EFFECTS OF LUMINANCE, CONTRAST, HOLD TIME, ANGULAR VELOCITY, AND PITCH, ON SIMULATED AIRCRAFT IDENTIFICATION RANGE

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ABSTRACT

This paper summarizes the findings from the second of two human factors evaluations conducted as part of the Immersive Display Evaluation and Assessment Study (IDEAS) program. In this evaluation experienced USAF F-16 pilots discriminated and positively identified distant fighter-sized aircraft. On each trial the ownship rapidly approached a pair of aircraft, one "friend" and one "foe," and the observers designated the foe as quickly and accurately as they could.

The first evaluation focused on the variables expected to be primary determinants of motion-induced blurring (e.g., hold time and angular velocity) for sample-and-hold display systems. This second evaluation filled out the data set required to validate a more complete model of the design variables expected to mediate task performance for very high resolution display systems. In this evaluation, task performance was measured as a function of 200 combinations of five practical display system design variables including: display luminance, display contrast, pixel hold time, angular velocity of the image, and pixel pitch (resolution).

Prior to conducting the evaluation, a computational model was prepared and used to make quantitative predictions of the effects of these design variables. The correlation between the model predictions and the results of this evaluation was high (e.g., $R^2 = 0.91$, $p < 0.001$, *199 df). The model parameters have not yet been optimized to the data collected in this evaluation.*

A significant benefit provided by the model is the quantification of the interactions among the design variables. Thus, the model is useful for examining the impact of design trades among the variables that affect task performance.

A summary of this evaluation was published at the IMAGE 2011 conference. The present report contains more of the details of the evaluation and a table of the mean response data for the 200 experimental conditions.

INTRODUCTION

This paper addresses the effects of five practical display design variables on the range at which pilots can identify aircraft: a visual task of great importance in the training of Air Force pilots. Few would argue that target identification range is not dependent on display resolution. The 5 m minimum dimension of a fighter sized aircraft viewed at a range of 3 km (2 nm) subtends an angle of 5.7 arcmin. At the typical resolution of training display systems of the past decade (e.g., pixel pitch = 2.5 arcmin) the minimum dimension of the aircraft would be 2.3 pixels, far less than the 13-ish pixels recommended by Johnson[8] for target identification tasks.

The use of Johnson's criteria assumes the threshold visual angle for target identification scales linearly with system resolution. Since Johnson's original paper, many similar studies have confirmed the utility of this simple method of analysis[5]. However, it has been pointed out that resolution requirements produced by the method are not precise as they depend on additional factors such as stimulus duration, background clutter, and observer capability[3].

Two recent works have confirmed the linear scaling assumption for the case of relatively coarse pixel pitch where performance is limited primarily by display resolution. However, as pixel pitch is reduced performance becomes primarily limited by observer capability as illustrated in Figure 1. The upper curve in the figure shows the data from of Gaska et. al.[6] for a triangle orientation discrimination task. The lower curve shows the results of one of our preliminary evaluations for a Landolt C orientation discrimination task.

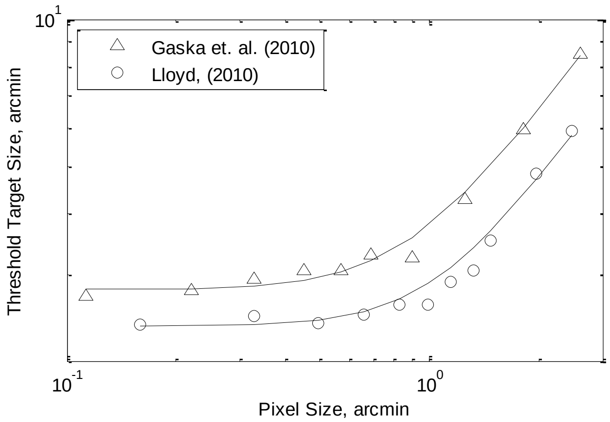

Figure 1. Threshold target size as a function of pixel pitch for triangle and Landolt C orientation discrimination tasks. Threshold target size is proportional to pixel pitch for pitches larger than about 1 arcmin. Threshold target size is constant for pitches below about 0.6 arcmin where it is mediated by observer acuity.

For pixel pitches larger than about 1 arcmin, these data show threshold target size is proportional to pixel pitch. In other words, the observer needs some minimum number of pixels across the target to accomplish the task. For pixel pitches below about 0.6 arcmin, pitch has no effect as performance is limited not by the display system but by the capability of the observer. For the case of static images, the expected effects of pixel pitch are by now well studied. In contrast, very little data are available which indicate how visual performance is affected by pixel pitch in the presence of image motion.

Motion Induced Blur

Motion induced blur has been recognized as a significant limitation of the "sample and hold" projectors (e.g., LCD, LCoS, and DLP) which are now being installed in many simulation trainers. Motion induced blurring occurs when an observer visually tracks a moving target that is drawn using pixels that remain on for a significant fraction of the frame time. Much research pertaining to the causes and remedies for motion induced blurring has been completed by researchers supporting the entertainment and advertising industries. Several recent papers provide overviews of the motion picture response time (MPRT) and related metrics and available methods for measuring the data required for computing them[2, 4, 14, 15, 16].

The International Committee for Display Metrology is expected to release their Display Measurement Standard[23] in the summer of 2011. This standard addresses the MPRT and related measures as well as several methods for their measurement. Concurrently with the development of these methods, the Air Force Research Laboratory (AFRL) in Mesa has conducted a series of evaluations that have focused on correlating a similar metric (hold time) with perceived blur and task performance[5].

Our preliminary evaluation of the standard indicates the measurement procedure should be no more complex than the AFRL-developed procedure. A strong correlation between the MPRT and hold time metric is anticipated as the MPRT is a measure of hold time convolved with the temporal step response of a display. In a future paper, we plan to address the relationship between MPRT and hold time more rigorously and expect to develop a conversion between the two methods of characterizing motion induced blurring so these literatures can be compared.

Pixel Hold Time

Hold time refers to the duration of time a pixel (and illumination system) is turned on at the commanded state during each frame period. A decade ago researchers at the AFRL developed a simple procedure for measuring hold time in which a fast photo sensor is used to measure a small portion of the screen. The luminance response of the display system is measured for a test pattern that alternates between full on and full off every other frame. The hold time is simply the width of the "on" time of the display device where width is defined using 50% peak luminance points on the measured curve. In the language used by the broader display community, the periodic temporal impulse response (TIR) of the display system is measured using a stationary pattern and stationary sensor. Hold time is computed as the half maximum width of the measured impulse response.

Correlation of Hold Time and Perceived Blur

A number of authors have demonstrated a strong correlation between MPRT and perceived blur[4]. Similarly, the data from a series of six evaluations at the AFRL demonstrate the strong relationship between hold time and perceived blur (Figure 2) as measured using a 2-line test pattern for which observers adjusted the width of the gap between the lines[5]. The AFRL evaluations indicate this relationship holds over a range of display technologies including CRT, LCoS, and DLP projectors.

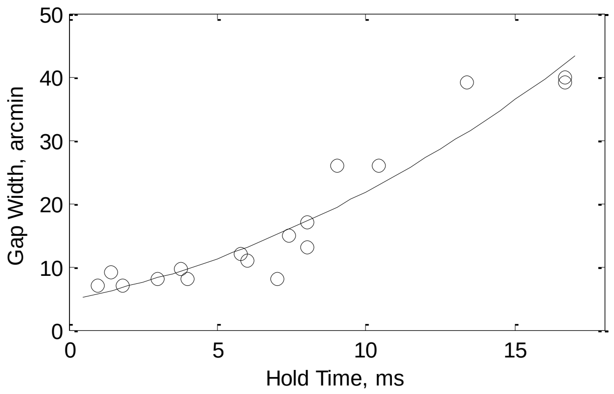

Figure 2 Gap Width measured using the 2-line perceptual blur test, as a function of Hold Time, showing a correlation of $R^2 = 0.91$ ($p < 0.001$, 16 df). Data are from six separate evaluations as summarized in Figure 8.3 of Gaska, et. al (2010) for a line speed of 40 deg/sec.

Correlation of Hold Time and Task Performance

While we expect hold time to correlate well with training task performance, relatively little work has been done to demonstrate this correlation. In a study conducted by Winterbottom et. al.,[18] aircraft roll detection threshold was measured as a function of hold time. The correlation obtained in this evaluation was moderate but statistically reliable ($R^2 = 0.4$, $p = 0.03$, 10 df). To date we have found no other papers describing evaluations in which task performance was measured as a function of hold time or MPRT. Thus, we do not yet have sufficient data to recommend the use of the hold time metric (or the MPRT) for the evaluation of simulation training display systems on the basis of task performance.

Model of Task Performance

In early 2010, work restarted on the development of a computational model of visual performance for display systems. This model is an extension of decades of image quality metric development work by Snyder, Barten, and their colleagues during the 80s and 90s[1, 11, 12, 13]. An overview of this model is provided in a paper presented at the IMAGE 2011 Conference[10].

At the heart of the task performance model is the calculation of the limiting resolution of the display system. A primary input to this calculation is the modulation transfer function (MTF) of the display system which is typically computed from a measured line spread function (LSF) of the display (See Figure 8 for example). Other inputs include angular pixel pitch, hold time, target velocity, contrast, luminance, noise, and anti-aliasing. The parameters MTF, pixel pitch, hold time, target velocity, contrast, and anti-aliasing are used to compute the system MTF. The parameters luminance and noise are used to compute the contrast threshold function (CTF) of the observer. The crossover point of the system MTF and CTF is used to determine the limiting resolution of the display system which is used in the calculation of identification range.

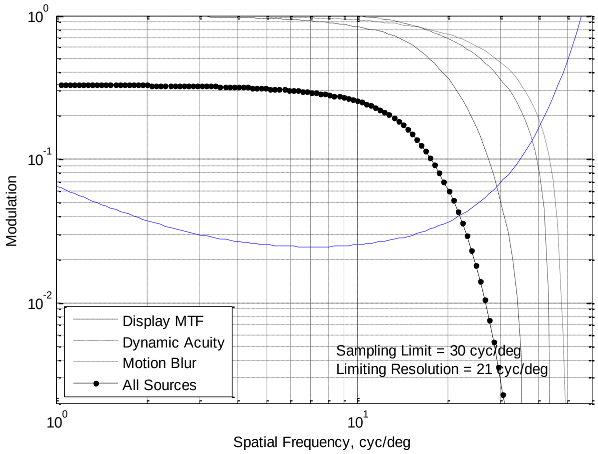

Figure 3. Illustration of the essential calculations performed within the task performance model. In this example the limiting resolution of the system is 21 cyc/deg for a pixel pitch of 1 arcmin, hold time of 8 ms, velocity of 5 deg/sec, luminance of 10 fL, and target CR of 2.2:1.

METHOD

Participants

A total of twelve male observers participated in this evaluation. Nine of the observers were experienced USAF F-16 pilots, three observers were highly practiced non-pilots. Nine of the observers completed three experimental sessions while the other three observers completed two. The observers ranged in age from 31 to 52 years with a mean age of 44 years.

Prior to participating in each experimental session, the visual acuity of each observer was tested using the Freiburg Visual Acuity test (FrACT) running on a laptop computer positioned 4 m from the observer. All observers had a visual acuity of 20:15 or better.

Evaluation Task

In this evaluation, a self-paced, two-alternative, forced choice procedure was used in which the participant selected the “foe” on each trial as quickly and accurately as practical. On each trial, the ownship started at a range of 3 to 6 km from a pair of aircraft, one friend and one foe. The starting position for each trial was set at 2.2

times the expected identification range and was randomized +/- 20 percent. Trial length was capped at a maximum of 15 seconds. On average the participants identified the foe after about 7-8 seconds and initiated the next trial immediately. Each observer participated in two experimental sessions on separate days.

On each trial, the aircraft traveled in straight and level flight at a ground speed of 250 to 300 knots, pointing either left or right as in Figure 4. The mean contrast of the aircraft against their background was 2.5:1.

At the typical identification range, the horizontal speed of the bogies would produce a negligible angular velocity from the point of view of the ownship.

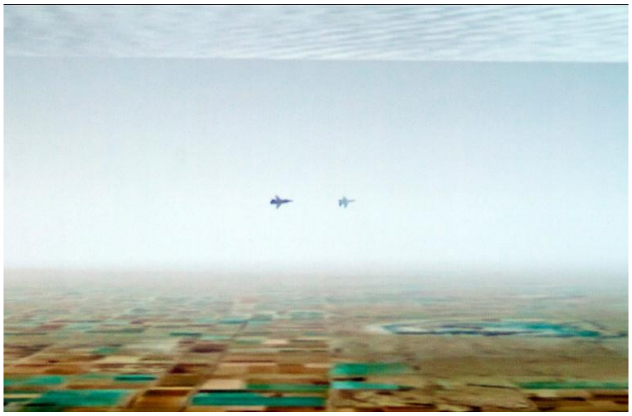

Figure 4. Photograph of a typical trial showing a pair of aircraft pointing to the right. The aircraft were always seen against the uniform portion of the sky.

The angular velocity of the targets/image was set to a constant and controlled level on each trial by changing the pitch and yaw of the ownship in a circular orbit. From the point of view of the observers, this gave the appearance of the ownship approaching the bogies in a spiraling motion. This orbital motion of the ownship allowed sustained high angular velocities for the duration of the trial while keeping the targets near the center of the screen. A second advantage of the spiraling motion was that it produced motion smearing in all orientations during the course of each trial. Angular velocity was controlled by the diameter of the orbit. The largest orbit used in the evaluations had a radius of 8 inches which kept the bogies within the central portion of the screen where our calibration of the hold time shutter was valid. The period of the orbit was 1.4 sec.

Prior to each experimental session, each observer studied larger images of the aircraft to become familiar with their appearance. Each session required about 50 minutes to complete.

Equipment

The same laboratory space and equipment was used in both evaluations except for the differences noted below.

Projector and Screen

Both evaluations were conducted in the OBVA laboratory at the AFRL facility in Mesa AZ using an 8 Mpix Sony SRX-S110 LCoS projector. The image was projected on a flat screen measuring 2.28 x 1.27 m (90 x 50 in). The center of the screen was 1.88 m (74 in) above the floor. The projector was mounted overhead on a stand which positioned the lens 2.39 m (94 in) from the floor and 6.3 m (248 in) from the screen. The walls in the laboratory were painted black, thus, very little scattered light was present.

Image Generator

The IG computer ran the Windows XP operating system on a custom built computer, consisting of an Intel Core I7 - 920 processor with 12 GB of ram. The graphics for the IG were driven by the Nvidia Quadroplex 2200 D2 model which provided the 4 channels required to drive the Sony projector. The IG software is MetaVR version 5.6. The Sim Host computer ran the MATLAB (The Math Works) software under the Windows XP operating system.

Motion blur reduction shutter

An LCD motion blur reduction shutter was purchased from VDC Display Systems in the fall of 2010. This device allows hold time to be controlled, from trial to trial, over a range of 1.5 to 14 ms. Two levels of hold time, 6 and 12 ms, were used in this evaluation. The luminance of the display system varied in proportion with hold time.

With the Sony projector used in this evaluation, the image is drawn from the horizontal centerline out. In other words, at the beginning of each frame the image begins updating along the central horizontal line separating the four quadrants of the display system. This method of updating the image must be taken into account when characterizing the effect of the hold time shutter. Since the hold time shutter does not follow the same spatial-temporal pattern of image update that the projector uses, different hold times can be produced at different vertical positions in the image.

For short hold time settings of the shutter it is possible to achieve the same hold time over most of the vertical extent of the image. As hold time increases, the vertical extent of the image over which a constant width, uni-modal pulse of light is created decreases.

Hold time was measured using a pair of silicon photodiodes with a very fast response time. One photodiode was vertically positioned at the center of the screen while the second was lowered (or raised) from the centerline.

In this evaluation, our goal was to exercise hold time over a wide range. We found that could obtain uni-modal temporal waveforms if we used a maximum hold time of 12 ms and restricted our use of the screen to +/- 8 inches from the horizontal centerline. With these constraints applied, we measured the temporal responses as shown in Figures 5 to 7.

For these measurements, the image generator was set to produce a full screen white image alternating with black every other frame. The plots below show the projector/shutter response over a period of 60 ms (3.6 frames). The upper trace in each figure shows the response at the horizontal centerline of the screen and the lower trace shows the response for the sensor placed 8 inches below the centerline of the screen. Hold time is defined as the half-maximum width of these functions.

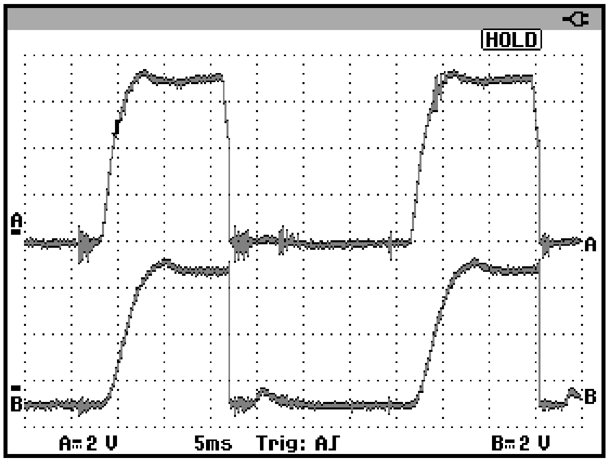

Figure 5. Luminance over a period of 60 ms for a long hold time condition (nominally 12 ms). Note that the hold time at the center of the screen was about 10% longer than the hold time at a position 8 inches down from the centerline of the screen.

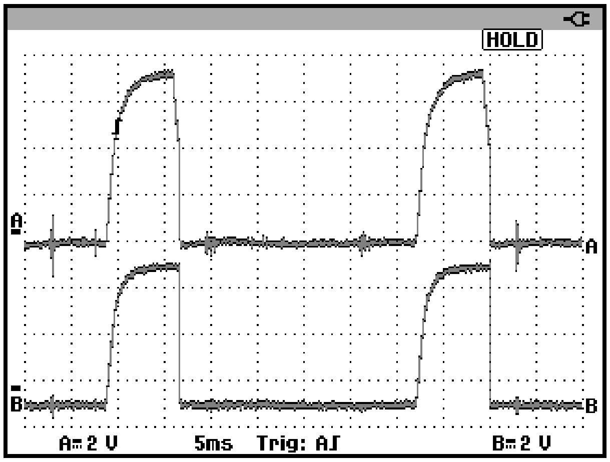

Figure 6. Luminance over a period of 60 ms for an intermediate hold time condition (nominally 7.5 ms).

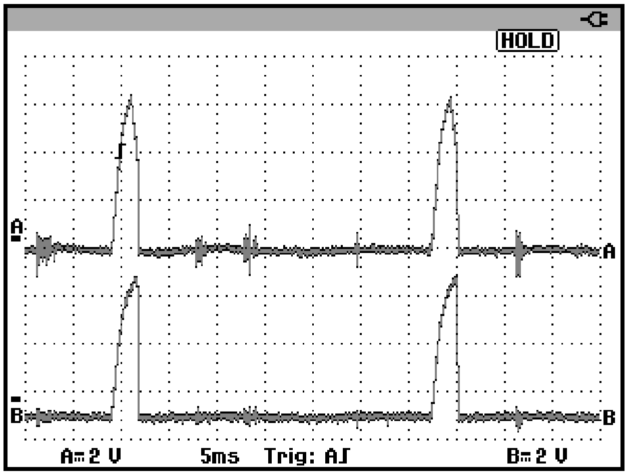

Figure 7. Luminance over a period of 60 ms for a short hold time condition (nominally 2 ms).

The hold time variable was measured and calibrated by fixing the “projector delay” at 100 and varying the “turn on delay” over a range of values from 250 to 1400. Hold times were measured ranging from 12 to 2 ms and were related to the projector delay setting of the shutter by fitting a regression line. The measured levels of hold time were found to be accurately linearly related to the projector delay settings and the resulting equation was used to compute the shutter setting for each hold time condition:

$$\text{Turn on delay} = 1622 - 116 * \text{hold time}$$

Filters and Luminance

Luminance was manipulated independently of hold time using two neutral-density (ND) filters that could be placed between the projection lens and screen. The ND filters consisted of partially-silvered mirrors that were placed in the light path, but at an angle relative the optical axis of the system to avoid creating double images.

The transmittances of the two ND filters were 0.61 and 0.23. The transmittance of the motion blur reduction shutter was 0.61 for the fully open position. Thus, for the conditions where the shutter was used, four filter (luminance) conditions produced total transmittances of 0.61, 0.37, 0.14, and 0.086. When the motion blur reduction shutter was removed from the light path the transmittance of the system was 1.0.

Contrast and flood lighting

When viewed in the darkened lab, the mean contrast of the aircraft models against the sky background was 2.5:1 with all aircraft being darker than the background. The dark laboratory and flat projection screen resulted in negligible scattered light from these sources. The primary source of scatter in the system was the hold time shutter. When the shutter was in place, the maximum display system contrast (checkerboard) was nominally 24:1. With the shutter and filters removed the maximum display system contrast was 99:1.

In this evaluation, the contrast of the display system was manipulated with the use of computer controlled flood lights that uniformly illuminated the screen. Use of the flood lights allowed simulation of the unavoidable “washout” that occurs in most training display systems due to light scattered from the projection screen (and mirror) that illuminates other portions of the screen. Six levels of washout lighting were used as indicated along the top of Tables 1-3.

Comparing across these tables shows the combinations of filter and washout lighting produced display luminance levels ranging from 5.7 to 170 cd/m^2 and display contrast ratios ranging from 3.1 to 99. Most of the luminance variation in the second evaluation was not confounded with hold time as it was in the first evaluation.

Table 1. Measured peak display luminance and black level for each of the 6 washout conditions for a hold time setting of 6 ms. Luminance is in cd/m^2, display contrast is indicated in bold.

Filter Trans	0 cd/m^2	0.5 cd/m^2	1 cd/m^2	2 cd/m^2	4 cd/m^2	7.5 cd/m^2
0.61	42 1.72 **24**	43 2.26 **19.0**	43 2.9 **14.8**	44 3.8 **11.6**	47 5.8 **8.1**	49 9.2 **5.3**
0.37	25.7 1.05 **24**	26.2 1.57 **16.7**	26.8 2.22 **12.1**	27.7 3.2 **8.7**	29.5 5.2 **5.7**	33.0 8.7 **3.8**
0.14	10.5 0.45 **23**	10.9 0.97 **11.2**	11.4 1.63 **7.0**	12.4 2.58 **4.8**	14.2 4.6 **3.1**	
0.085	5.7 0.26 **22**	7.0 0.82 **8.5**	7.5 1.40 **5.4**	8.5 2.40 **3.5**		

Table 2. Measured peak display luminance and black level for each of the 6 washout conditions for a hold time setting of 12 ms. Luminance is in cd/m^2, display contrast is indicated in bold.

Filter Trans	0 cd/m^2	0.5 cd/m^2	1 cd/m^2	2 cd/m^2	4 cd/m^2	7.5 cd/m^2
0.61	86 3.5 **24**	86 4.1 **21**	87 4.6 **18.7**	88 5.6 **15.7**	90 7.6 **11.9**	93 11.0 **8.5**
0.37	52 2.14 **24**	52 2.67 **20**	53 3.3 **16.1**	54 4.2 **12.7**	56 6.2 **9.0**	59 9.7 **6.1**
0.14	21 0.89 **24**	21.5 1.42 **15.1**	22.1 2.04 **10.8**	23.0 3.0 **7.7**	25.0 5.0 **5.0**	28.5 8.5 **3.4**
0.085	11.0 0.48 **23**	12.2 1.03 **11.8**	12.7 1.64 **7.7**	14.0 2.65 **5.3**	16.0 4.7 **3.4**	

Table 3. Measured peak display luminance and black level for each of the 6 washout conditions with filters and hold time shutter removed. Luminance is in cd/m^2, display contrast is indicated in bold.

Filter Trans	0 cd/m^2	0.5 cd/m^2	1 cd/m^2	2 cd/m^2	4 cd/m^2	7.5 cd/m^2
1.0	163 1.65 **99**	163 2.18 **75**	164 2.80 **59**	165 3.8 **44**	167 5.7 **29**	170 9.2 **18.5**

Pixel Pitch and Resolution

In this evaluation, the practical variable viewing distance was used to control the angular pixel pitch of the display system. No other manipulations were made that independently affected the relationship between pixel pitch, viewing distance, and measured resolution (MTF), thus, the three variables Pixel Pitch, Viewing Distance, and Resolution were completely confounded and are used inter-changeably in this report.

For most training display systems, the linear Pixel Pitch (in mm) and viewing distance are clearly defined and relatively immutable attributes of the system. The angular Pixel Pitch (in arcmin) of the system is easily computed from these two quantities and is thus also clearly defined and not often misinterpreted. In contrast, the “effective” or “limiting” resolution of a display system is not nearly as easy to define or measure as is pixel pitch. This is primarily because this system attribute depends on a number of additional factors such as optical blur, pixel hold time, angular velocity, mis-convergence, luminance, contrast, anti-aliasing, and observer acuity.

For these evaluations, the pixel pitch (pixel-to-pixel spacing) measured at the center of the screen was 0.60 mm (100 pixels measured 60 mm). The vertical and horizontal pitches differed by no more than 2%.

For each trial, the observer was seated at one of two viewing distances, 1.5 or 4.2 m, which produced angular pixel pitches of 1.38 and 0.49 arcmin. The trials were blocked by viewing distance so that the observers had to change viewing distance no more than about 8 times per experimental session.

The line spread function (LSF) of the projected image was measured using a calibrated color camera (Canon G-9) positioned approximately 12 inches from the screen (see Figure 8). For this measurement, a pair of widely spaced single pixel wide white lines on a black background were projected on the screen and photographed. The space between the pair of lines was measured with a ruler and used to determine the sampling rate of the camera arrangement which measured 11.4 camera pixels per mm.

The MTF of the display system was used as an input to the model along with the settings of each of the five independent variables used in the evaluations. The limiting resolution of the display system and the expected threshold target size were computed separately for each of the 200 experimental conditions.

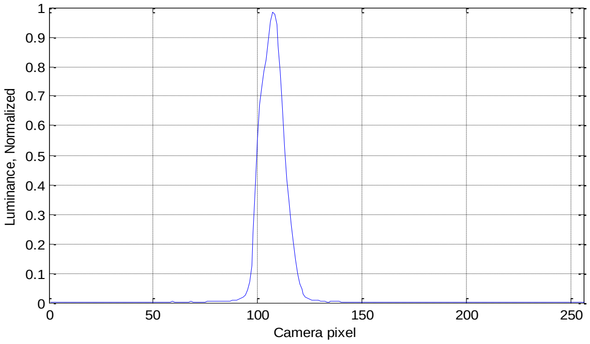

Figure 8. Line spread function for a single white line on a black background. Camera calibration was 0.088 mm / camera pixel, thus, about 25 camera pixels spanned the line spread function.

Aircraft Models

For this second evaluation the number of aircraft models was increased to 14 friendly and 13 enemy aircraft. On each trial one aircraft was selected at random from each of these pools. The aircraft model numbers were recorded for each trial so that a table of the relative discriminability of model pairings could be constructed. An average of 33 trials were used to estimate the level of each aircraft pairing and these data were used to remove the variance due to the pairings.

Independent Variables

The primary goal for the experimental design was to cover the design trade space, making sure to gather enough data to fully characterize the expected interactions among the variables. The independent variables and levels used in this evaluation were:

- Pixel Hold Time, 2 levels: 6 and 12 ms
- Target Velocity, 2 levels: 3 and 12 deg/sec
- Pixel Pitch, 2 levels: 0.5 and 1.4 arcmin
- 25 combinations of the variables Filter and Washout which produced a wide range of luminance and contrast conditions.

Looked at a different way, each of the four combinations of target Velocity and Pitch were used with the 44 conditions described in Tables 1 and 2 for a total of 176 conditions employing the hold time shutter. For the case of no hold time shutter, 24 more conditions (Table 3) were added consisting of 6 levels of Washout, 2 levels of Velocity, 2 levels of Pixel Pitch, for a total of 200 experimental conditions.

RESULTS

Effects of Hold Time, Angular Velocity, and Pixel Pitch

The data reduction and analyses for Evaluation 2 are identical to the first evaluation. The analyses below are based 6350 trials for an average of 31.7 trials per experimental condition. At the time this paper was prepared, the model parameters had not yet been optimized to fit the model to the data from the second evaluation. The parameters were left at the settings that maximized the correlation with the data from Evaluation 1. With these pre-determined settings the correlation between the model and the Evaluation 2 data is $R^2 = 0.91$ ($p < 0.001$, 199 df). The standard deviation of the residuals is 0.028. Converting from log10 of the residuals, the standard deviation is 6.5% of the target size (or range).

The results of this second evaluation are illustrated in Figures 9 and 10 which show the effects of the filter and washout conditions for selected levels of Velocity, Hold, and Pixel Pitch. These plots are designed to show the degree to which the model fits the data. Figures 11 to 13 provide more easily interpreted views of these effects.

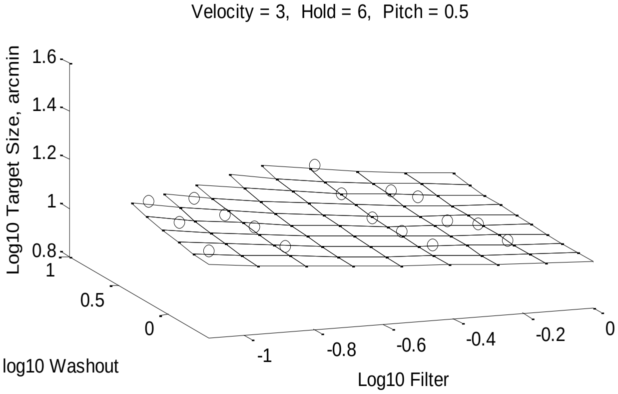

Figure 9. Threshold target size as a function of Filter transmittance and Washout Luminance for the case of very fine Pitch and low motion induced blurring.

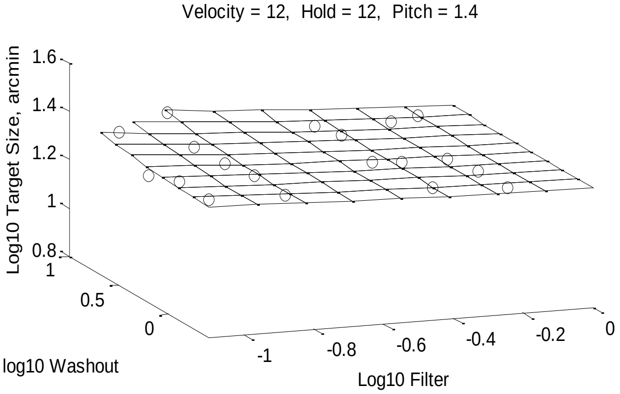

Figure 10. Threshold target size as a function of Filter transmittance and Washout Luminance for the case of coarser display pitch and moderate motion induced blurring.

DISCUSSION

In the previous section, the data and model were shown together on surface plots that were scaled in a transform space that homogenizes the variance across the experimental conditions so that the fit of the model to the data could be assessed. In this section, we plot several views of the model in a transform space that is more immediately useful to a display system specifier or design engineer.

Figure 11 illustrates the effects of the three variables that had the largest impact on performance: Pitch, Hold time, and angular Velocity. These surfaces represent the mean performance of our 8 observers for a peak display luminance of 30 fL, a display contrast of 20, and a fighter-sized aircraft (11 m wingspan).

Figures 12 and 13 illustrate the effects of display luminance and contrast which had smaller effects on performance than did the first three variables. Figure 12 represents the case of dark targets against a bright background that is near the peak luminance of the display system. Figure 13 shows the effect of contrast is expected to be stronger when the target background is only 25% of the peak display luminance.

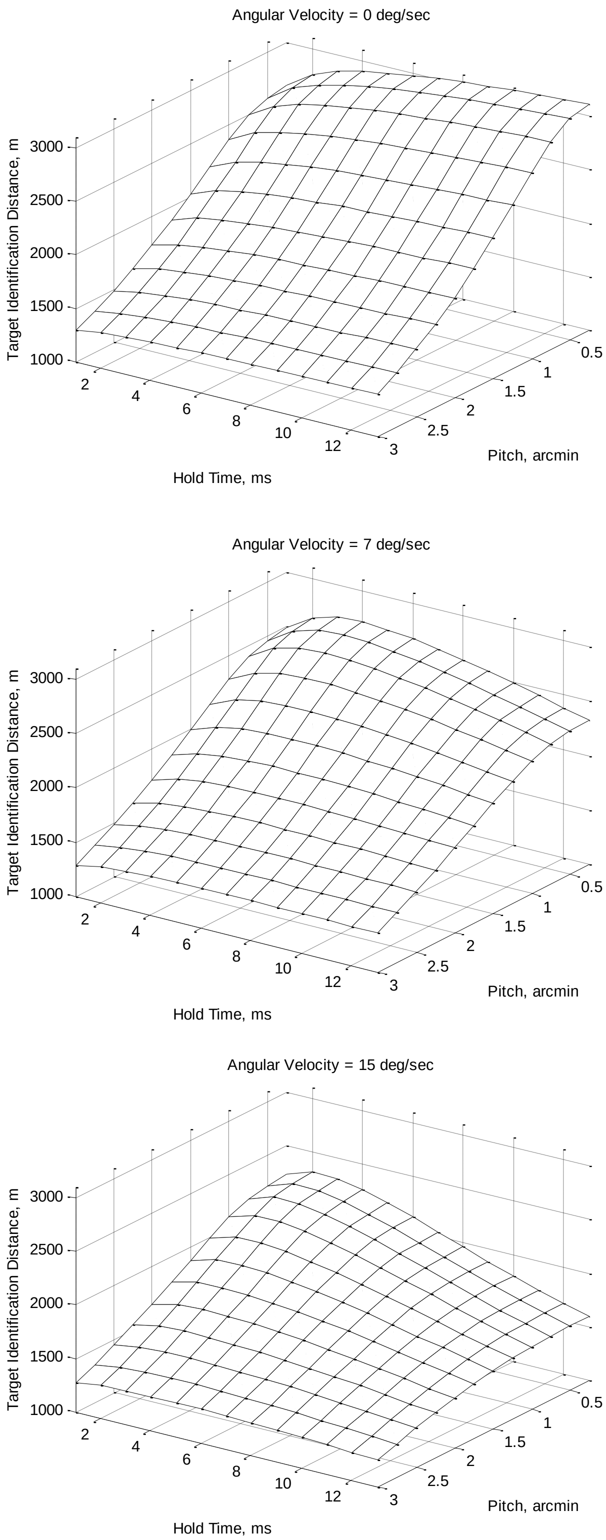

Figure 11. Threshold target identification range for fighter-sized aircraft as a function of Pitch and Hold time for three levels of target Velocity.

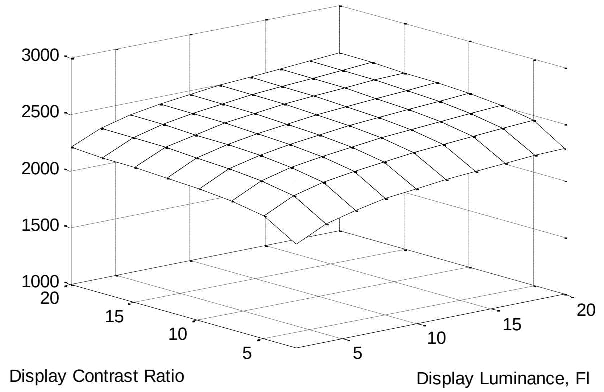

Figure 12. Aircraft identification range as a function of display Luminance and Contrast for a display Pitch = 1 arcmin, Hold time = 8 ms, Velocity = 5 deg/sec, and target background at 85% of the peak display luminance.

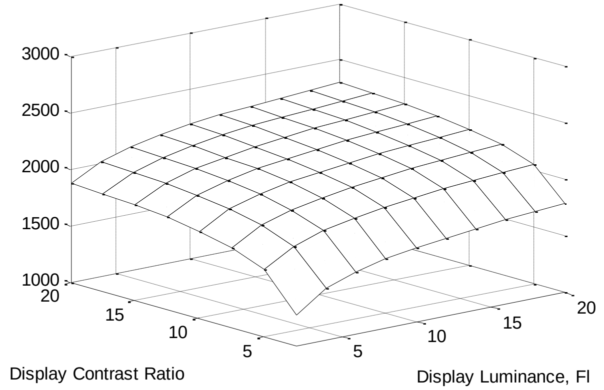

Figure 13. Aircraft identification range as a function of display Luminance and Contrast for a display Pitch = 1 arcmin, Hold time = 8 ms, Velocity = 5 deg/sec, and target background at 25% of the peak display luminance.

CONCLUSIONS & RECOMMENDATIONS

- The expected effects of the five design variables on task performance have been confirmed with high statistical reliability across hundreds of combinations of parameter settings.
- The model accurately quantifies the interactions between the five practical design variables, thus, the model is well suited for supporting design trades among these variables.
- The data and model presented here indicate larger improvements in training task performance are available through decreased display pitch and hold time than are available through increased display luminance and contrast.

Beware of Flicker

To obtain near-eye limited resolution in the presence of even moderate image motion, hold times of only a few ms will be required (see the bottom panel of Figure 11). A substantial literature recommends the use of frame rates of 75 Hz or greater for short hold time displays (e.g., CRTs) to avoid the detrimental effects of flicker[24].

We know of no other means by which motion induced blurring can be reduced to inconsequential levels but to reduce hold time. Thus, it appears the simulation training industry will have to move to higher frame rates as we move towards eye-limited resolution.

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APPENDIX A: INSTRUCTIONS TO PARTICIPANTS

In this evaluation we are asking you to imagine yourself in the roll of a fighter pilot who has been called to help your wing mate who is embroiled in a battle with an enemy fighter. The “friend” and “foe” have been stuck in a turn circle and have shed velocity down to a few hundred knots. You are approaching their battle space at a much greater velocity from a range of 2 to 4 nm. Unfortunately, you do not know which fighter is the enemy and must determine this visually as soon as possible so that you can take action to assist your wing mate.

> Experimenter runs a few trials to demonstrate the procedure

During the evaluation you will be presented with a series of trials in which one bogie is chasing another as you rapidly approach. Your task on each trial is to positively identify the foe as soon as you can and to press the left or right button to indicate the side of the screen that the foe is on. The trial will stop as soon as you make your selection.

> Point out the buttons to the participant; let them run a few trials

You can begin the next trial by pressing either of the two buttons. You may take a break between trials as you see fit. During the evaluation we will present about 250 trials which should take us about one hour to complete.

On each trial you will be presented with one friend and one foe aircraft. The aircraft from each category are shown on this chart.

> Display the aircraft models and give the participant a minute to study

During each trial we will be systematically manipulating several display design variables so that we can measure their effects on aircraft identification performance. One of these variables is resolution which we control by changing your viewing range. After every 15 to 20 trials we will ask you to move to a different position relative to the screen. These positions are marked on the floor with tape.

> Point out the participant seating positions marked on the floor

Another variable we will manipulate during the evaluation is the angular velocity of the bogies, that is, the speed with which the bogies move relative to the projection system. For some of our trials we wish to produce high angular velocities. Unfortunately, we could not afford to set up a very wide and high resolution display system for this evaluation. Our FOV is limited to only a single channel. If we were to use linear motions our bogies would be on and off the screen in less than a second, too short a time for our experimental task.

The only way we know how to produce high angular velocities and keep the targets on the screen for the entire trial is to move the scene in circles. The primary method we use to produce this circular motion through changes in the pitch and heading of the ownship.

We understand that the motions of the ownship are unnatural; in fact, we acknowledge it is probably not possible to get a fixed wing aircraft to move in this way.

Please also accept our apology for not providing you with a set of controls that would allow you to fly the aircraft. Given the limited budget available for this program we were not able to set up a cockpit with controls typical of fast jets.

Assuming you can tolerate the limitations of our experimental setup, we believe the angular velocity effects we measure here will fairly represent the effect of angular velocity when you are in control of the aircraft and can produce more natural movements of the image.

Do you have any questions regarding the procedure?

Answer questions

Prior to starting the evaluation we would like you to complete a series of practice trials so that you can get used to the procedure and can become familiar with the aircraft models. We will conclude the practice trials when you get to the point that you can correctly identify the foe on 15 trials in a row.

Remember that your main goal is to identify the foe as quickly as you can but without making errors.

APPENDIX B: MEAN RESPONSE DATA

The data provided in this table contains the mean data from the 12 participants in the evaluation. Nine of the observer participated in three experimental sessions and two participants completed two. Each of the 200 range estimates is the average of 31.7 trials. Trials on which identification errors were made were eliminated.

Column Descriptions

1. Viewing distance, observer to screen, m
2. Pixel hold time, ms
3. Angular velocity of image, deg/sec
4. Filter transmittance
5. Washout luminance
6. Log10 of the measured threshold angular subtense, arcmin
7. Standard deviation of the thresholds
8. Number of correct observations for each condition

Threshold Identification Distance

During each experimental session the threshold distance was recorded on each trial. Preliminary analyses of the data indicated the data were more normally distributed and the variance distributed more homogeneously across the experimental variables when it was transformed from distance to angular subtense. Thus, threshold distance was converted to angular subtense assuming an 11 m wingspan as the representative dimension of the fighter aircraft. All subsequent analyses were performed on the angular data.

The angular threshold data in Column 6 of Table B can be converted back to threshold distance (meters) using the formula:

threshDist = wingspan ./ tand(10.^logMeasured / 60)

For example, the threshold distances for the first and last conditions in the table are 2046 and 1887 m.

Table B. Data from Second IDEAS Evaluation

1.5	6	3	0.085	0.0	1.2667	0.1050	32
1.5	6	3	0.085	0.5	1.3015	0.1302	33
1.5	6	3	0.085	1.0	1.2893	0.1286	32
1.5	6	3	0.085	2.0	1.3122	0.0994	29
1.5	6	3	0.140	0.0	1.2480	0.1516	38
1.5	6	3	0.140	0.5	1.2571	0.1722	38
1.5	6	3	0.140	1.0	1.2481	0.1142	36
1.5	6	3	0.140	2.0	1.2352	0.1275	33
1.5	6	3	0.140	4.0	1.2725	0.1111	31
1.5	6	3	0.370	0.0	1.2360	0.1678	28
1.5	6	3	0.370	0.5	1.2084	0.1423	27
1.5	6	3	0.370	1.0	1.2267	0.1275	30
1.5	6	3	0.370	2.0	1.1947	0.1208	28
1.5	6	3	0.370	4.0	1.2091	0.1371	29
1.5	6	3	0.370	7.5	1.2322	0.1265	25
1.5	6	3	0.610	0.0	1.1963	0.1141	32
1.5	6	3	0.610	0.5	1.1930	0.1511	29
1.5	6	3	0.610	1.0	1.1775	0.1294	31
1.5	6	3	0.610	2.0	1.1766	0.1235	29
1.5	6	3	0.610	4.0	1.1882	0.1533	28
1.5	6	3	0.610	7.5	1.1479	0.1222	26
1.5	6	12	0.085	0.0	1.2990	0.1420	33
1.5	6	12	0.085	0.5	1.3643	0.1272	33
1.5	6	12	0.085	1.0	1.3362	0.1304	28
1.5	6	12	0.085	2.0	1.3857	0.1493	29
1.5	6	12	0.140	0.0	1.3179	0.1238	38
1.5	6	12	0.140	0.5	1.3113	0.1273	34
1.5	6	12	0.140	1.0	1.3595	0.1349	38
1.5	6	12	0.140	2.0	1.3190	0.1149	36
1.5	6	12	0.140	4.0	1.3549	0.1337	36
1.5	6	12	0.370	0.0	1.2676	0.1292	32
1.5	6	12	0.370	0.5	1.2677	0.1265	31

1.5	6	12	0.370	1.0	1.2870	0.1243	30
1.5	6	12	0.370	2.0	1.2952	0.1480	28
1.5	6	12	0.370	4.0	1.2890	0.1210	32
1.5	6	12	0.370	7.5	1.2786	0.1390	27
1.5	6	12	0.610	0.0	1.2644	0.1234	29
1.5	6	12	0.610	0.5	1.2254	0.1159	33
1.5	6	12	0.610	1.0	1.2673	0.1493	32
1.5	6	12	0.610	2.0	1.2650	0.1078	28
1.5	6	12	0.610	4.0	1.2817	0.1429	31
1.5	6	12	0.610	7.5	1.2244	0.1473	32
1.5	12	3	0.085	0.0	1.2540	0.1440	34
1.5	12	3	0.085	0.5	1.2679	0.1100	28
1.5	12	3	0.085	1.0	1.2405	0.1296	31
1.5	12	3	0.085	2.0	1.2638	0.1130	32
1.5	12	3	0.085	4.0	1.2726	0.0979	30
1.5	12	3	0.140	0.0	1.2401	0.1314	38
1.5	12	3	0.140	0.5	1.2024	0.1147	36
1.5	12	3	0.140	1.0	1.2153	0.1163	40
1.5	12	3	0.140	2.0	1.2252	0.1256	35
1.5	12	3	0.140	4.0	1.2441	0.1315	33
1.5	12	3	0.140	7.5	1.2438	0.1011	37
1.5	12	3	0.370	0.0	1.2157	0.1288	32
1.5	12	3	0.370	0.5	1.1622	0.1372	32
1.5	12	3	0.370	1.0	1.2270	0.1274	23
1.5	12	3	0.370	2.0	1.1755	0.1428	28
1.5	12	3	0.370	4.0	1.2001	0.1299	31
1.5	12	3	0.370	7.5	1.2030	0.1550	32
1.5	12	3	0.610	0.0	1.1811	0.1200	31
1.5	12	3	0.610	0.5	1.2121	0.1414	30
1.5	12	3	0.610	1.0	1.1646	0.1181	30
1.5	12	3	0.610	2.0	1.1240	0.1300	30
1.5	12	3	0.610	4.0	1.1868	0.1328	29
1.5	12	3	0.610	7.5	1.1891	0.1227	29
1.5	12	12	0.085	0.0	1.4042	0.1498	35
1.5	12	12	0.085	0.5	1.3829	0.1264	32
1.5	12	12	0.085	1.0	1.3892	0.1326	32
1.5	12	12	0.085	2.0	1.3566	0.1395	33
1.5	12	12	0.085	4.0	1.4379	0.1399	29
1.5	12	12	0.140	0.0	1.3578	0.1202	38
1.5	12	12	0.140	0.5	1.3760	0.1418	35
1.5	12	12	0.140	1.0	1.3572	0.1232	39
1.5	12	12	0.140	2.0	1.3733	0.1113	37
1.5	12	12	0.140	4.0	1.3548	0.1192	35
1.5	12	12	0.140	7.5	1.3919	0.1134	35
1.5	12	12	0.370	0.0	1.3636	0.1252	31
1.5	12	12	0.370	0.5	1.3488	0.1341	31
1.5	12	12	0.370	1.0	1.3368	0.1283	32
1.5	12	12	0.370	2.0	1.3111	0.1096	30
1.5	12	12	0.370	4.0	1.3723	0.1379	33
1.5	12	12	0.370	7.5	1.3502	0.1404	32
1.5	12	12	0.610	0.0	1.3191	0.0943	33
1.5	12	12	0.610	0.5	1.3260	0.1061	26
1.5	12	12	0.610	1.0	1.3207	0.1107	31
1.5	12	12	0.610	2.0	1.3284	0.1329	32
1.5	12	12	0.610	4.0	1.3754	0.1292	30
1.5	12	12	0.610	7.5	1.3103	0.1156	31
1.5	16	3	1.000	0.0	1.1738	0.1443	30
1.5	16	3	1.000	0.5	1.1485	0.1201	30
1.5	16	3	1.000	1.0	1.1464	0.0981	29
1.5	16	3	1.000	2.0	1.1987	0.1216	30
1.5	16	3	1.000	4.0	1.1749	0.1174	31
1.5	16	3	1.000	7.5	1.1709	0.1249	29
1.5	16	12	1.000	0.0	1.3714	0.1451	31
1.5	16	12	1.000	0.5	1.3665	0.1168	26
1.5	16	12	1.000	1.0	1.3428	0.1167	32
1.5	16	12	1.000	2.0	1.4015	0.1482	29
1.5	16	12	1.000	4.0	1.3582	0.1086	30
1.5	16	12	1.000	7.5	1.3671	0.1206	32
4.2	6	3	0.085	0.0	1.1650	0.0977	31
4.2	6	3	0.085	0.5	1.1775	0.1410	29
4.2	6	3	0.085	1.0	1.2085	0.1212	31
4.2	6	3	0.085	2.0	1.2475	0.1341	25
4.2	6	3	0.140	0.0	1.1699	0.1508	35
4.2	6	3	0.140	0.5	1.1823	0.1294	34
4.2	6	3	0.140	1.0	1.1775	0.1226	36
4.2	6	3	0.140	2.0	1.1812	0.1360	35
4.2	6	3	0.140	4.0	1.1620	0.1271	31
4.2	6	3	0.370	0.0	1.0843	0.1051	30
4.2	6	3	0.370	0.5	1.1277	0.1429	34
4.2	6	3	0.370	1.0	1.0865	0.1246	34
4.2	6	3	0.370	2.0	1.1066	0.1104	30
4.2	6	3	0.370	4.0	1.1020	0.1109	31
4.2	6	3	0.370	7.5	1.1282	0.1364	25
4.2	6	3	0.610	0.0	1.0534	0.1135	32
4.2	6	3	0.610	0.5	1.1063	0.1462	33
4.2	6	3	0.610	1.0	1.1121	0.1272	32
4.2	6	3	0.610	2.0	1.0861	0.1234	31
4.2	6	3	0.610	4.0	1.0833	0.1301	34
4.2	6	3	0.610	7.5	1.0786	0.1401	33
4.2	6	12	0.085	0.0	1.2373	0.1460	27
4.2	6	12	0.085	0.5	1.2764	0.1288	31
4.2	6	12	0.085	1.0	1.2764	0.1039	29
4.2	6	12	0.085	2.0	1.2995	0.1387	29
4.2	6	12	0.140	0.0	1.2981	0.1148	34
4.2	6	12	0.140	0.5	1.2504	0.1181	33
4.2	6	12	0.140	1.0	1.2979	0.1313	35
4.2	6	12	0.140	2.0	1.2465	0.1132	36
4.2	6	12	0.140	4.0	1.2758	0.1463	29

4.2	6	12	0.370	0.0	1.2246	0.1254	31
4.2	6	12	0.370	0.5	1.2635	0.1225	33
4.2	6	12	0.370	1.0	1.1958	0.1407	35
4.2	6	12	0.370	2.0	1.2383	0.1225	35
4.2	6	12	0.370	4.0	1.2318	0.1311	34
4.2	6	12	0.370	7.5	1.2094	0.1079	29
4.2	6	12	0.610	0.0	1.1840	0.0933	32
4.2	6	12	0.610	0.5	1.2297	0.1254	33
4.2	6	12	0.610	1.0	1.1621	0.1391	32
4.2	6	12	0.610	2.0	1.1885	0.1262	35
4.2	6	12	0.610	4.0	1.1691	0.1158	31
4.2	6	12	0.610	7.5	1.2039	0.1095	32
4.2	12	3	0.085	0.0	1.1437	0.0954	31
4.2	12	3	0.085	0.5	1.1992	0.0972	30
4.2	12	3	0.085	1.0	1.1997	0.1161	30
4.2	12	3	0.085	2.0	1.1712	0.1440	29
4.2	12	3	0.085	4.0	1.1961	0.1073	28
4.2	12	3	0.140	0.0	1.1604	0.1489	35
4.2	12	3	0.140	0.5	1.1505	0.1225	35
4.2	12	3	0.140	1.0	1.1410	0.1218	35
4.2	12	3	0.140	2.0	1.1289	0.1279	33
4.2	12	3	0.140	4.0	1.1488	0.1424	30
4.2	12	3	0.140	7.5	1.1397	0.1040	30
4.2	12	3	0.370	0.0	1.1148	0.1126	33
4.2	12	3	0.370	0.5	1.0640	0.1261	33
4.2	12	3	0.370	1.0	1.1220	0.1161	33
4.2	12	3	0.370	2.0	1.0981	0.1123	35
4.2	12	3	0.370	4.0	1.1247	0.1635	32
4.2	12	3	0.370	7.5	1.0709	0.1243	30
4.2	12	3	0.610	0.0	1.1001	0.1184	35
4.2	12	3	0.610	0.5	1.0898	0.1224	31
4.2	12	3	0.610	1.0	1.0996	0.1331	30
4.2	12	3	0.610	2.0	1.0709	0.1471	30
4.2	12	3	0.610	4.0	1.0628	0.1162	32
4.2	12	3	0.610	7.5	1.1193	0.1424	36
4.2	12	12	0.085	0.0	1.3485	0.1178	26
4.2	12	12	0.085	0.5	1.3345	0.1032	32
4.2	12	12	0.085	1.0	1.2878	0.1395	31
4.2	12	12	0.085	2.0	1.3530	0.1541	30
4.2	12	12	0.085	4.0	1.3256	0.1011	28
4.2	12	12	0.140	0.0	1.3003	0.1013	32
4.2	12	12	0.140	0.5	1.3350	0.1055	36
4.2	12	12	0.140	1.0	1.3095	0.1066	36
4.2	12	12	0.140	2.0	1.3127	0.1159	35
4.2	12	12	0.140	4.0	1.3000	0.1258	37
4.2	12	12	0.140	7.5	1.3189	0.1128	33
4.2	12	12	0.370	0.0	1.2767	0.1104	34
4.2	12	12	0.370	0.5	1.2588	0.0827	35
4.2	12	12	0.370	1.0	1.2956	0.1214	32
4.2	12	12	0.370	2.0	1.2842	0.0954	31
4.2	12	12	0.370	4.0	1.2569	0.1322	34
4.2	12	12	0.370	7.5	1.2687	0.1035	31
4.2	12	12	0.610	0.0	1.2656	0.1471	27
4.2	12	12	0.610	0.5	1.2724	0.1220	33
4.2	12	12	0.610	1.0	1.2965	0.1224	34
4.2	12	12	0.610	2.0	1.2627	0.1061	34
4.2	12	12	0.610	4.0	1.2770	0.1135	34
4.2	12	12	0.610	7.5	1.2903	0.1224	32
4.2	16	3	1.000	0.0	1.0737	0.1208	32
4.2	16	3	1.000	0.5	1.0992	0.1393	34
4.2	16	3	1.000	1.0	1.0827	0.1181	35
4.2	16	3	1.000	2.0	1.0686	0.1317	30
4.2	16	3	1.000	4.0	1.0780	0.1020	29
4.2	16	3	1.000	7.5	1.0534	0.1434	32
4.2	16	12	1.000	0.0	1.3410	0.1695	32
4.2	16	12	1.000	0.5	1.3171	0.1404	30
4.2	16	12	1.000	1.0	1.2837	0.1030	27
4.2	16	12	1.000	2.0	1.3729	0.1325	28
4.2	16	12	1.000	4.0	1.3305	0.1090	30
4.2	16	12	1.000	7.5	1.3018	0.1508	29