Accurately Representing Target Distance in a Flight Simulator

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ABSTRACT

Rendering an essentially continuous IG image onto the discrete-pixel array of most display devices, as well as graphical processing such as antialias filtering, can result in significant variations in displayed target size and hence simulated distance. Using videotape recordings obtained from a CRT-based, flight-simulator display, we have directly measured changes in size, over a three-second simulation interval, of target aircraft simulated at distances between 3000 and 11000 feet. In Experiment 1, the percentile of the measured target-size distribution which corresponded to the nominal target size was found to change with simulated distance. Additionally, an interaction was found between pixel count (1280×1024 and 2048×1536) and antialias filtering (0 and 2×). In Experiment 2, a single intermediate pixel count (1600×1200) was tested, and in addition, eight target gray-levels were tested perceptually, in order to directly compare the videotaped imagery with what was visible on the screen. It was found that the percentile corresponding to nominal target size varied with both simulated distance and antialiasing condition (0 and 4×). In both experiments, for the larger (i.e., closer) targets, the nominal target size corresponded to about the 96th percentile of the distribution of measured sizes. As target size was decreased, nominal size was found to correspond to as low as the 60th percentile. Further, in both experiments, the functions relating the relevant size-distribution percentiles to simulated distance were nonlinear, and in Experiment 2 they were different for each of the antialiasing conditions tested. The data indicate that the average size of targets displayed in CRT-based flight simulators is smaller than would be expected from their nominal distance as defined by the IG. In addition, the unexpected complexities found in the size-distribution data indicate that accurately adjusting displayed target size to reflect a chosen target distance will require corrections that are dependent on simulated distance.

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GENERAL INTRODUTION

An accurate representation of target distance is required in many flight-simulator training tasks. Griffith, Kosnik, and Siefert (2000), for instance, have summarized a variety of tasks particularly relevant to distributed-mission training, and noted that tasks such as detecting air-to-air threats, delivering missiles and munitions, and maintaining tactical formation are particularly dependent on target-size cues. The size of simulated targets is a major cue to apparent distance, and if not accurately simulated could negatively affect the transfer of simulated tasks to those performed in the real-world.

Whereas many factors may affect the apparent distance of a simulated target (Sedgwick, 1986), target size is the only factor explicitly varied when producing flight simulator imagery. Target models are typically well defined in the IG, but IG space has to be mapped to the pixel array of most displays (Foley, van Dam, Feiner, & Hughes, 1992). This process does not necessarily involve a one-to-one correspondence between IG pixels and displayed pixels. As a result, the same target may change size and shape when it is displayed at the same location at different times, or when it is moved while keeping viewing distance constant. Further, the changes in size and shape could be dependent on the size of the displayed pixel array, the number of pixels in the array, and the display resolution (Winterbottom, Geri, & Pierce, 2003; Geri, Winterbottom, & Pierce, 2004).

In addition to the interaction between the generated and displayed pixel arrays, image processing functions such as antialiasing can also affect the size and shape of simulated targets. This processing is often performed by graphics cards that are largely independent of the IG. Antialiasing can use significant processing resources and so it would be useful to identify practical situations and applications where it either is not needed, or where it confers a disadvantage in the overall simulation.

Extensive data are available on the target distances required to perform various flight tasks (Brown, 1984; Warner, Serfoss & Hubbard, 1993), and these data are routinely used, at least as a first approximation, to verify that effective training is feasible for a given task on a given flight simulator. The size-calibration procedure described here can be used to better assess flight-simulator usefulness for training tasks in which target size is known to be a critical factor. Further, the data obtained from this procedure may have practical implications for determining when a more extensive target-size calibration is required in a particular flight-simulator application.

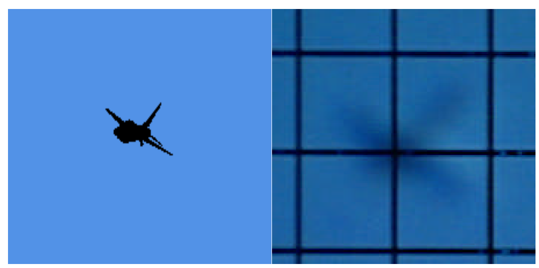

Figure 1. Left- An aircraft model (30º bank, -15º heading) used as one of the targets in the present study. Right- A photograph of the model as simulated at a distance of 3281 ft., magnified 3.4×, for illustrative purposes. The grid shown was present only during the size-calibration portion of the present studies.

EXPERIMENT 1

In this experiment, displayed target size was measured by videotaping targets simulated at various distances, and displayed at two pixel counts and under two antialiasing conditions. The largest targets were chosen to assure that luminance variations among the pixels making up their edges would not significantly affect measured target size. The smallest targets were chosen to approximately correspond to a 2×2 pixel array, which is the smallest that can be expected to reflect differences in object size or shape. Pixel count was varied (with spatial display resolution held constant) in a preliminary attempt to determine whether more closely spaced pixels would improve the accuracy with which target size is simulated. In addition, a no-antialiasing condition was compared to 2× antialiasing in order to determine how the well-known changes in spatial structure associated with antialiasing affect an IG-specified target characteristic, in this case target size.

Methods

Stimuli, Apparatus, and Observers

The two test stimuli were F-16 models simulated at a bank of 30° and headings of either ±15°. Targets were presented on a sky-blue background whose luminance was about 4 fL. Shown on the left side of Figure 1 is a digitized image of the model used as a target stimulus. Shown at the right in the figure is a photograph of the model simulated at a distance of 3281 ft and magnified 3.4×. The grid in the image at the left was used for size calibration. It consisted of 5 mm black squares and was placed over the target presentation location on the rear projection screen.

The target imagery was produced using a MetaVR (Brookline, MA), PC-based, image generator and a NVIDIA (Santa Clara, CA) GeForce3 video card. The imagery was displayed at pixel counts of either 1280×1024 or 2048×1536 (referred to here as pixel counts of 1280 and 2048, respectively). Aircraft were simulated at distances ranging from 3281 to 10663 feet and were rear-projected onto the front channel of an operational flight-simulator display [the M2DART, see Best *et al.* (1999)]. The display consisted of a Barco Model 808 (Barco, Inc., Xenia, OH) CRT projector, and a 1.2-gain, rear-projection screen (Proscreen, Inc. Medford, OR). The targets were moved in a small circle (0.06° radius), with heading held constant, and completed one revolution during each 3 sec. trial. This was done so that the target would move about the pixel mosaic thus providing a more realistic distribution of target sizes.

The effects of antialiasing on displayed target-size were tested by comparing non-aliased targets with targets displayed with 2× antialiasing (see NVIDIA Corp., 2002).

A Sony DCX637 video camera and a Canon BVP3 J8×6 4 f/1.7 lens, located approximately 36 inches from the display screen, were used to videotape the target stimuli. The videotapes were analyzed using a Sony VCR and Sony HR monitor. Target size measurements were made by two evaluators (authors MW and CC). Both evaluators had normal or

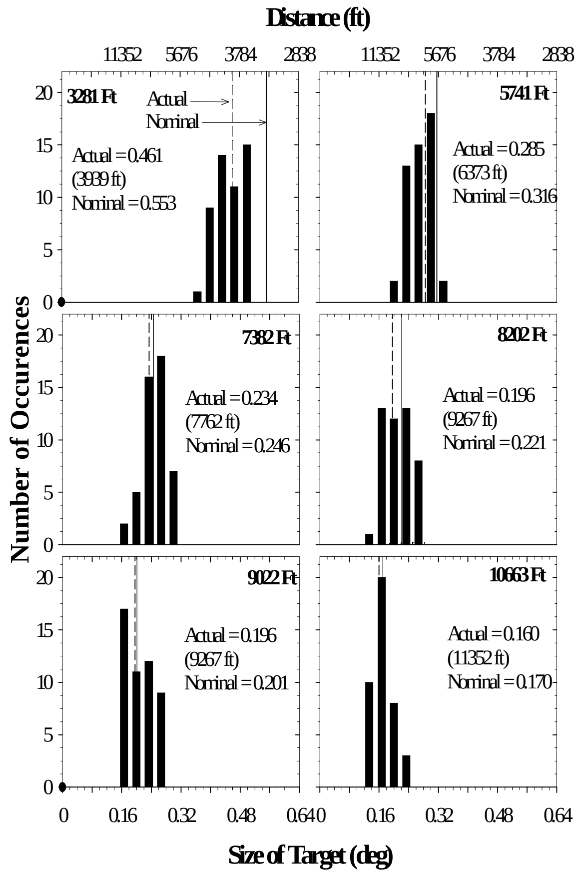

Figure 2. Typical target-size distributions for each simulated distance under the 1280/no-antialiasing condition. Data are from one evaluator. Solid vertical lines indicate nominal target-size defined as the visual angle of a real F-16 aircraft for each simulated distance. Dashed vertical lines indicate the means of the target-size distributions.

corrected-to-normal acuity, and normal binocular vision, color vision, and phoria as determined by the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

The spatial resolution of the M2DART display was measured using standard procedures (Geri, Winterbottom & Pierce, 2004; VESA, 2001). The horizontal and vertical resolutions were found to be 704 and 651 resolved pixels (7.0 and 6.3 arcmin/pixel), respectively, for the 1280 pixel-count condition, and 641 and 626 resolved pixels (6.7 and 6.6 arcmin/pixel), respectively, for the 2048 pixel-count condition.

Procedure

Independent target-size estimates were obtained by the two evaluators in 0.5 mm increments for 9-10 targets at each simulated distance, pixel-count, and antialiasing condition. The estimates were converted to degrees of visual angle as required for analysis and comparison to the nominal target sizes as specified by the image generator.

Results

Shown in Figure 2 are typical target-size distributions obtained for each of the simulated distances for the 1280 pixel-count/no-antialiasing condition. The solid vertical line associated with each distribution indicates the nominal target size defined as the visual angle of a real F-16 aircraft at the specified distance. The dashed vertical line associated with each distribution indicates the mean of the target sizes for that distribution. Shown in Figure 3 is the percentile of each target-size distribution which corresponds to the nominal target-size for each experimental condition. The open circles in the upper graph (1280, no antialiasing) were obtained from an average, over the two evaluators, of the data corresponding to the solid lines in Figure 2. The remaining data points were obtained from the analogous nominal sizes for the other conditions. The percentile to which the nominal sizes correspond varies between about 82% and 98% and generally decreases as simulated distance increases. Percentages above 50 indicate that the nominal target-size is greater than the mean measured target size.

A repeated measures ANOVA applied to the data of Figure 3 showed a significant main effect of Simulated-Distance [$F(5,40)=13.9$, $p<0.001$], which is associated with the general decrease in the data as simulated distance is increased. In addition there was a significant Pixel-Count × Antialiasing-Condition interaction [$F(1,9)=50$, $p<0.001$], reflecting the fact that the 1280 pixel-count data are higher than the 2048 pixel-count data for the 2x-antialiasing condition, but lower than the 2048 data for the no-antialiasing condition. Finally, there was a significant three-way interaction [$F(5,45)=3.5$, $p<0.01$] indicating that the differences just described were also different over the various simulated distances tested (the clearest indication of this is the crossover in the two functions in the lower graph of Figure 3).

Discussion

A visual inspection of most flight simulator imagery will indicate that the size of simulated targets varies over time even when simulated distance is held constant. To our knowledge this phenomenon has not previously been quantified. This suggests that

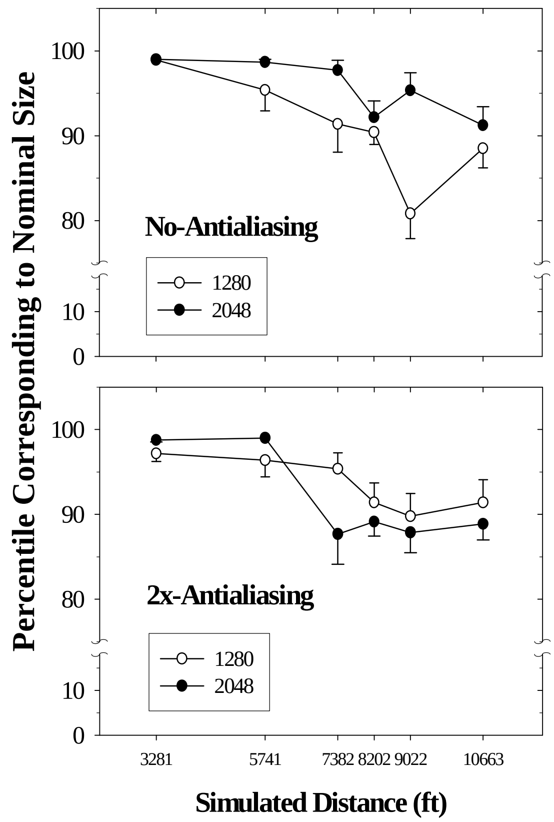

Figure 3. The percentile of the target-size distribution which corresponds to the nominal target-size for each combination of simulated distance, pixel count, and antialiasing level. Error bars are ±1 standard errors of the mean.

simulator users and those performing research on simulators generally consider these target-size variations to be insignificant. The data of Figure 3 indicate that this is not the case. Given the changes over time in the measured sizes of a target simulated at the same distance, it might be expected that the mean (i.e. the 50th percentile of the measured size distribution) of those sizes would correspond to the nominal target size (i.e. the properly simulated size). The present data show, however, that the nominal target size corresponds to about the 90th percentile for tested target distances greater than about 8000 ft, and to about the 96th percentile for the nearer tested distances. The question arises, therefore, as to what target-size is actually used by pilots and other flight-simulator operators to judge target distance. If operators use a time-weighted average of the target-sizes displayed, they will underestimate target-size and hence overestimate target distance. If, on the other hand, they use the largest size displayed, they will estimate target distance more accurately.

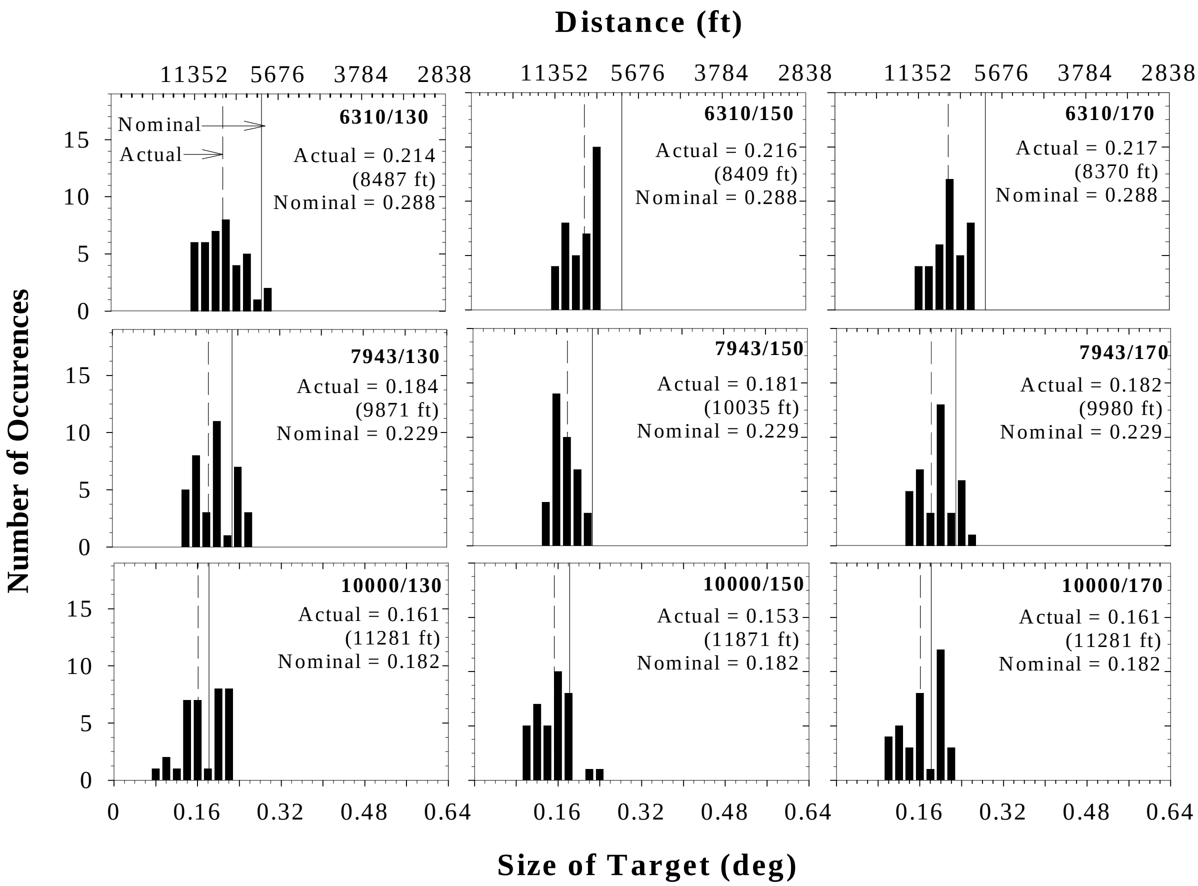

Figure 4. Typical target-size distributions for each of the target distances and contrasts tested under the 4×-antialiasing condition. The data shown are from one evaluator.

The fact that there were no significant main effects of either pixel-count or antialiasing condition would simplify target-size corrections for the present simulator system. It should be noted, however, that there were visible differences among targets displayed at the two antialiasing conditions tested here. Thus, the present calibration procedure does not capture all of the differences among targets that may be relevant in flight-simulator applications. On the other hand, the significant interaction between pixel-count and antialiasing condition might complicate calibration procedures in that the results obtained from one system may not be applicable to another when both of these characteristics are different for the two systems. A visual inspection of the data of Figure 3 suggests, however, that this interaction is due largely to a single data point (9022 ft under the 1280/no-antialiasing condition). Therefore, these data should be verified on other systems of interest before concluding that this interaction is of practical concern.

EXPERIMENT 2

In this experiment, we verified for an intermediate pixel count, the generality of the size-calibration procedure described in Experiment 1. The lack of an antialiasing effect in Experiment 1 was surprising given the significant visual difference in the appearance of targets displayed with and without antialiasing. We therefore, increased the level of antialiasing in Experiment 2 in order to better quantify the effects of this variable. Finally, to further validate the present size-calibration procedures, we obtained perceptual data to verify that the target images visible on the videotape were also visible on the simulator display. This correlation is critical if the present calibration procedure is to be used to choose target sizes that will serve as appropriate cues in flight-simulator training (Brown, 1984; Griffith, *et al.*, 2000).

Methods

Videotape Analysis

Target-size estimates were again obtained, from a videotape of the target presentations, by two evaluators, one of whom (CC) had performed the videotape analysis in Experiment 1.

The test targets were the same as in Experiment 1 except that only three nominal simulated target distances (6310, 7943, and 10000 ft) were used. In addition, an intermediate pixel-count of 1600×1200, two antialiasing levels (no-antialiasing and 4×-antialiasing), and six target gray-levels (90, 110, 130, 150, 170, and 190) were tested. The size and temporal properties of the targets precluded a direct measurement of their luminance (and hence their contrast as displayed on the background imagery). Such measurements are not required for the purposes of the present study, but target luminance and contrast may be estimated, if necessary, from the perceptual data described below. The apparatus and videotape analysis procedures were the same as described in Experiment 1 except that a different Barco 808 projector and Proscreen 1.2-gain rear-projection screen were used. The spatial resolution of the displays was similar to those of Experiment 1.

Perceptual Analysis

Four observers (including authors GG and CC) participated in the perceptual study. All observers had normal or corrected-to-normal acuity, and normal binocular vision, color vision, and phoria as determined by the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

The stimuli and display system were the same as those used for the videotape analysis. The perceptual analysis was performed using a two-alternative forced choice procedure whereby observers were asked to determine which of two presentation intervals contained a stimulus. Each interval lasted 1.5 seconds, and was preceded by an audio cue. A third audio cue was used to indicate when a response was required. The observers used the left and right buttons of a mouse to respond.

Each combination of simulated distance, antialiasing level, and contrast was tested during the course of six experimental sessions. In addition, there were a total of 4 repetitions within which target heading, and the presentation order within each presentation interval were randomized.

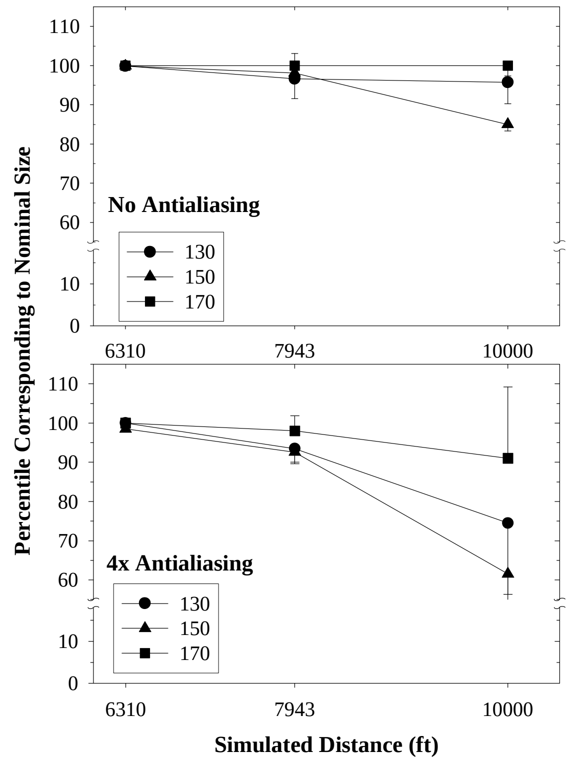

Figure 5. Target-size distribution percentile corresponding to the nominal size of the target at each simulated distance, contrast, and antialiasing level tested in Experiment 2. Error bars are ±1 standard errors of the mean.

Results

Videotape Analysis

Shown in Figure 4 are the target-size distributions, for each of the target distances and contrasts tested under the 4×-antialiasing condition, averaged over the estimates of the two evaluators. Also shown in Figure 4 are the simulated distances corresponding to actual target size. Once again the horizontal solid and dashed lines indicate the nominal and actual (50^{th} percentile of measured size distribution) target sizes, respectively. Shown in Figure 5 are the target-size distribution percentiles corresponding to the nominal size of the target at each simulated distance. The data are shown for both antialiasing conditions (0 and 4×) and for three target gray-levels (130, 150, and 170). As was the case in Experiment 1, the percentile corresponding to nominal size decreased as simulated distance increased. This decrease was statistically significant as indicated by the significant Simulated-Distance main effect [$F(2,6)=45$, $p<0.001$]. The main effect of Antialiasing-Condition was also statistically significant [$F(1,3)=13.7$, $p=0.034$]

indicating that the mean of all data for the no-antialiasing condition (upper graph of Figure 5) was larger than the analogous mean for the 4×-antialiasing condition (lower graph of Figure 5). The Distance × Antialiasing-Condition interaction was significant [$F(2,6)=13.2$, $p=0.006$] as evidenced by the overall greater decrease in the three contrast functions found for the 4×-antialiasing condition as compared to the no-antialiasing condition. Finally, the Distance × Antialiasing × Contrast interaction was also significant [$F(4,12)=5.6$, $p=0.009$].

Perceptual Analysis

Shown in Figure 6 is the proportion of correct target detection as a function of target gray-level, antialiasing condition, and simulated distance. The data are averaged over the four observers. The proportion correct is greater than 0.97, on average, for the target gray-levels of 90, 100, and 190, and it varies between about 0.55 and 0.95 for the intermediate gray-levels of 130, 150, and 170. A repeated-measures ANOVA indicated that the overall change in Proportion Correct with Gray-Level was statistically significant [$F(5,15)=6.0$, $p=0.0015$]. The effect of Simulated-Distance was also significant [$F(2,6)=16.6$, $p=0.0036$], which is reflected in the changes in mean Proportion Correct for the three functions in each graph of Figure 6. Finally, there was a significant interaction between Gray-Level and Simulated-Distance [$F(5,15)=5.48$, $p=0.005$] as indicated by the changes in shape of the three functions in each graph.

Shown in Figure 7 are the percentages of the targets that were not visible on the videotape for the three target gray-levels for which the proportion of correct detection was less than about 0.97 (see Figure 6). The percentages of targets that were not visible increased with simulated distance, did not vary on average with antialiasing condition, and were somewhat higher for a gray-level of 130 than for gray levels of 150 or 170.

Discussion

The data of Figure 5 are similar to those of Figure 3 (Experiment 1) and indicate that the measured mean size of simulated targets is significantly smaller than the nominal target sizes required to accurately portray target distance. It was found in Experiment 1 that for the 1280 pixel-count condition, measured target-size was smaller for no-antialiasing than for 2×-antialiasing. In Experiment 2, antialiasing level was increased to 4×, which did significantly affect the measured size of simulated targets as compared to the

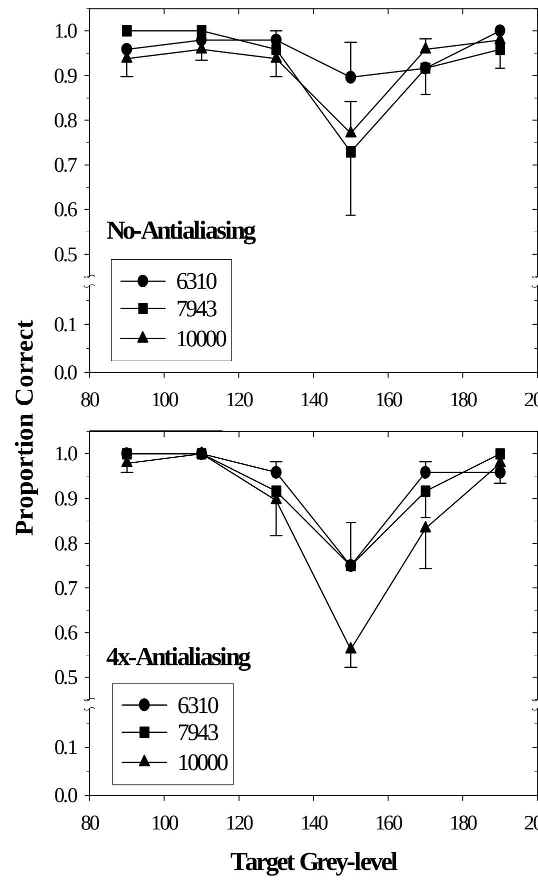

Figure 6. Proportion of correct target detection as a function of target contrast for each of the three simulated target distances and both antialiasing levels (none and 4×). The data are averages over four observers, and error bars are ±1 standard errors of the mean.

no-antialiasing condition. This result suggests that spatial smoothing over 2-4 pixels (i.e. 2× antialiasing) does not affect the time-average size of even small objects. Antialiasing that affects six to eight times as many pixels (i.e. 4× antialiasing) does affect the size distribution of smaller targets—in this case targets simulated at between about 7900 and 10000 ft. If the mean of the target-size distribution is taken as the criterion for assessing the accuracy of simulated distance, 4× antialiasing would be considered to have improved the quality of the simulation.

The perceptual data of Figure 6 indicate that most targets presented on the simulator were clearly visible. The only targets that were not visible on at least 97% of test trials were in a narrow luminance band corresponding to gray levels of between 120 and 180. Even the targets whose luminance fell within this band were visible, on average, on more than 80%

of the test trials. For comparison, the data of Figure 7 show that, on average, more than 93% of the targets whose luminance fell within the band described above were visible on the videotape. Although a comparison of the data shown in Figure 6 and 7 is preliminary in that the data were obtained from a single display system and only two observers, the clear correlation between the videotape and perceptual data is sufficient to tentatively conclude that the visibility of the target stimuli was similar on both the simulator and videotape displays. Consequently, we conclude that the size-distributions (Figs. 2 and 4) and derived functions (Figs. 3 and 5) are valid measures of the size of the targets presented by the IG and display system evaluated here.

CONCLUSION

We have developed a technique for calibrating the size of targets displayed in a CRT-based flight simulator. It was found that the simulated target size varied by as much as a factor of four for a fixed simulated distance. This variation in target size was also affected by the level of antialias filtering and stimulus gray-level. In general, the mean of the measured-target sizes was less than the size required to accurately simulate target distance. It remains to be determined if the mean (i.e., 50th percentile) of the target size distribution is the parameter that correlates with performance on flight simulator tasks.

Crane (1999) reported that pilots participating in a distributed mission training (DMT) exercise found the training to be useful for a number of mission tasks. The only exceptions were "tasks involving visual detection and recognition of aircraft". The limitation in performing tasks of this type is inherent in the display properties of large field-of-view simulators (Geri, *et al*., 2004; Winterbottom, *et al*., 2003). The use of the target-size calibration procedure described here cannot eliminate this problem, but it may improve the effectiveness of simulator training by helping to assess simulator capability, and better match simulators with the tasks that need to be trained.

Variations in stimulus size were found to be nonlinear functions of simulated distance. Therefore, a single factor would not be sufficient to correct target size variations like those described here. Such corrections would have to be performed in real time, resulting in an increased computational demand and a slower simulation. It may be possible to avoid real-time correction by using a single intermediate correction factor, but this would provide only a limited solution.

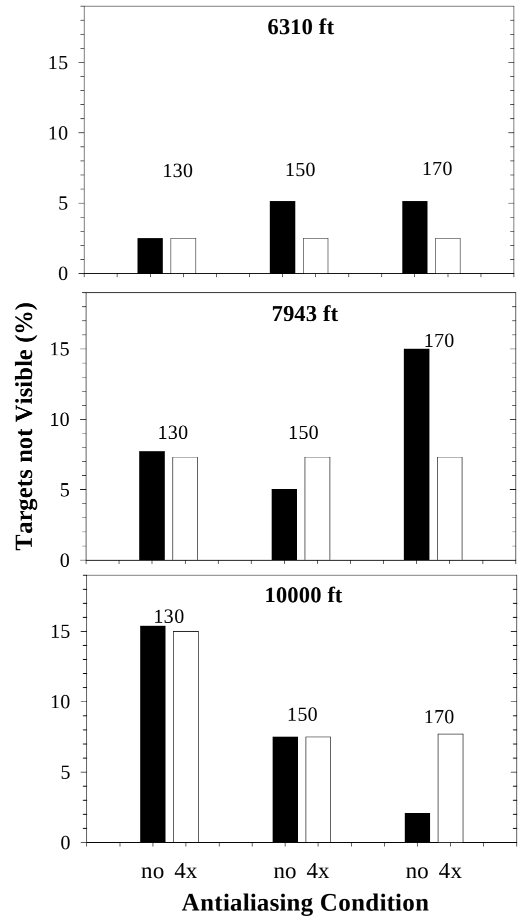

Figure 7. Percentage of targets not visible on the videotape for the three target gray-levels, three distances, and two antialiasing levels.

A somewhat better solution would be to use one of several models of different sizes in accordance with the levels of detail provided by the graphics system. Current full field-of-view flight simulators can accurately simulate targets to only about 8000 ft. The data of Figure 2 suggest that two levels of detail, corresponding to ranges of 0-6000 ft, and 6000-10000 ft, would be sufficient to adequately correct for the full range of target distances that can currently be simulated.

Brown (1984) has estimated the ranges at which various basic-fighter-maneuver and air-combat-maneuver tasks can be performed. These tasks require an accurate visual assessment of target orientation, and as such are also dependent on simulated target-size. The effective range for performing the various tasks cited by Brown is between 2000 ft and 18000 ft. This range encompasses the range of target distances tested in the present study, and over which target distance was not accurately simulated--based on the 50th percentile of target size as measured here. The maximum distance tested in the present study exceeds the distance at which aircraft orientation can be accurately detected in a typical wide field-of-view flight simulator (i.e., the M2DART, see Winterbottom, *et al*., 2003). Thus, it is clearly important to accurately simulate target size in order to effectively train tasks such as those discussed by Brown (1984). This conclusion is also supported by the data of Warner, *et al*., (1993) who found that aircraft orientation identification performance decreased significantly for target distances greater than about 5000 ft.

The present data indicate that the target-size calibration described here must also take into account both antialiasing level and pixel-count. However, both of these simulator characteristics are typically fixed and hence can be addressed by an easily applied, constant correction factor. The present data are not sufficient to determine what target-size distribution percentile should be matched to nominal target size. Thus, further experimentation will be necessary to determine what correction factor, or set of factors, should be used in a particular flight simulator application.

Finally, the present target calibration technique was performed by comparing the visibility of targets displayed in both an operational flight simulator and targets appearing in a videotape of the flight-simulator display. In the present case the two visibilities were similar, but this cannot generally be assumed. Therefore, a comparison of the visibility of displayed and videotaped targets would have to be performed whenever the proposed calibration procedure is used.

ACKNOWLEDGEMENTS

This research was performed by Link Simulation and Training, a division of L-3 Communications Corp., under U.S. Air Force Contract F41624-97-C-5000. We thank Steven Gustafson of The Boeing Company for programming support and Jennifer Winner of Link Simulation for research assistance.

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