Eye Limited Resolution Displays: On The Cusp?

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ABSTRACT

As the cost per pixel of image generation and display hardware has fallen, it has become economically feasible to consider constructing a wide field of view visual system having eye-limited resolution. Many simulation and training visual systems have been fielded over the years with resolution barely equivalent to legally blind levels of acuity, so it is certainly a welcome opportunity to improve training capability by bringing these new technologies to bear. It is hard to argue that incrementally better resolution is not always incrementally better, but trade-offs made simply to provide more pixels to the display may actually reduce overall image quality. This paper focuses on identifying those trade-offs and how they must be managed so that truly eye-limited displays can be fielded.

ABOUT THE AUTHOR

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INTRODUCTION – WHAT IS EYE-LIMITED RESOLUTION?

Most of the common definitions of eye-limited resolution are either incomplete or misapplied when used to refer to visual systems for simulation and training. Such definitions generally use descriptions of pixel format, equivalent system acuity in terms of the Snellen eye chart, or Modulation Transfer Function (MTF) of the display device. These factors are all important for defining the characteristics of an eye-limited display but each can only communicate a small part of a complex problem. It is beyond the scope of this paper to develop a rigorous definition of eye-limited resolution. Nevertheless, some discussion of the term will help to put some critical near-term issues into perspective

Operational Definition of Eye-Limited Resolution

An operational definition of an eye-limited display would be a display that enables the operator of a system to make decisions and perform tasks based upon inputs from that display to the best of their own visual ability. This definition assumes that the decisions and tasks are sufficiently difficult tests of visual acuity that even a perfect display does not guarantee success and that there is a standard level of performance that allows us to determine when the eye-limited requirements have been met.

For a display intended for tactical training, eye-limited would mean that the display allows the Warfighter to make decisions and perform tasks based on information gathered visually about air and ground targets at tactically significant ranges. A standard for performance might be successful target identification in the simulator at ranges comparable to those achieved under ideal viewing conditions in the real world.

Empirical Definitions of Eye-Limited Resolution

It is not possible to separate human visual ability from human performance at visual tasks. That is why our tools for predicting the capability of a visual display to support tactical decision-making are based on empirical methods. An example of such an empirical method is the use of Johnson's Criteria.

Although not originally developed for such application, Johnson's Criteria have become the de facto standard for relating pilot performance in the simulator to engineering definitions of display resolution. Johnson (1958) distinguished four levels of tactical decision-making, Detection, Orientation, Recognition and Identification (DORI). Johnson performed thousands of trials with many different individuals and types of targets. From these experiments he found that human performance at each of the four DORI decision-making tasks could be predicted to a high degree of accuracy from the limiting frequency of the imaging device. To determine this frequency he measured the response of the imager to simple bar patterns at the average contrast of the more complex target images. He then calculated the number of cycles at this limiting frequency that fell across the target minimum dimension in each case. His conclusion was that for a wide range of target types and target contrasts there is a fairly constant number of cycles on target required to perform the DORI decision task at each level. Although Johnson's criteria produces an intuitively acceptable result by a simple calculation, it is misapplied if target contrast and human sensitivity to contrast are not handled rigorously.

The Contrast Sensitivity Function, (CSF), is arguably the most powerful tool we have today for characterizing human visual performance and for expressing the quality of images and displays. The CSF is a measure of human visual system sensitivity as a function of spatial frequency. Although not formalized until after Johnson did his work, he incorporated it implicitly in his experiments by making sure the bar patterns used to transform his targets into spatial frequencies were at the same contrast as the target image. Ginsburg and Evans (1985) found that under their experimental conditions, "a pilot's contrast sensitivity predicts his ability to detect a small, semi-isolated air-to-ground target; the pilot's visual acuity does not"

SYSTEM CONTRAST REQUIREMENTS FOR EYE-LIMITED DISPLAYS

According to Brown and Brunderman (1985), determination of aircraft aspect at range is the most critical of visual tasks in Air Combat Maneuvering Training (ACM) training and it is as heavily influenced by contrast as by limiting resolution of the display.

Modern visual and sensor system models can predict system performance for a wide range of target contrasts by applying the Contrast Threshold Function (CTF), which is the inverse of the CSF, (Volmerhausen, Driggers,& Tomkinson, 2000). Using this method, the actual target-to-background contrast is determined. The limiting resolution of the system at that target contrast is then plotted by multiplying the sensor MTF by the actual target contrast. The point where the displayed target contrast intersects the CTF curve is projected down to the frequency axis to find the limiting frequency of the display and/or sensor for the contrast of that particular target. The range at which any given DORI task can be performed is then determined from the relationship shown in equation 1.

$$d / D = \tan(C / c) \qquad (1)$$

d= target minimum dimension
D = target range
C = cycles on target for DORI task
c = limiting frequency in cycles per degree

This method can be used to predict the performance of a display system in a simulator as well by using measured or predicted values of system MTF and target contrast in the simulator. Using this data, a target contrast Vs. spatial frequency curve can be generated and its crossover with the CTF curve appropriate to simulator brightness can be determined. The range to target at which the DORI decision task is then determined by applying Johnson's criteria of cycles on target at the limiting frequency of target contrast as shown above. In practice however, the limiting resolution for full contrast bar patterns is assumed to apply at all target contrasts while the system modulation at lower frequencies is ignored. This may lead to overly optimistic or pessimistic predictions of system performance, depending upon the shape of the Modulation Transfer Function (MTF) of the actual display used. MTF curves (Smith, 1966) are used to express displayed contrast as a function of spatial frequency for full contrast inputs.

In figure 1, the MTF curves for two different displays are shown. Display B has a lower limiting frequency but higher contrast in the mid-range of frequencies than display A. The target contrast curves shown in the figure are for display of a 30% contrast target. In the figure, display A is preferred for 100% contrast targets because the displayed contrast crosses the contrast threshold at a higher frequency. For a more realistic 30% contrast target, this threshold is crossed at a higher frequency for Display B. Johnson's criteria requires 1.4 cycles at the limiting frequency of target contrast for discerning target orientation. The limiting frequency determined by the intersection of the 30% target contrast curve with the CTF curve is shown in figure 1 to be about 15 cycles per degree for display A and 17 cycles for display B. For an air target with an 18 ft minimum dimension such as an F-15, 1.4 resolvable cycles would seen on target at about 11,000 ft on display A and about 12,500 feet on display B. The difference therefore, between the ranges at which a pilot could determine orientation of an F-15 sized target at 30% contrast would be around 1500 feet more for the display which actually has a lower maximum frequency response!

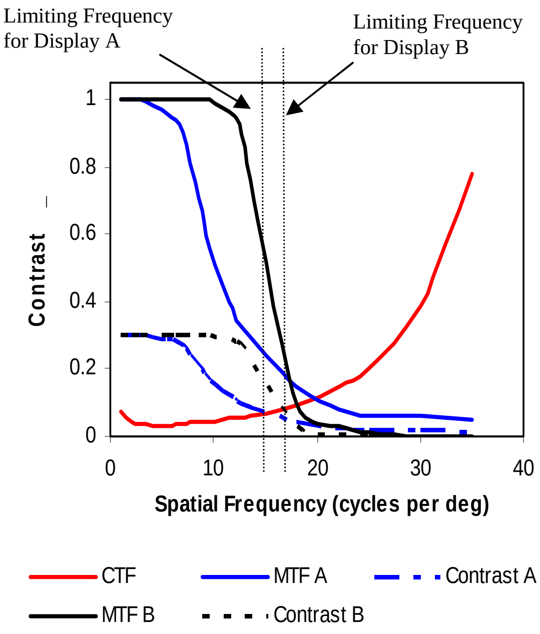

Figure 1. CTF and Target Contrast for Two Displays

The above analysis is consistent with Johnson's emphasis on limiting frequency at target contrast. Most modern sensor models as well as image quality metrics take into account more than just the limiting frequency. Low and mid-range spatial frequency above the contrast threshold has been shown to play a significant part in target identification (Driggers, Vollmerhausen, & Krapels, 2000). Improved predictions of man-in-the-loop sensor system performance has been demonstrated by targeting metrics which weight and sum the difference between the displayed target contrast and the human contrast threshold over the entire range of human visual contrast sensitivity (Volmerhausen). The human contrast threshold rises sharply as limiting acuity is approached. For a display with peak luminance of 10 ft-lamberts for example, the contrast threshold is about 30% at two arc-minutes per line pair. Displays with low modulation in the mid range of frequencies and just-noticeable modulation at 2-arc-minutes per line pair will not be capable of eye-limited performance. Displays with lower limiting resolution but higher contrast at mid range frequencies will perform better in realistic scenarios. This assessment has important implications for the selection of a display technology to use to satisfy an eye-limited display requirement. Since fixed matrix technologies such as Liquid Crystal on Silicon (LCoS) and Digital Light Processing (DLP) are known to have higher modulation in the mid range than CRT or laser projectors, they may be preferred even if they display fewer total pixels.

SPECKLE AS NOISE IN EYE LIMITED DISPLAYS

In general, noise in displays causes a reduction in contrast sensitivity. Modern digital displays do not suffer from the types of noise encountered in analog sensor displays of Johnson's day. They do however exhibit noise in the form of sampling effects (or aliasing), and fixed pattern noise. They may also suffer from speckle. Speckle has recently been analyzed as form of display noise by Gaska, Tai, & Geri (2007).

Speckle has been a problem for eye limited rear projection displays for many years. Some of the earliest published work and patents on speckle reduction were for application to microfiche and microfilm readers, (Rawson, Nafarrate & Norton, 1976; Huber, 1972). Although speckle is normally associated with laser projectors, Rawson identified problems of reduced resolution and eye fatigue encountered on microfiche readers as being due to speckle. Microfiche readers were designed to have eye-limited resolution at a close viewing distance. In order to do this they needed an optical system with high magnification to achieve maximum density for film based information storage. The rear projection screens used on microfiche readers needed to have high resolution and contrast to resolve fine characters. These conditions, very similar to those typical on rear projected simulator displays, are ideal for observing speckle. Rawson also identified the trade-off between resolution and speckle reduction; except for moving screen methods, attempts to reduce speckle at the screen generally resulted in reduced resolution and brightness.

More recently, the problem of speckle on rear projection displays using modern arc-lamp based fixed matrix projectors has been recognized. Goldenberg, Huang, & Shimzu (1997) showed that the introduction of objectionable speckle when arc lamp illuminated LCD projectors replaced CRT projectors in high resolution rear-projected displays could be explained as a result of partial coherence. The van Cittert Zernike theorem quantifies the spatial coherence of an extended source in terms of its spatial extent (Born and Wolf, 1981). For a circular aperture such as the exit pupil of a projection lens, the lateral coherence width can be shown to be:

$$L_t = 1.22(\lambda / \theta_S) \qquad (2)$$

where θ_S is the angle subtended by the exit pupil as seen from the display screen.

As shown in Goldberg et al. (1997) the high magnification and small lamp arcs required to project large images from small format micro displays result in large coherence widths. Depending upon the characteristics of the screen, this high degree of coherence can create significant speckle.. High resolution screens are more susceptible to speckle because the diffusing elements in the screen must be small to provide high resolution, but large relative to the coherence width of the projector. Table 1 modifies the analysis in the Goldberg et al (1997) to be representative of rear-projected displays used on tactical aircrew trainers. At the 1-meter viewing distance used in the calculations for Table 1, a one arc-minute pixel is about 290 μm on the screen. Speckle is minimized when the scattering elements of the screen are much larger than the coherence width.

This is easily achieved with CRT displays but becomes more difficult when coherence width approaches pixel size.

Table 1. Comparison of Two Projector Technologies and Coherence Width on a Rear Projected Screen (per Goldenberg)

	9" CRT Projector	**.9" Diagonal Light Valve**
Screen Width (inches)	54	54
Object Width (inches)	6	0.72
f/#	1	2.7
Magnification	9.0	75.0
Pupil Size (inches)	4.3	0.2
Coherence Width (μm)	6.0	135.9

Several researchers have attempted to quantify the effect of speckle on resolution in coherent imaging systems. Kozma and Christensen (1976) reported that the effect of speckle was much worse for trying to identify an object in a continuous tone image than for resolving a high frequency grating pattern. Artigas and Felipe (1994) found a significant reduction in contrast sensitivity at all spatial frequencies. In addition, they noticed that when speckle is present contrast sensitivity does not improve at higher illumination levels, as is the case for non-coherent imaging systems

For the type of projectors likely to be used on eye limited displays, the illumination will probably not be fully coherent and the effects on resolution will not be as severe as for fully developed speckle. Gaska et al. (2007) looked at the reduction in contrast sensitivity caused by speckle in a partially coherent imaging system and confirmed Kozma's (1976) result that speckle effects CSF at all frequencies. They also identified and proposed a metric for speckle that accurately predicts its effect on contrast sensitivity.

MOTION REPRODUCTION FOR EYE-LIMITED DISPLAYS

Although it is generally accepted that visual acuity decreases with target motion, there is evidence that the loss is not significant up to about 20 degrees per second (Ludvigh and Miller, 1958). In order to be considered eye limited then, it would seem that a display would need to reproduce motion with minimal loss in sharpness for motion rates up to 20 degrees per second.

A widely accepted measure of motion reproduction for digital displays is the Moving Picture Response Time (MPRT). Someya (2005) reported a high degree of correlation between MPRT and subjective impressions of motion blur. The MPRT is determined by direct measurement of the blur width of the edge of a test pattern as captured by a pursuit camera tracking its progression across the display.

The MPRT metric has reduced the specification for quality of motion reproduction for LCD and LCoS display types to a single number, independent of motion rate. A single number representation is possible because the blur width is proportional to the motion rate.

$$\text{MPRT} \propto (\text{Blurred Edge Width} \div \text{Motion Rate}) \quad (3)$$

The only way to reduce motion blur is to reduce the fraction of the time that the pixels representing the moving edge are illuminated in their fixed locations during each image frame time. This fraction is known as the hold time which is related to motion blur by the relation:

$$B = uphT \qquad (4)$$

where:

B = blurred edge width (pixels)

u = edge motion rate (degrees per second)

p = pixel pitch (pixels per degree)

h = hold time (fraction of frame time)

T = frame time(seconds)

For displays with the same hold time, motion rate and frame time, equation 4 shows that the blur width in pixels will be proportional to the pixel pitch. Therefore it does not appear that a single value of hold time would be appropriate for all display resolutions. In order for motion blur reduction mechanisms to limit blurred edge width to a certain number of pixels, hold time must be reduced as the pixel resolution is increased.

Winterbottom, Geri, Eidman & Pierce (2007). associated perceptual measures of motion blur with LCoS projector hold time. Pilot subjects viewed aircraft targets and terrain scenes with controlled motion rates on a representative simulator display with varying amounts of hold time.

Among pilot assessments of moving image quality were that motion blur on target images was significant when the target motion rate was 10 degrees per second for 50% hold time and 20 degrees per second for 25% hold time. The pixel pitch of the LCoS display used in these tests was about 18.6 pixels per degree. From equation 4, we find the threshold for blur to be about 1.5 pixels in either case. 1.5 pixels is hardly more than ½ of a line pair for an antialiased display, indicating that the pilots were able to detect very minimal loss of resolution relative to the static case. Assuming the blur threshold in pixels is the same for a display with 60 pixels per degree as it was for the display with 18.6 pixels per degree, a hold time as low as 16% may be required to maintain moving image sharpness for motion rates of 10 degrees per second. The loss of illumination due to shorter hold times will become more significant if these hold-type displays are to be used in eye limited applications.

DISCUSSION

Significant trade-offs in performance have been identified here which may cause display resolution to fall short of eye-limited even when adequate pixels-per-degree requirements have been met. These trade-offs include:

- Contrast Vs. Resolution – Contrast requirements of the human eye increase as eye-limited frequencies are approached while display MTF tends to decrease. Trade-offs that reduce mid-frequency range contrast in favor of limited resolution may be unacceptable.

- Brightness Vs. Motion Reproduction - Brightness loss necessary to meet the extreme demands of full motion reproduction at eye-limited resolution may be result in reduced capability to perform other training tasks.

- Speckle Reduction Vs. Resolution - Methods that would completely eliminate speckle may not allow the high contrast required for eye-limited performance to be achieved at high spatial frequencies.

More research will be necessary to better quantify the optimum trade-offs for a successful eye-limited visual display for tactical training.

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