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14. ABSTRACT The work described here was part of the Operational Based Vision Assessment (OBVA) program, the goal of which is to develop an eye-limited flight simulation laboratory to establish the relationship between clinical measures of visual capabilities and performance in simulated operationally relevant tasks. Because the design of such a high resolution flight simulation laboratory is ground breaking, and because angular pixel size is such a large cost driver, we used psychophysical methods to determine the pixel size specification. In the first series of experiments, the angular size required to identify the orientation of a triangle was estimated using angular pixel sizes ranging from 0.11 arcmin/pixel (eye-limited condition) to 4 arcmin/pixel (display-limited condition). From these data, along with an analysis of projector cost versus performance improvement, we concluded that 0.5 arcmin is a practical display pixel size specification. In the second experiment, we used a 0.5-arcmin display and a MetaVR IG to measure the range required to identify the aspect of an F-15 aircraft and found a strong correlation between the simulator results and clinical measures of acuity. Finally, because wide field of view simulators require multiple projectors and it is possible that multi-projector blending may lower performance, we also measured triangle orientation identification performance using the Survivability Performance Laboratory developed by Boeing. We found that current blending technology is sufficient to yield near eye-limited results in the blend zones. Taken together, these studies suggest that 0.5 arcmin/pixel is a practical specification for the OBVA simulator in that it provides a good cost benefit ratio and can be used to quantify the relationship between clinical measures of visual capabilities and performance in simulated operationally relevant tasks.				
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PIXEL SIZE REQUIREMENTS FOR EYE-LIMITED FLIGHT SIMULATION

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ABSTRACT

The work described here was part of the Operational Based Vision Assessment (OBVA) program, the goal of which is to develop an eye-limited flight simulation laboratory to establish the relationship between clinical measures of visual capabilities and performance in simulated operationally relevant tasks. Because the design of such a high resolution flight simulation laboratory is ground breaking, and because angular pixel size is such a large cost driver, we used psychophysical methods to determine the pixel size specification.

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Taken together, these studies suggest that IMAGE0.5 arcmin/pixel is a practical specification for the OBVA simulator in that it provides a good cost benefit ratio and can be used to quantify the relationship between clinical measures of visual capabilities and performance in simulated operationally relevant tasks.

INTRODUCTION

The display resolution, or angular pixel size, required to support certain critical flight simulation tasks, such as air-to-air target identification, has been subject to significant debate. The work described here is part of the Operational Based Vision Assessment (OBVA) program, the goal of which is to develop a high fidelity flight simulation laboratory to establish the relationship between clinical measures of visual capabilities and performance in simulated operationally relevant tasks. In order for these relationships to be meaningful, we must ensure that the performance measured in the simulated operational task is limited by the observer's visual system and not the display.

One of the more important clinical measures of visual capability is acuity. In order to accurately compare clinical measures of acuity with acuity-dependent operational tasks, we must ensure that the pixel size of the simulation display is small enough to accurately represent

spatial stimulus features whose size is near an observer's acuity limit. In general, if the pixel size relative to the feature to be displayed is sufficiently small, the rendered image will be perceptually equivalent to a continuously sampled real-world image. We will use the term eye-limited to refer to a display that meets this condition. However, reducing pixel size increases the number of pixels (and projectors) required to fill a fixed field of view and is, therefore, a major cost driver. Thus we must generate simulator specifications that approach but do not exceed those required to yield eye-limited performance measures. This paper reports on the procedures used to generate specifications that can meet this requirement. The data generated by the OBVA flight simulation laboratory will ultimately be used to update Air Force vision standards to refine vision screening methods and retention criteria.

BACKGROUND

As an example, we start with the goal of evaluating an observer with 20/10 acuity. As shown in figure 1, the height of one line of a 20/10 optotype is 0.5 arcmin and, if the lines of the optotype are aligned with the pixel grid, the 20/10 optotype can be accurately represented using a 0.5 arcmin display.

However, if the optotype is rotated or translated it will most often fall off the pixel grid and sampling artifacts will distort the rendered image (Figure 2a). We can reduce the effects of spatial sampling errors by decreasing pixel size (2b). We can also reduce the perceptual saliency of spatial sampling errors using antialiasing techniques (2c, 2d), which remove spatial frequencies that are higher than Nyquist sampling frequency. However, antialiasing can reduce image contrast and alter target size.

The most common method used to compute resolution is the Kell factor which is the ratio of the effective resolution of a device relative to the Nyquist frequency based value. Models based on the consideration of position (or phase) dependent sampling artifacts typically yield Kell factors of 0.707 [1]. Using this value, the pixel size required for the 20/10 optotype would be $0.5 \times 0.7 = .35$ arcmin

While Kell factor metrics can serve as guidelines for design of the OBVA simulator, we concluded that additional research was needed. First, other simulator artifacts, in addition to sampling artifacts, could influence observer performance in the simulator. Second, we wanted to estimate the magnitude of the performance loss

as pixel size was increased beyond the Kell-factor-generated specification. Finally, we wanted to estimate how performance was influenced by stimulus contrast and background luminance. Because of these concerns, we used psychophysical methods to characterize deviation from eye-limited performance as pixel size increased.

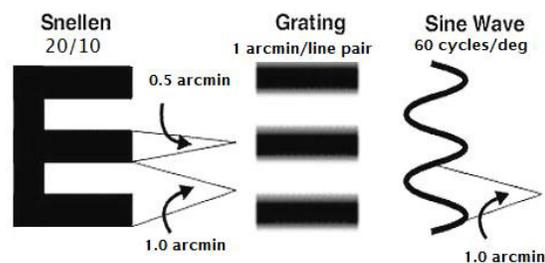


Figure 1.

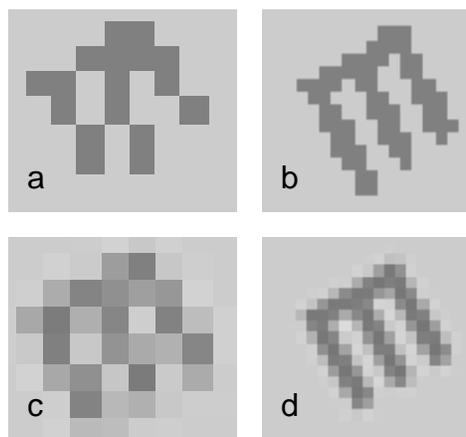


Figure 2.

EXPERIMENTS

Triangle Orientation identification and Pixel size

The magnitude of sampling artifacts will depend on the rendered target and its position with respect to the pixel sampling grid. We chose to use an equilateral triangle as our test target for several reasons. First, an equilateral triangle can never be aligned to an orthogonal, rectilinear sampling grid such as a display and will therefore generate sampling artifacts at all positions. In addition, an equilateral triangle has been successfully used to study spatial sampling artifacts generated human-in-the-loop military sensors [2, 3]. Finally, because a triangle is an important graphics primitive used in 3D simulation software, it is particularly relevant to examining the pixel size and performance trade space in the OBVA simulator.

Methods

Five observers with Snellen acuities that ranged from 20/10 to 20/17 participated in the experiment. They were asked to identify the orientation of equilateral triangles whose apex was randomly pointed either up, right, left or down. The QUEST procedure [4] was used to estimate the threshold size of the triangle required for 0.72 orientation identification accuracy. Triangle size was manipulated by down sampling a 400 pixel (base length) triangle without pre-sample filtering (no antialiasing).

On each stimulus presentation trial, the position of the triangle was randomly shifted by $\frac{1}{2}$ pixel along the horizontal, vertical and two diagonal axis using bilinear interpolation (similar to full-scene anti-aliasing). Pixel size was increased using integer pixel replication (native pixel size = 0.11 arcmin at the 6 m observer distance).

An imaging photometer (Lumetrix 500A) was used to measure the average luminance of the triangle (L_t) and background (L_b) for a range of triangle RGB values, triangle sizes and pixel sizes. These data were used to hold triangle contrast, $(L_t - L_b) / L_b$, constant for the different triangle and pixel sizes used in the study (for a given contrast condition).

Results

The colored symbols in Figure 3 plot the threshold target size for individual observers (A-E) as a function of angular pixel size. For the eye-limited measurement (0.11 arcmin/pixel) there is a range of performance that reflects the observers' acuity. However, when threshold target size is measured using 1.8 arcmin/pixel triangles, the range of thresholds is reduced and the lowest acuity observer (E) has the second best measured performance. The 1.8 arcmin/pixel condition illustrates display-limited performance and if we used this pixel size in the OBVA simulator we would not be able to relate clinical measurements of acuity and performance in simulated operationally relevant tasks.

An explanation of this result is that, as pixel sizes become large, the ability to perform the orientation discrimination task becomes less limited by an observer's acuity and more limited by the loss of orientation information in the rendered image. For a constant triangle size, as pixel size is increased, orientation information decreases (as illustrated by the images above the horizontal axis in Figure 3). When the pixel size is larger than the triangle, the "triangle" is rendered as square pixel and contains no orientation information. The finding that the

measurements cluster along the 3.0 pixels/triangle line suggests that, regardless of an observer's acuity, they need about 3 pixels across the base of a triangle (a 3 by 3 grid) to preserve threshold orientation information. This is illustrated by the images below the dashed line in Figure 3.

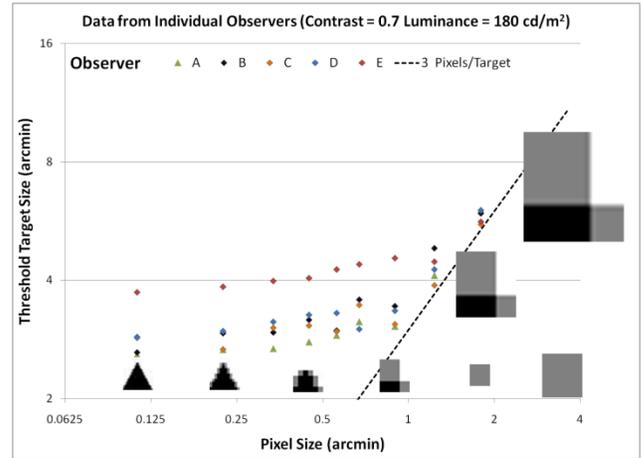


Figure 3. Individual data. The images show triangles rendered using various pixel and triangle size. In these figures the apex of the triangle was shifted by $\frac{1}{2}$ pixel to the left of monitor sampling grid.

Figure 4 shows the average results (and 1 standard error of the mean) for the four highest acuity observers (A-D). For this high acuity group, the mean Snellen fraction was 20/11.5. The solid curves plots threshold, T , as a function of pixel size and were generated by minimizing the squared difference between the data and the Euclidean norm of the eye limited threshold T_{EYE} and the display limited threshold $T_{DISPLAY}$,

$$T = \sqrt{T_{EYE}^2 + T_{DISPLAY}^2} \quad \text{Equation 1.}$$

where $T_{DISPLAY} = M \cdot PixelSize$.

The fit parameters are shown in Table 1. Note that the slope parameter M is the same for all conditions.

Condition	T_{EYE} arcmin	M pixels/triangle
$L = cd/m^2, C = \text{contrast}$		
$C = 180, C = -0.7$	2.68	2.78
$L = 180, C = -0.1$	5.12	2.78
$L = 2.2, C = -0.7$	5.71	2.78

Table 1.

For all conditions, as pixel size becomes larger, threshold triangle size increases relative to the eye-limited measurements. At smaller pixel sizes, the rate of increase is small. At larger pixel sizes, the rate of deviation increases and data points for all conditions approach a line with a slope of 2.78 pixels per triangle (dashed line).

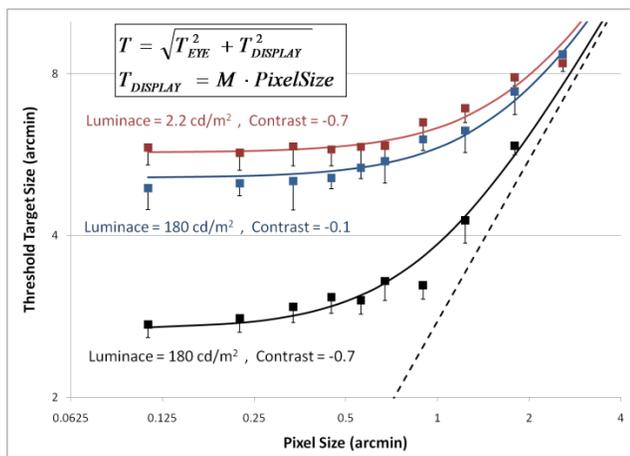


Figure 4. Average data for the four highest acuity observers (A-D)

The data represented using black symbols in figure 4 represents the “worst case” condition – high luminance, high contrast targets and high acuity observers. For this condition, we measured a small deviation (approximately 11%) from eye-limited performance using a 0.5 arcmin pixel size. As the contrast of the target is reduced, holding luminance constant, (blue symbols) the eye-limited threshold triangle size is increased and the pixel size at which performance begins to deviate from the eye-limited case also increases. These shifts are even more pronounced for the low luminance, high contrast condition where a 0.5 arcmin pixels size produces performance that is not measurably different from the eye-limited case.

Under the worst case conditions, the model fit shows an 11% deviation from eye-limited performance using a 0.5 arcmin pixel size. Note that the curve also deviates from the eye limited line for a 0.35 arcmin pixel size (the sampling Kell factor estimate) and that there is approximately a 3% deviation for a 0.25 arcmin pixel width. Because the required number of pixels is, with a fixed field of view, inversely proportional to pixel area, a 0.25 pixel size would quadruple the cost relative to a 0.5 arcmin specification and the added cost would not be justified given the small performance benefit.

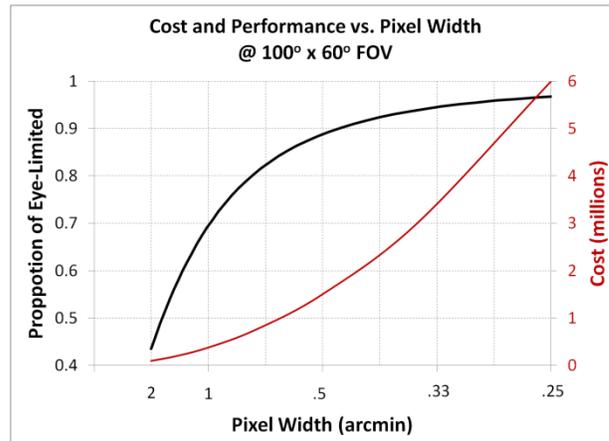


Figure 5. Cost and performance vs. pixel width. The black curve (performance relative to eye-limited, Teye/ T) was computed using equation 1 and the high luminance, high contrast parameters in table 1. The red line estimates the current cost of tiling multiple 8-10 megapixel projectors to achieve a 100° by 60° field of view.

In figure 4, we illustrate this relationship by showing the performance (relative to eye-limited) and the estimated current cost of tiling multiple 8-10 megapixel projectors to achieve a 100° by 60° field of view. A 0.5 arcmin pixel size produces a performance that is about 89% of eye-limited with a cost of \$1.5 million whereas a 0.25 arcmin/pixel size would cost \$6 million for 97% of eye-limited performance. Using this analysis we concluded that 0.5 arcmin is a practical, albeit not perfect, display pixel size specification for OBVA.

Correlation between visual acuity and performance in a simulated operational task

As stated in the introduction, the purpose of these experiments is to generate a pixel size specification that will allow meaningful comparisons between clinical measures of acuity and performance in simulated operationally relevant tasks. In this experiment, we use a 0.5 arcmin/pixel simulator display to measure the range required to identify the aspect of an F-15 aircraft and compare the results to the acuities of the same observers measured using eye charts.

Methods

The simulator was composed of a MetaVR IG and Sony SRX-S110 8 megapixel projector. The output of the projector was front-projected onto a flat screen and

adjusted to produce a $34^\circ \times 22^\circ$ field of view at a 4 meter viewing distance. The angular pixel size at the target location was 0.5 arcmin. The sky luminance in the vicinity of the plane was 198 cd/m^2 which is slightly higher than the 180 cd/m^2 used in the high luminance triangle experiments.



Figure 6.

Six observers with Snellen acuities that ranged from 20/11 to 20/17 (decimal equivalent 1.9 to 1.2) participated in this study. In this air-to-air scenario, subjects were asked to determine if the nose of an F-15 aircraft was facing toward or away from the ownship. Figure 6 illustrates the target used at different aspects and ranges. However, in the experiment, only a single aircraft was presented at the center of the display. The target aircraft was presented statically for one second on each trial and the QUEST procedure was used to estimate the distance required for 0.82 identification accuracy.

Results

Figure 7 shows that individuals with higher acuities tend to identify the aircraft aspect at larger distances ($R^2=0.91$). This is the expected result if performance in the simulator task is limited by visual capabilities and not the resolution of the display. If pixel size was increased and the system became more display limited, the range of aspect identification performance across observers (and, the correlation between operational and clinical measurements) would decrease. For display limited pixel sizes the correlation would approach zero.

It should be noted that, all of the observers in this experiment have measured acuities that exceed the current Air Force standard of 20/20 (decimal 1.0) and if we can relate acuity and operational performance over this small range we will certainly be able to characterize this relationship for a range that includes lower acuity observers.

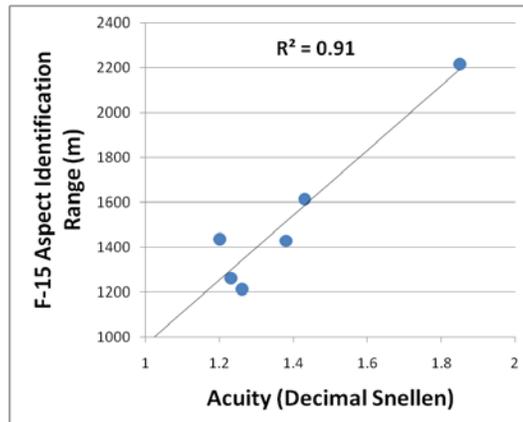


Figure 7. Aspect identification performance vs. acuity.

Multi-Projector Simulator Evaluation

Wide field of view simulators require multiple projectors and it is possible that multi-projector blending may lower performance. For this reason, we also measured triangle orientation identification performance using the *Survivability Performance Laboratory* developed by Boeing.

Methods

The visual simulator used 8 Barco LX-5 10 megapixel projectors to generate a $120^\circ \times 30^\circ$ field of view on a 25 foot radius cylindrical screen. This design resulted in an average pixel size of 0.4 arcmin. Four observers with Snellen acuities that ranged from 20/13 to 20/17 (mean = 20/14) were used in this evaluation.

Triangle size thresholds were measured with the observer at the design eye-point (25 feet) using high (-0.85) and moderate (-0.14) contrast triangles that were positioned within and outside a two-projector blend zone. These results were compared to those obtained using a flat panel LCD with an angular pixel size of 0.125 arcmin (eye-limited condition). For all conditions, the background luminance of the monitor and simulator was about 22 cd/m^2 .

Results

As shown in Figure 8, the monitor (eye-limited) threshold sizes were smallest followed by no blend and blend conditions. However, variation across display conditions was not significant using a two-factor analysis of variance (Table 2). As expected, the contrast factor was statistically significant.

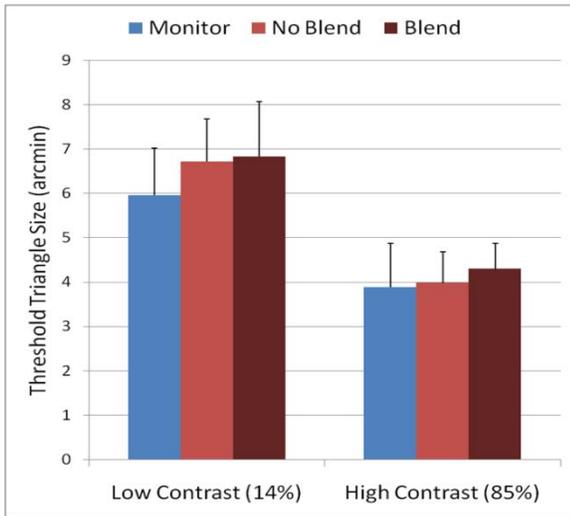


Figure 8.

ANOVA

Source of Variation	df	F	P-value
Display Condition	2	3.786	0.209
Contrast	1	158.027	0.006

Table 2.

These results suggest that current blending procedures can be used to produce near eye-limited performance within the blend zones. However, the background luminance in this study was 22 cd/m² and the desired high luminance of the OBVA simulator is about 200 cd/m². As shown in Figure 4, the eye-limited triangle size and pixel size required for a criterion deviation from eye-limited performance decreases as luminance is increased. Therefore, we would expect a larger difference between the monitor and simulator values as luminance is increased. Further study is required to estimate the magnitude of this difference

CONCLUSIONS

This research illustrates how psychophysical methods can be used to derive angular pixel size design specifications for an eye-limited simulator. We started by measuring a performance versus pixel size trade-space. We chose a 0.5 arcmin pixel size, which, while not perfectly eye-limited, provided a better cost benefit ratio than smaller pixel sizes. We then tested this specification in a simulator using military targets and found a strong correlation between the simulator results and clinical measures of acuity. Finally, we compared performance using a multi-projector

simulator with that of an eye-limited monitor and concluded that current blending technology may be sufficient to yield eye-limited results in the blend zones, although we have yet to test this using the provisional high luminance specification of the OBVA simulator (about 200 cd/m²)

Although using psychophysical methods to design simulator specifications is labor intensive relative to simple computational metrics, we chose this approach because the OBVA simulator is relatively unprecedented and we wished to carefully map out the cost vs. performance trade-space in order to choose the most cost effective display resolution specification. By choosing a pixel size that, while not truly eye-limited, provides usable correlations between clinical measures of acuity and operational tasks we achieve substantial cost reductions. The data also show that a simulator designed for mesopic or night operations could achieve even greater savings.

These techniques will also prove useful as we finalize the design of our simulator and determine which vendors will supply the components. This procedure will be less labor intensive because we do not have to evaluate the full trade space. In addition to displays, we can also use these methods to evaluate IGs and multi-projector warping and blending solutions.

Finally, although the purpose of this research was specific to generating specifications for the development of the OBVA laboratory, we believe that the data that has been generated, and the percent of eye-limited metric used here could be relevant to other visual systems, such as those used by the Air Force mission training center. For example, the data from this analysis shows that performance increases from approximately 45% of eye-limited performance at 2 arcmin/pixel to approximately 70% of eye-limited performance at 1 arcmin/pixel. Of course the cost quadruples in increasing resolution from 2 arcmin/pixel to 1 arcmin/pixel, but the gain in performance is largest on this part of the curve illustrated in Figure 5. Increasing resolution beyond 1 arcmin/pixel results in diminishing performance returns with rapidly increasing cost.

These studies suggest that a 0.5 arcmin pixel width specification is sufficient to generate meaningful comparisons between simulator based measurements of performance and clinical measurements of visual capabilities. However, it is possible that larger pixel sizes could yield similar results with greater cost savings. For

example, in the triangle orientation experiment, triangle size was manipulated by nearest-neighbor down-sampling of a 400 pixel (base length) triangle. It is possible that pre-sample anti-aliasing filters could increase the pixel size required for a criterion deviation from eye-limited performance.

In addition, the study used a single triangle presented on a uniform background whereas simulated military targets will most often consist of multiple polygons with multiple luminance values. These targets will produce contrast near the target features used to perform the visual task and it is well known that thresholds for identifying a target embedded in a scene with local contrast variations are higher than those measured on a uniform field. This effect, often referred to as masking or crowding, will increase the eye-limited size, and, as shown Figure 4, this will also increase the pixel size required for a criterion deviation from eye-limited performance.

In summary, these studies suggest that the 0.5 arcmin specification is sufficient but further research is required to determine if it is necessary. Because we are nearing the build phase of the project we have settled on a somewhat conservative specification.

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