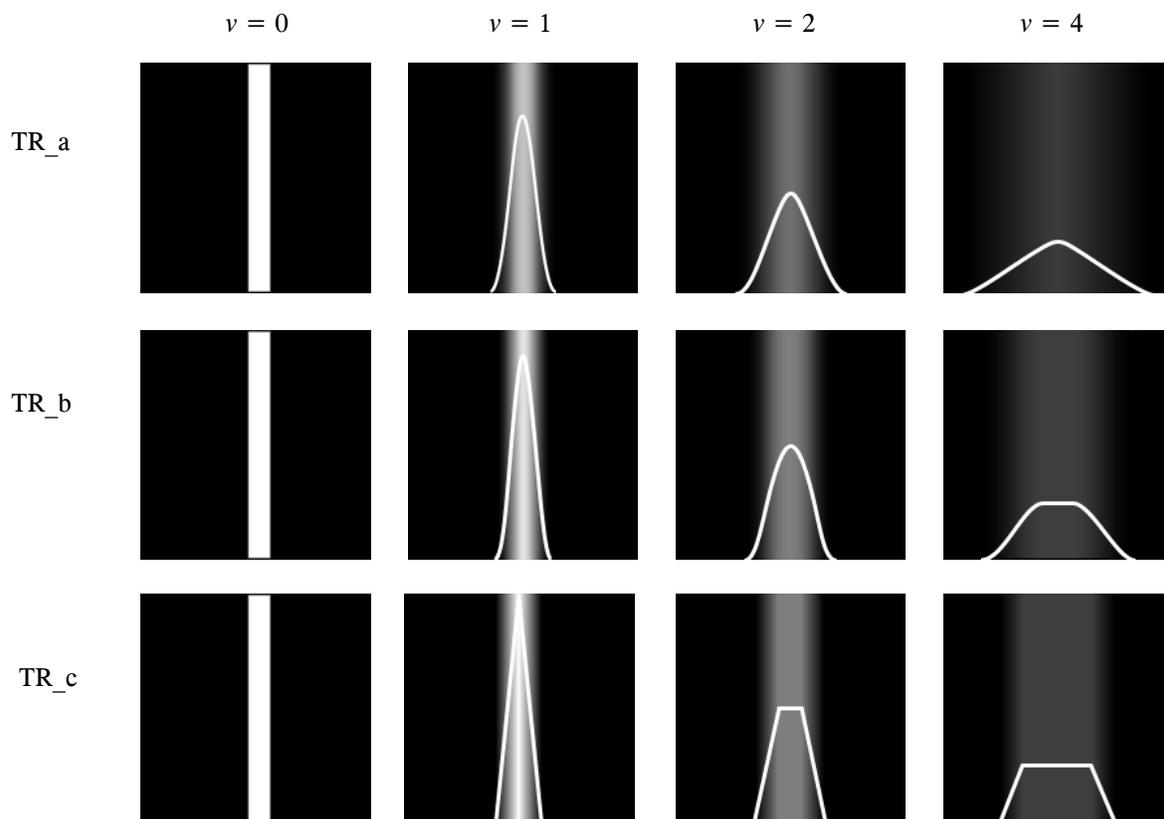
Figure 5. Predicted spatial percepts during smooth tracking of a one-pixel-wide vertical bar that is displaced 0, 1, 2, or 4 pixels to the right (v = 0, 1, 2, or 4) on successive frames of LCDs with TR_a, TR_b, and TR_c, respectively. Each predicted percept is shown as a gray-scale image. In addition, for $v > 0$, the pattern's luminance profile (relative to the luminance for v = 0) is superimposed on the gray-scale image. For v = 0, the luminance profile is a one-pixel-wide square wave.

Figure 6. Predicted spatial percepts during smooth tracking of one-pixel-wide letters that are collectively displaced 0, 1, 2, or 4 pixels to the right on successive frames of an LCD with temporal response TR_b.

We have obtained data indicating that the model's predicted percepts approximate observers' actual percepts during tracking of a moving pattern in an LCD image. The pattern consisted of two one-pixel-wide white bars separated by a single one-pixel-wide black bar; the background was black (Figure 7). In computer-generated, constant-velocity motion sequences, the pattern was successively displaced to the right by 0, 2, 4, or 8 pixels per refresh period.

The temporal response of the display was similar to TR_b, which we used to compute the predicted spatial percepts for the four velocities. We then created pixelated, and thus displayable, versions of the predicted percepts by averaging subpixel intensity values. During the experiment, the pixelated versions of the four predicted percepts were displayed above the moving pattern.

Ten observers participated in this study. Each viewed a random ordering of four repetitions of the four motion sequences. They were instructed to track the moving target and to indicate which, if any, of the four stationary patterns provided a good match. As indicated at the bottom of Figure 7, the percentage of trials on which the predicted percept was chosen varied from 100 % for $v = 0$ to 82.5% for $v = 4$. These results provide strong support for the view developed here.

SUMMARY AND CONCLUSIONS

The extended temporal response of an LCD pixel serves as a low-pass, temporal reconstruction filter. Because the temporal frequency of a drifting sinusoid is equal to the product of its spatial frequency and its velocity, the higher spatial frequencies in the spectrum of a smoothly moving pattern may be severely attenuated in an LCD image. The perceptual significance of component attenuation depends upon the visibility of the component, which depends, in turn, upon the observer's eye and head movements during the observation period. Smooth tracking of a moving pattern roughly stabilizes its retinal location. Thus, the spatial frequencies that compose the pattern all have relatively low temporal frequencies in the retinal image, typically well within the passband of the HVS.

We have used idealized temporal responses and simple stimuli to model the effects of a pixel's temporal response on display, retinal, and perceptual images. If one of these idealized responses is assumed to apply to all transitions, we can also compute the predicted percepts for constant-velocity motion of complex patterns with many gray levels. In actuality, however, the initial and target gray levels of an LCD pixel affect its transition time. This variation greatly complicates the task of predicting observer percepts during tracking of complex chromoluminance patterns.

For the idealized responses considered here, blur is a function of feature speed relative to feature size. For example, the predicted spatial percept for a two-pixel-wide bar moving four pixels per refresh period is equivalent to that for a one-pixel-wide bar moving two pixels per refresh period. The extended temporal responses of current LCDs thus make them a poor choice for applications, such as flight simulation, in which the speed of a critical feature may be high relative to its size. On the other hand, typical LCD responses may not degrade image quality for applications in which relative speed is generally low.

An issue confronting display engineers is the optimum temporal response (reconstruction filter) for moving-image applications. In our view, all other things being equal, the shorter the better. However, for some applications a brief temporal response is not needed, and reducing the response duration will generally lower the display luminance. Estimation of the temporal-filter bandwidth *necessary* to preserve critical information in flight simulation, or any other specific application, will require careful analysis of the size, contrast, and speeds of critical features in a variety of scenarios.
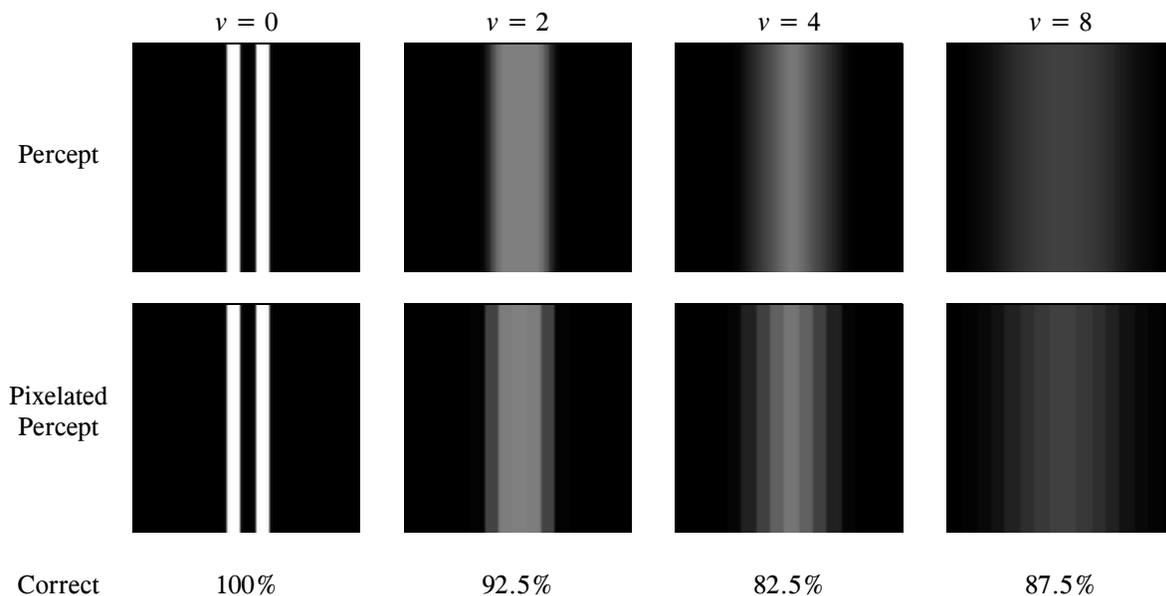
Figure 7. Predicted spatial percepts during smooth tracking of two one-pixel-wide white bars, separated by a single one-pixel-wide black bar, that are collectively displaced 0, 2, 4, or 8 pixels to the right on successive frames of an LCD with temporal response TR_b. Identification accuracy is provided at the bottom of the figure.

REFERENCES

Holst, G. C. (1998). *Sampling, aliasing, and data fidelity for electronic imaging systems, communications, and data acquisition*. Winter Park, FL: JCD Publishing & Bellingham, WA: SPIE Optical Engineering Press.

Larimer, J. (1997). [Letter to the editor]. *Information Display*, *13*(8), 95-96.

Lindholm, J. M., Askins, T. M., & Krasnicka, K. (1993). Image update rate and apparent self motion speed, *SID Digest of Technical Papers*, *XXIV*, 506-509.

Lindholm, J. M., & Scharine, A. A. (2000). Pulse-width modulation, smooth-pursuit eye movements, and moving-object perception. In A. M. Frank & J. S. Walton (Eds.), *Proceedings of SPIE*, *3968*, 107-115.

Macpherson, I. (1998, May) Trends in lowering the cost of display systems. *Royal Aeronautical Society Flight Simulation Proceedings*.

Parker, D. (1997) The dynamic performance of CRT and LC displays. In L.W. MacDonald, L.W. & A. C. Lowe, (Eds.), *Display systems*, West Sussex, England: Wiley.

Poynton, C. (1996). Motion portrayal, eye tracking, and emerging display technology. *Proceedings of the 30th SMPTE Advanced Motion Imaging Conference,* 192-202. New York: SMPTE.

Rosenfeld, A., & Kak, A. C. (1976). *Digital picture processing*. New York: Academic Press.

Watson, A. B., Ahumada, A. J., Jr., & Farrell, J. E. (1986). Window of visibility: A psychophysical theory of fidelity in time-sampled visual motion displays, *Journal of the Optical Society of America A*, *3*, 300-307.

Video Electronic Standards Association (1998) *VESA flat panel display measurement standard, Version 1* (pp. 84-85). San Jose, CA: Author.