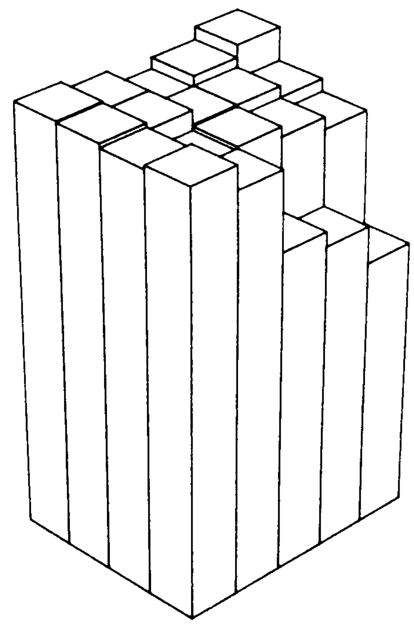
# A Psychophysical Approach to Assessing the Quality of Antialiased Images

James A. Ferwerda and Donald P. Greenberg
Cornell University

As the complexity of object models used in image synthesis increases, the image distortions caused by aliasing are exacerbated. Since methods for eliminating aliasing artifacts from synthetic images involve a filtering operation, the subjective clarity of the images is reduced. Thus it is often assumed that antialiasing destroys useful visual information about object features. We challenge this assumption in three experiments that examine the effects of antialiasing on the visual information for object location and motion.

Taken together, the results of these experiments show that proper antialiasing eliminates the spurious visual information produced by sampling processes in image synthesis and allows the viewer's visual system to produce a precise representation of object location and a continuous representation of object motion. These results suggest that in designing imaging systems simply increasing the spatial and temporal addressability and resolution beyond limits set by the human visual system will have a negligible impact on image quality, but that effective use of antialiasing techniques can allow visual information about object features to be presented with great fidelity.



In the quest for greater realism, computer graphics researchers are producing ever more complex object and environment models. Yet the very complexity of these models exacerbates the image distortions produced by aliasing in the rendering process. Antialiasing techniques reduce the visibility of these distortions at the cost of a loss in subjective image clarity and, it is often assumed, reduced image quality. The greater image detail gained by increased model complexity is considered lost through the filtering performed during antialiasing.

This apparent dilemma comes from looking at the issue of image quality with regard only for the physical features of images. In many computer graphics applica-


0272-1716/88/0900-0085$01.00 1988 IEEE

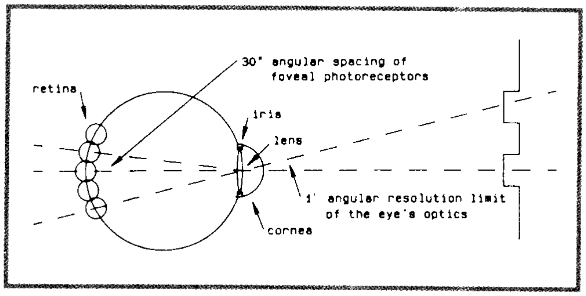



**Figure 1. Schematic view of the eye showing the limiting resolution of the eye's optics and the spacing of foveal photoreceptors in terms of visual angle.**

tions, computer-generated images provide viewers with the visual information necessary to make some decision or perform some task. Useful measures of image quality must consider the perceptual issue of how the informative content of images is affected by the processes used to create them.

Raster images are formed by sampling processes. Scene descriptions are sampled spatially to produce quantized pixel intensity values and temporally to produce the individual frames of a dynamic image sequence. An improperly formed image can exhibit visible aliasing artifacts that limit the image's quality by revealing the discrete nature of the sampling processes that created the image.

If the spatial sampling process used to create an image is insufficient, then the continuous contours of objects depicted in the image will sometimes have a jagged appearance. Long thin objects may appear segmented, and small objects in the original scene may be entirely absent from the image. If the temporal sampling process used to create a dynamic image sequence is insufficient, then the motions of objects depicted in the sequence will appear jittery. Spinning objects may appear stationary or seem to be rotating in a direction opposite to their true course of motion.

These image distortions are examples of what is known in the computer graphics literature as the aliasing problem. One obvious approach to reducing these distortions is to increase the addressability and resolution of the imaging system. This ad hoc method reduces aliasing in some situations, but it provides neither a comprehensive nor cost-effective solution to the problem, as it assumes that aliasing can be eliminated simply by sampling more often and relies on extending the current limits in display technology.

Aliasing occurs because the discrete sampling processes used to create an image are insufficient to accurately represent the objects being displayed. Only by using antialiasing methods that allow displayed objects to be properly sampled can the image distortions produced by aliasing be eliminated. While these methods are well understood, what is not known is how antialiasing affects the useful information content of images. Only recently have researchers attempted to analyze and quantify the effects of aliasing and antialiasing on performance in tasks involving interaction with synthetic images.[1]

In this article, the effects of antialiasing on the visual information for object location and motion are examined. It is commonly assumed that since antialiasing methods are essentially filtering operations and reduce the subjective clarity of an image, they necessarily destroy useful visual information for location and motion. On the contrary, we will show that for tasks requiring detailed knowledge about the spatiotemporal features of imaged objects, proper antialiasing eliminates the spurious visual information produced by sampling and allows visual processes to work effectively to the limits of their accuracy.

## Image formation in the eye

In the human eye, the cornea, iris, and lens constitute an optical system that forms an image on the retinal surface. As with any optical system, aberrations in the optical components and diffraction produced by the entry aperture limit the resolution of the image. Resolution is a term used loosely in the computer graphics literature. Our use is close to its optical definition. By the term resolution we mean the fidelity with which object features are represented in an image. Features smaller than the resolution limit are not discernable in the image. Measurements have shown that the resolution of the image produced by the eye's optics is limited to about 1 minute of visual angle (see Figure 1).[2]

The image formed by the eye's optics falls on the photosensitive cells of the retina. The cells are arrayed in a roughly hexagonal grid. A centrally located region known as the fovea has the highest cell density. Here cell centers have an angular separation of approximately 30 seconds.[3] The photosensitive cells sample the retinal image to produce a neural image representation. In terms of sampling theory, the spacing of the retinal photoreceptors is well matched to the optics of the eye. The filtering provided by the eye's optics allows the photoreceptors to create an accurate discrete representation of the continuous retinal image through sampling at intervals given by the spacing of cells in the retinal mosaic.[4]

The photosensitive cells in the retinal mosaic are interconnected in clusters known as receptive fields. These receptive fields have an opponent organization with an excitatory central region and an inhibitory surround. Receptive fields vary greatly in size, being maximally sensitive to different scales of image features. The smallest receptive fields are in the fovea and are most sensitive to patterns with elements on the same scale as the spacing of the foveal photoreceptors.[5]

These three factors—optical filtering, receptor sampling, and the receptive field organization of early visual processing—affect the fidelity with which the visual system represents the patterns of light arriving at the eye. The perceptual measure of this fidelity is known as visual acuity.

## Visual acuity

From a bright line in the visual field the eye's optics will produce a retinal image that has an Airy pattern intensity profile (see Figure 2a). If there are two bright lines side by side in the visual field, their retinal intensity profiles will overlap, producing a composite intensity distribution with a central minimum (see Figure 2b). As the two lines are brought closer together, the intensity of the central minimum will increase, reducing the contrast in this region of the image. The limiting distance necessary to allow these two points to be visually discriminated is a measure of the resolving power of the visual system.

This is one measure of visual acuity. It shows that acuity is a function of contrast sensitivity. The acuity limit is determined by the visual system's ability to detect the small contrast gradient in the center of the composite distribution. Contrast sensitivity limits this kind of visual acuity to approximately 1 minute of visual angle.[2]

Vernier acuity is another measure of visual acuity. It is not a measure of resolution, but instead specifies the visual system's ability to localize the positions of objects in the visual field. If two bright lines are laid end to end, observers can detect misalignments of the lines as small as 4 to 6 seconds of visual angle.[6] This precision is remarkable in that it corresponds to approximately one fifth of the distance between the foveal photoreceptors. While there is much speculation on how the visual system produces such a fine-grained representation of position,[7-10] what is clear is that this fine positional acuity must be based on information contained in the discrete image representation produced by photoreceptor sampling of the optically filtered retinal image.

## Experiment 1: Spatial antialiasing and acuity

Image contours must be antialiased if the artifacts produced by the spatial sampling process in image synthesis are to be eliminated. It is commonly assumed that the visible blurring produced by spatial antialiasing destroys accurate visual information for the locations of objects in the image.

Experiment 1 used a vernier discrimination task to determine the precision with which the visual locations of objects can be specified in an antialiased image displayed on a raster-scan CRT.

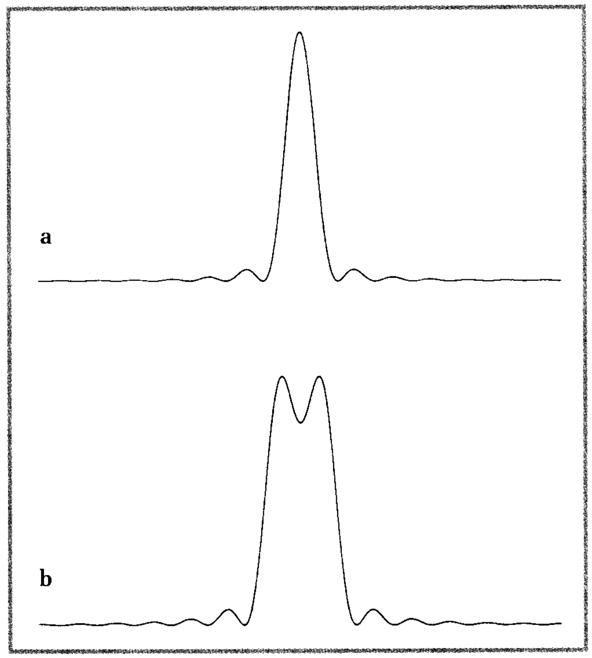



**Figure 2. (a) Airy pattern intensity profile of an imaged line source, (b) intensity profile of two closely spaced line sources.**

### Methods

Achromatic two-segment vernier targets were displayed on a Conrac Model 7300 high-resolution color monitor driven by a Rastertek Model 1/380 frame buffer with 1,280 horizontal by 1,024 vertical addressable pixel locations, and 256 specifiable pixel intensity levels in each of the red, green, and blue color channels. While it was not possible to measure the actual spatial intensity distribution of a pixel on the monitor screen, all calculated target characteristics were based on the well-founded assumption of pixels with gaussian intensity profiles and halfwidths equal to the spacing of the addressable pixel raster.[11,12] The display system was calibrated to ensure a linear relationship between the calculated intensity levels in the target images and the achromatic luminous intensities on the monitor screen.

Figure 3 shows a schematic representation of the experimental setup. Observers viewed the monitor under photopic conditions from a distance of 70 inches. At this distance each picture element subtends approximately 30 seconds of visual angle. The distance was chosen so that the spatial structure of the CRT raster would be below the resolution limit of the eye's optics and would therefore be invisible to the observer. Thus the image would appear to be a continuous luminous intensity dis-

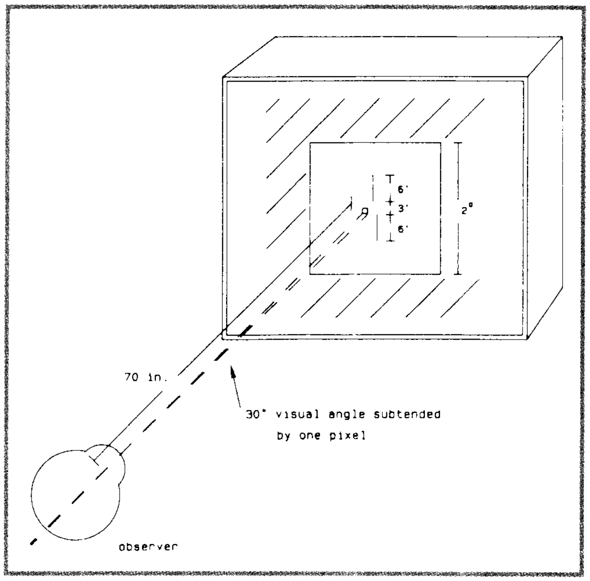



**Figure 3. Experimental setup: angular subtents of display elements at a viewing distance of 70 inches.**

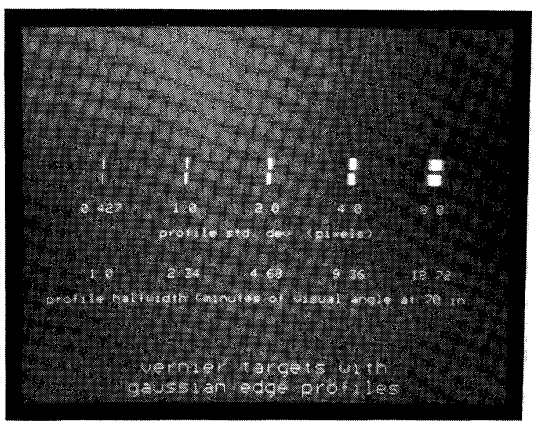



**Figure 4. Vernier targets used in the experiments.**

tribution. Targets appeared in a square window in the center of the monitor screen. The window subtended approximately 2 degrees of visual angle on a side at the specified viewing distance. The remainder of the monitor screen was masked from view. Using standard methods,[13] target contrast was calculated to be 80 percent, with peak target luminance set to 25 footlamberts and background luminance set to 2.75 footlamberts.

Examples of the test targets are shown in Figure 4. At the specified viewing distance each target segment subtended 12 minutes of visual angle in the vertical direction. The top and bottom segments were separated by a 6-minute gap, yielding a target whose overall angular extent in the vertical direction was 30 minutes. Targets of this form were found by Westheimer to yield optimal vernier acuity thresholds.[14]

In the horizontal direction the target segments were defined to have gaussian intensity profiles. The standard deviations of the profiles were defined with respect to the horizontal dimensions of the pixel raster and ranged from 0.427 to 8.00 pixels. This yielded segment profiles with calculated angular halfwidths (the distance spanning the 50-percent intensity points in the gaussian profile) ranging from 1.0 minute to 18.72 minutes at the specified viewing distance. This range of profile widths, which is seen as an increasing degree of blur in the target segments, corresponds to segment profiles with increasingly limited Fourier spectra. The narrowest target had the widest spectral bandwidth, which fell to 50 percent amplitude at 30 cycles/degree. These spectral characteristics ensured that the target intensity profiles would not alias significantly when sampled at the addressability of the pixel raster, thus allowing the real continuous positions of the vernier segments to be represented in the displayed image.

The target intensity profiles were quantized to 256 discrete levels before display. Quantization is a form of intensity sampling that limits the accuracy with which a continuous intensity distribution can be represented by an imaging system.[15] Given that continuous variation in target position is represented in the image by incremental changes in its quantized intensity profile, the physical limit of positional addressability in the imaging system used in the experiments was determined by the smallest real target movement that caused a change in the quantized intensity profile. The magnitude of this movement varied with the halfwidth of the continuous intensity profile. In the worst case (for the broadest profile) the movement was found to be 0.037 pixels. This figure was used as the limiting offset in the vernier threshold experiments.

## Procedures

Subjects participated in a vernier discrimination task. Thresholds for perceived offset of the two target segments were established for each of the vernier targets shown in Figure 4. Threshold measures were taken using a forced-choice staircase procedure similar to that described by Cornsweet.[16] This procedure allowed the rapid determination of threshold values for the target conditions in a short number of trials. On each trial a subject saw a brief (183.33-millisecond) presentation of a vernier target with the top segment horizontally offset from the bottom segment. The subject's task was to say whether the top segment was to the right or the left of the bottom one. For every correct response, the offset was

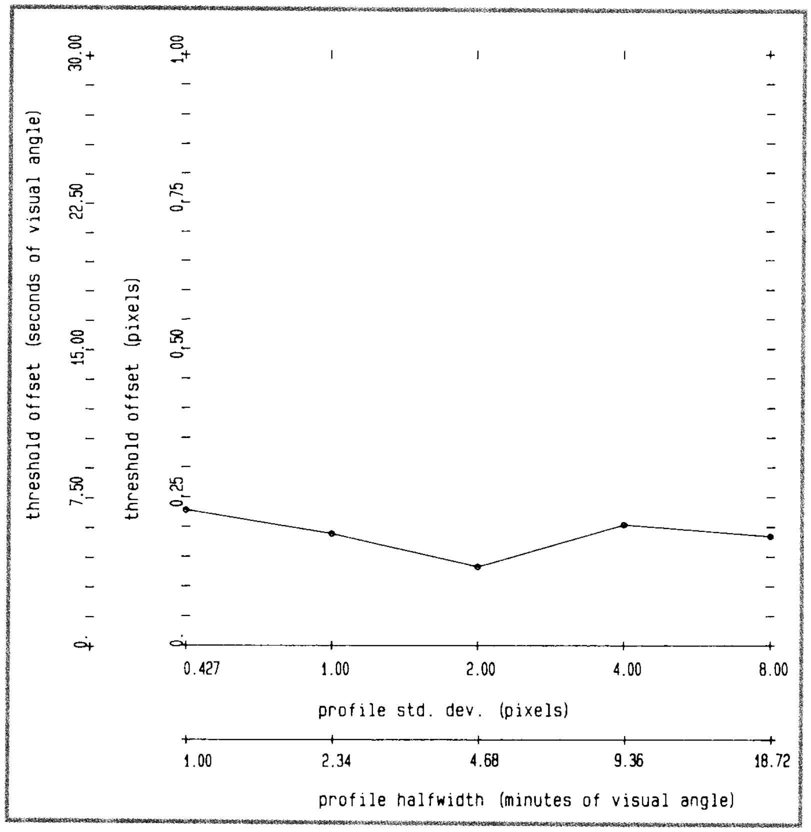



**Figure 5. Results of experiment 1.**

reduced by a small interval. For every wrong response, the offset was increased by the interval. When the subject's responses changed from correct to incorrect or vice versa, the size of the interval was halved. The steplike appearance of the trial record showing closer and closer approximations to the threshold value gives the staircase procedure its name.

Two staircases, each thirty trials long, were used to establish separate thresholds for leftward and rightward offset for each target condition. The trials of each staircase were randomly interleaved to prevent response biases. Thresholds were taken to be the average of the last ten trials in a staircase. Four separate measures of threshold offset were taken for each of the target conditions over the course of four experimental sessions. The order of presentation of target conditions was randomized from session to session. Subjects were instructed to maintain fixation on the targets during the trials. A fixation pattern defined by the bounding corners of a square frame, 1 degree on a side, helped subjects maintain gaze direction and signaled trial onset and completion. This fixation pattern appeared 1.5 seconds before a trial and disappeared 0.5 seconds after.

The subjects were the first author and two male graduate students who did not know about the design of the experiment. All were in their late twenties. One had normal vision and the other two were corrected myopes.

## Results

The results from the combined data of the three subjects are summarized in Figure 5. Parallel axes show the data defined with respect to the dimensions of the pixel raster and in terms of visual angle. Three results stand out:

- All the offset thresholds are smaller than a pixel. This means that in a properly antialiased image, the visual locations of objects can be detected on a scale that is finer than that defined by the addressability of the pixel raster.
- At the given viewing distance, the offset values, measured in fractions of a pixel, correspond to angular offsets that are on the order of the optimal vernier acuity thresholds of 4 to 6 seconds of visual angle found by Westheimer.[14] Taken with the first result, this means that in a color raster-scan CRT viewed at a distance where the raster structure is not resolvable by the eye, the usable spatial addressability in a gray-scale image quantized to 256 intensity levels is on the order of the finest visual positional acuity. The

reason is that the visual system has the ability to convert gray-scale intensity gradients that depict antialiased object contours into information about the precise spatial locations of the objects.

- The thresholds are remarkably stable over the range of target conditions, which correspond in appearance to increasing levels of blur, and in physical specification to targets that have been antialiased with larger and larger gaussian filter kernels. This means that the visual process that allows such fine positional acuity does not necessarily rely on information contained in sharp image contours to perform its task. Work supporting this result has been done by Stigmar.[17]

Thus antialiased raster images can provide visual information for the locations of objects that is much more precise than the limit suggested by the addressability of the pixel raster. This finding lends empirical validity to earlier anecdotal investigations of subpixel positioning,[18-20] and refutes the notion that the visual information for object location is degraded by the filtering that occurs with gaussian antialiasing.

## Stroboscopic motion

Early researchers Wertheimer[21] and Korte[22] discovered that an impression of continuous motion could be elicited by the rapid alternation of two images showing a target at discrete locations. Different researchers have called this phenomenon beta motion, phi motion, and apparent motion. These motion phenomena show that there can be significant differences between the motion stimulus and its percept. They also raise the theoretical question of how the visual system can produce an impression of continuous motion from a sequence of discrete images.

Neuhaus mapped out the relationship between distance and time in two-image apparent motion displays.[23] He found that image pairs with large interimage displacements (greater than 2 degrees) and long interimage intervals (200-300 milliseconds) produced the most convincing impressions of continuous motion.

Sperling, studying motion perception in computer-driven displays, compared the distance and time relationships in two-image apparent motion displays and in multiple-image stroboscopic motion displays of the kind seen in motion pictures and television.[24] He found that the interimage displacements and interimage intervals that produced the best impressions of continuous motion in stroboscopic displays were much smaller than those that produced the best motions in the classical two-image displays. In addition he found great discrepancies in how convincing the simulated motions were. On a scale of 0 to 10 with 10 being the rating of highest quality, only a small percentage of the two-image displays received a rating greater than 0, while many of the multiple-image displays received ratings in the upper half of the scale. In computer-generated displays, multiple-image sequences of this sort are used to produce impressions of object motion.

## Experiment 2: Temporal antialiasing and stroboscopic motion continuity

A stroboscopic image sequence formed by instantaneously sampling the motion of an object may contain visible distortions introduced by the sampling process that reduce the visual quality of the depicted motion. Temporal antialiasing methods lessen these distortions by making each image in the sequence account for motion that occurs in a finite time interval. A smoothly moving object will occupy a continuous range of positions in an interval and will thus produce a blurred record in each image. The temporal filtering effected by antialiasing facilitates the perception of continuous motion in stroboscopic image sequences.

Experiment 2 examined the phenomenology of stroboscopic motion and revealed conditions under which stroboscopic image sequences depicting motion yielded high ratings of motion continuity.

### Methods

The methods and apparatus used in this experiment were the same as those used in experiment 1. The targets were vertical line segments 30 minutes in length, defined in their horizontal dimensions by the set of gaussian intensity profiles used in the first experiment.

Target motions were depicted in stroboscopic image sequences. Each sequence was 11 images in length and had a duration of 183 milliseconds when displayed at the rate of 60 images/second. The duration of the image sequence was chosen to be long enough to give a good impression of motion[25] and short enough to preclude the complicating effects of eye movements sometimes found in motion studies.[26,27]

In stroboscopic motion studies it is important to consider how the temporal response properties of the display system affect the characteristics of the stroboscopic motion stimulus. A major factor is the decay time of the monitor phosphors. If the decay time of the phosphors is longer than the frame rate, then the images will be superimposed in the display. The 100-microsecond decay time of the phosphors in the monitor used in these studies ensured that the individual images in the sequence were presented discretely.

Target motions at velocities of 0.5, 1.0, 2.0, and 4.0 degrees of visual angle per second were simulated. The target motions were sampled at two different temporal rates to produce two sets of image sequences. At the "fast" sampling rate the target position was sampled for every frame of the image sequence. At this rate the defined target velocities correspond to interframe target displacements (IFDs) of 1, 2, 4, and 8 pixels per frame. At the "slow" sampling rate, the target position was only sampled every other frame. Frame pairs showed the same image. At this rate the defined target velocities correspond to target displacements of 2, 4, 8, and 16 pixels per frame pair. The fast and slow sampling rates correspond to sampling the continuous target motion at temporal frequencies of 60 Hz and 30 Hz, respectively, but displaying the resulting image sequence at an update rate of 60 Hz. Image sequences created and displayed in this way allow the effects of sampling rate to be studied without the flicker usually associated with slow sampling and display rates.

### Procedures

Twenty dynamic target conditions were formed by pairing each of the gaussian target profiles with each of the defined target velocities. The calculated motion courses of the dynamic targets were sampled at both the fast and slow rates to produce two sets of stroboscopic image sequences.

On each trial in the experimental session the subject viewed one of the image sequences and was asked to rate how continuous the depicted motion appeared on a scale from 1 to 9, with 9 being the highest continuity rating. Subjects rated 20 image sequences of each target condition. Ten depicted the target motion at the fast sampling rate, and ten showed it at the slow sampling rate. Half of the image sequences depicted leftward motion and half showed motion to the right. The order of presentation of the trials was randomized. Subjects maintained central fixation throughout each trial with the aid of a fixation pattern as in experiment 1. The extents of the motion paths always remained within the bounds of the fixation pattern and were always equally divided around the center of fixation. The subjects in this experiment were the first author and two male graduate students, all in their late twenties and with corrected vision.

### Results

The results of this study are summarized in the histograms shown in Figure 6. Each histogram represents the combined data of the three subjects. Separate histograms show the ratings given to target motions depicted in image sequences formed at the fast (Figure 6a) and slow (Figure 6b) sampling rates. Parallel axes on the histograms show the target parameters defined both with respect to the dimensions of the pixel raster and in terms of visual angle. Three results stand out:

- Subjects rated the motion sequences of the targets with broad-profile halfwidths as appearing more continuous than the sequences depicting the motions of targets with narrow-profile halfwidths.
- Motion sequences showing low-velocity target motions were rated as more continuous than those showing high-velocity target motions.
- The sampling rate at which an image sequence was made had a major effect on continuity ratings.

These results show that in stroboscopic image sequences there are three factors that influence the visual continuity of the depicted motion. *A three-way relationship exists between target profile halfwidth, target velocity, and the sampling rate at which an image sequence is made.*

For a target moving at a constant velocity, the sampling theorem specifies the spatial and temporal sampling rates that must be used if the target's form and motion are to be correctly represented. These rates depend on the gradient of the target's edge profile and the velocity at which the target is moving. Lower sampling rates can be used if the spatiotemporal bandwidth of the moving target is limited by antialiasing methods before sampling.[28]

In the experiment, a trade-off was seen between target edge profile and target velocity. Within a bounded range, as the velocity parameter was increased, a given continuity rating was achieved only by targets with more extremely filtered edge profiles. When a less filtered target was used, the target's velocity had to be reduced to receive a given continuity rating.

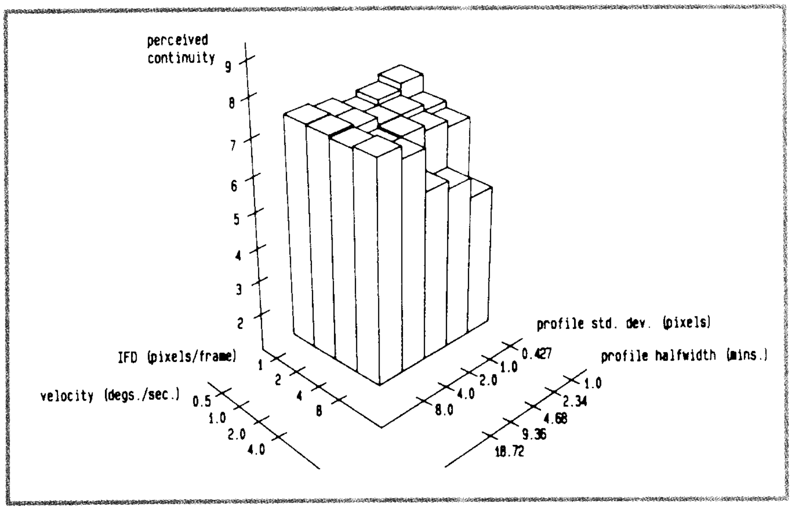
Similarly, there was a trade-off between the sampling rate at which an image sequence was made and the spatiotemporal characteristics of the moving target. At the slow sampling rate, a continuity rating given at the fast sampling rate could be maintained only if the target's velocity was reduced or its edge profile was broadened by more extreme filtering.

The image sequences of moving targets used in this experiment can be characterized in two ways: either as instantaneous samples of spatially antialiased targets, or as temporally antialiased samples of targets with step-edged intensity profiles. In either case the resulting images are the same and will be perceived in the same way by the viewer. Thus there is a reciprocity between the effects of spatial and temporal gaussian antialiasing on perceived motion continuity that is modulated by the sampling rate at which an image sequence is made.

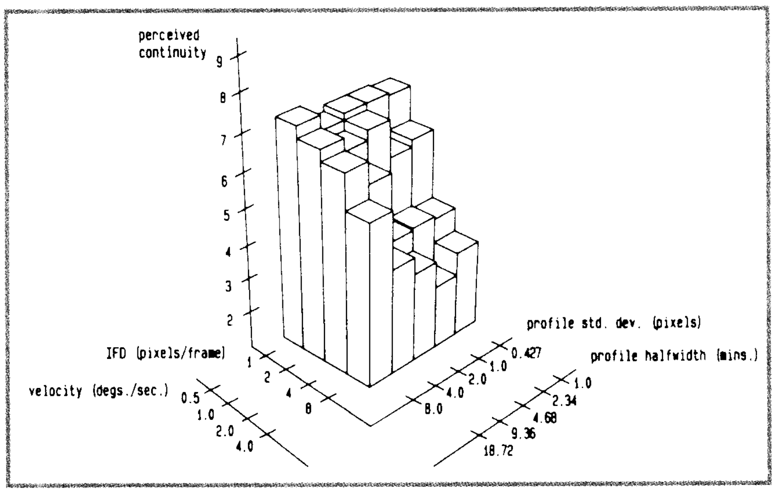
## Visual persistence

One of the earliest observations about the temporal properties of vision was that the sensations from brief visual events persist for a period of time beyond their actual duration. Newton was one of the earliest researchers to do a systematic study of the persistence of vision. The following quotation illustrates his method and hypothesis:

> And when a Coal of Fire moved nimbly in the circumference of a Circle, makes the whole circumference appear like a Circle of Fire; is it not because the Motions excited in the bottom of the Eye by the Rays of Light are of a lasting nature, and continue till the Coal of Fire in going round returns to its former place?[29]




a




b

**Figure 6. Results of experiment 2: (a) "fast" 60-Hz sampling rate, (b) "slow" 30-Hz sampling rate.**

Newton found that the circle appeared complete at about one revolution per second and concluded that 1 second was the temporal summation period of vision. More recent studies are in rough agreement with his results for conditions of low overall illumination, but find that at normal levels of illumination the summation period is about 120 milliseconds.[30]

## Motion blur

Psychologists have suggested that our ability to perceive motion in stroboscopic image sequences is due to an integrative process in vision evidenced by the phenomenon of visual persistence.[31,32] If motion perception is served by a process that integrates the stimulus energy of a moving object over time, we would expect that visual information for the precise features of moving objects would be destroyed by the process of integration. Support for this notion is given by the blurred visual impressions created by rapidly moving objects.

In stroboscopic image sequences that depict motion, it is often necessary to temporally antialias the images to eliminate visible artifacts of the temporal sampling process that created the image sequence. This temporal antialiasing is often likened to the blurring of rapidly moving objects produced as a by-product of the film recording process. Because these processes produce a visible blurring of moving objects in the images, it is often assumed that they destroy visual information about detailed features of the moving objects.

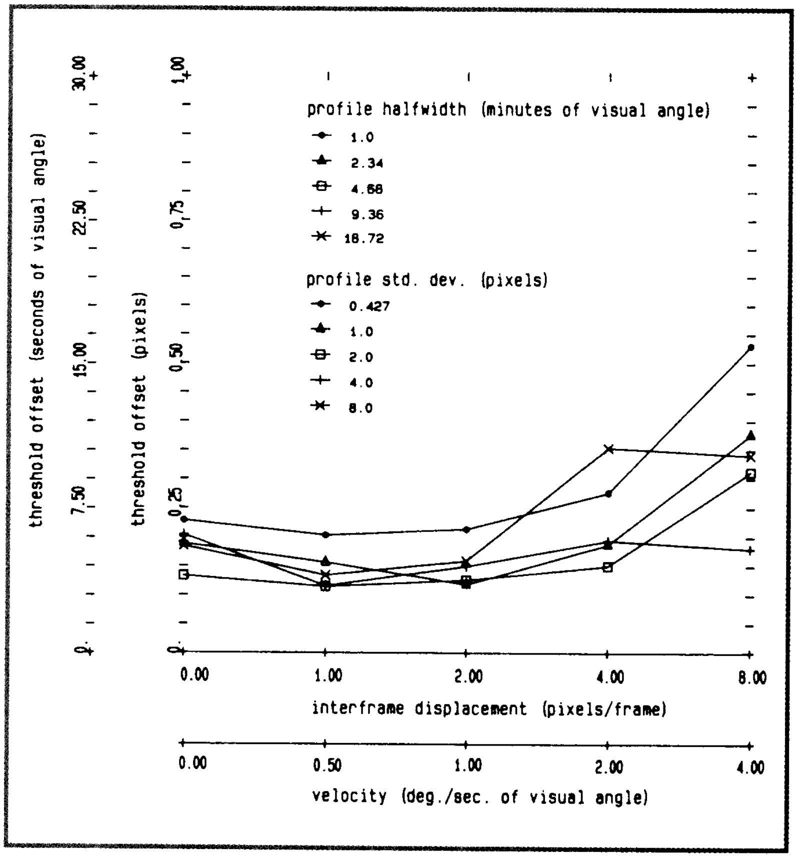



**Figure 7. Results of experiment 3.**

## Experiment 3: Antialiasing and acuity for stroboscopically moving objects

Experiment 3 used a vernier discrimination task to examine visual acuity for the features of moving objects depicted in stroboscopic image sequences.

### Methods

The methods and apparatus used in this experiment were the same as those used in the previous experiments. The vernier targets shown in Figure 4 were presented in stroboscopic motion sequences of the form developed in experiment 2. Twenty target conditions were established by creating stroboscopic image sequences of the target motions sampled at the fast rate used in experiment 2.

### Procedures

The subject's task on each trial was to indicate whether the top segment of the moving vernier target appeared to the left or right of the bottom segment. Offset thresholds for each target condition were established by staircase procedures of the kind described in experiment 1. Four measures of offset threshold were taken for each target condition. A fixation pattern of the form described in experiment 1 helped subjects maintain fixation throughout each trial. The subjects were the same as in experiment 1.

### Results

The results for the combined data of three subjects are shown in Figure 7. The results of experiment 1 are also included in the figure to allow comparison of the offset thresholds for stationary and moving vernier targets. These results appear as the cluster of data points at 0.00 on the horizontal axes. Three major effects can be seen:

- Offset thresholds for the moving targets are smaller than the dimensions of a pixel and are on the order of optimal vernier acuity thresholds.[14] This confirms the result of experiment 1 that showed that in an antialiased image, gray-scale intensity gradients can specify the visual locations of objects to a degree approaching the limits of positional acuity.
- Offset thresholds are unaffected by a wide range of visible target blurs. This reconfirms the assertion

made as a result of experiment 1 that the visual process allowing positional acuity on such a fine level does not depend on the information present in sharp image contours to perform its function.[17]

- Offset thresholds are not disturbed when the targets are seen in stroboscopic image sequences depicting target motions of up to 2.0 degrees/second. This means that, contrary to the belief that visual acuity for the details of objects is diminished when those objects are seen in motion, visual acuity for the features of moving objects seen in stroboscopic image sequences remains constant over a considerable range of velocities. These results are similar to those obtained by Westheimer and McKee under somewhat different conditions.[27]

## Overview and conclusions

The experiments in this article focused on the visual information for object location and motion available in gaussian antialiased images and image sequences. The first experiment found that in a color raster-scan CRT viewed at a distance where the raster structure is not resolvable by the eye, the usable spatial addressability in a gray-scale image quantized to 256 intensity levels is much finer than the pixel raster and is on the order of the visual system's finest positional acuity. Also it was found that this subpixel addressability is not degraded by the blurring of image contours produced by gaussian antialiasing.

The second experiment demonstrated that there are three factors that influence the perceived continuity of gaussian antialiased image sequences. The continuity ratings that the sequences received were determined by a three-way relationship between the gradient of the object's edge profile produced by antialiasing, the object's velocity, and the sampling rate at which the image sequence was made.

The final experiment demonstrated that the near-threshold subpixel addressability found in the first experiment is not reduced in stroboscopic image sequences showing objects moving at velocities of up to 2.0 degrees/second. Even at the highest velocity tested, usable addressability remains in the subpixel range.

All these experiments suggest that antialiasing removes spurious visual information introduced by sampling processes in image synthesis. It allows the visual system to provide a precise representation of object location and a continuous representation of object motion. The results of the experiments run counter to conventional notions of image quality, which tend to equate quality with image addressability and resolution, and therefore hold that antialiasing, while removing objectionable artifacts, also degrades the quality of the visual information available in the image.

Image addressability and resolution are important aspects of image quality, and simply increasing the addressability and resolution of display systems will improve the quality of the images to the point where the displayable picture elements are at the resolution limit of the eye's optics and the image update rate is faster than the visual system's temporal summation period. But the experiments have shown that useful measures of image quality must also take perceptual processes into account.

To correctly assess the quality of the visual information available in synthetic images, it is necessary to use psychophysical methods that allow the quantitative investigation of the relations between the physical properties of images and the perceptual impressions they create. Only by understanding the complete chain of processes from model to percept will it be possible to create images that consistently provide useful information to their viewers. Future work in this area should focus on techniques to allow accurate visualization of modeled objects in the context of an analysis of the visual information needed to perform the tasks demanded by an application. ■

## Appendix: Statistical analysis

Observed results were confirmed with the Unixstat statistical package.

### Experiment 1

An analysis of variance performed on the combined data of the three subjects confirmed the reported results. Offset thresholds were all smaller than a pixel, and the threshold values for the different target conditions were not significantly different from one another ($F(4,8)=0.787$, $p=0.565$).

### Experiment 2

An analysis of variance was performed on the data from the three subjects confirming the reliability of the reported trends. The velocity and sampling-rate parameters had the greatest effects on the ratings of continuity with probabilities of ($F(3,6)=32.22$, $p<0.001$) and ($F(1,2)=73.21$, $p=0.013$), respectively. An interaction of the profile-width parameter and the velocity parameter was also significant at ($F(12,24)=3.02$, $p=0.01$). There were also interactions between velocity and sampling rate ($F(3,6)=24.52$, $p=0.001$), and between velocity, sampling rate, and profile width ($F(12,24)=2.74$, $p=0.017$). One subject's directional bias carried through as a minor effect in the combined analysis, producing an interaction with velocity and profile width ($F(4,8)=4.1$, $p=0.043$) and one with velocity sampling rate and profile width ($F(12,24)=2.93$, $p=0.012$).

The direction parameter had relatively little impact on the continuity ratings for the image sequences. This allowed the data from the leftward and rightward motion sequences to be combined to produce the two histograms shown in Figure 6. One subject showed a directional bias that resulted in leftward moving targets being rated more highly than ones moving to the right.

## Experiment 3

An analysis of variance done on the combined data of the three subjects confirmed the reported results. First, the offset thresholds for the four broadest target profiles were not significantly different from each other at any target velocity. Thresholds for the narrowest target profile were significantly higher than the others at the ($F(4,8)=5.27$, $p=0.022$) level. While the thresholds for vernier acuity are not much affected by target blur,[17] it is well known that target contrast has a significant effect on vernier thresholds.[2] Though the target images were all calculated to have the same contrast, the resulting images might differ in contrast because of the finite diameter of the electron beams in the CRT or because of diffraction effects produced by the optics of the eye. The resulting loss of contrast in the retinal image of the narrowest target could account for the elevation in the measured thresholds.

Finally, the analysis showed that the offset thresholds for the moving vernier targets were not significantly different from those measured for stationary targets (experiment 1) at target velocities of 0.5, 1.0, and 2.0 degrees/second. The offset thresholds for the target that moved at 4.0 degrees/second were significantly higher than the others at the ($F(3,6)=11.12$, $p=0.007$) level.

## References


1. K.S. Booth et al., "On the Parameters of Human Visual Performance: An Investigation of the Benefits of Antialiasing," *CG&A*, Vol. 7, No. 9, Sept. 1987, pp. 34-41.
2. J.P. Thomas, "Spatial Resolution and Spatial Interaction," *The Handbook of Perception, Volume 5: Seeing*, E.C. Carterette and M.P. Friedman, eds., Academic Press, New York, 1975, pp. 233-263.
3. G. Osterberg, "Topography of the Layer of Rods and Cones in the Human Retina," *Acta Ophthalmologica, Supplement*, Vol. 6, No. 1, Jan. 1935, pp. 11-97.
4. A.W. Snyder and W.H. Williams, "Photoreceptor Diameter and Spacing for Highest Resolving Power," *J. Optical Soc. America*, Vol. 67, No. 5, May 1977, pp. 696-698.
5. D. Marr, T. Poggio, and E. Hildreth, "Smallest Channel in Early Human Vision," *J. Optical Soc. America*, Vol. 70, No. 7, July 1980, pp. 868-870.
6. G. Westheimer, "Spatial Frequency and Light Spread Descriptions of Visual Acuity and Hyperacuity," *J. Optical Soc. America*, Vol. 67, No. 2, Feb. 1977, pp. 207-212.
7. H.B. Barlow, "Reconstructing the Visual Image in Space and Time," *Nature*, Vol. 279, No. 5710, May 17, 1979, pp. 189-190.
8. F.C. Crick, D.C. Marr, and T. Poggio, "An Information Processing Approach to Understanding the Visual Cortex," MIT A.I. Memo 557, MIT, Cambridge, Mass., 1980.
9. R.J. Watt and M.J. Morgan, "Mechanisms Responsible for the Assessment of Visual Location: Theory and Evidence," *Vision Research*, Vol. 23, No. 1, Jan. 1983, pp. 97-109.
10. E.P. Krotkov, "Visual Hyperacuity: Representation and Computation of High Precision Position Information," *Computer Vision, Graphics, and Image Processing*, Vol. 33, No. 1, Jan. 1986, pp. 99-115.
11. D.E. Pearson, *Transmission and Display of Pictorial Information*, Halsted Press, New York, 1975.
12. *Raster Graphics Handbook*, Conrac Division, Conrac Corp., Covina, Calif., 1980.
13. F.W. Campbell and D.G. Green, "Optical and Retinal Factors Affecting Visual Resolution," *J. Physiology*, Vol. 181, No. 3, Dec. 1965, pp. 576-593.
14. G. Westheimer and S.P. McKee, "Spatial Configurations for Visual Hyperacuity," *Vision Research*, Vol. 17, No. 7, July 1977, pp. 941-947.
15. Q. Tian and M.N. Huhns, "Algorithms for Subpixel Registration," *Computer Vision, Graphics, and Image Processing*, Vol. 35, No. 2, Aug. 1986, pp. 220-233.
16. T.N. Cornsweet, "The Staircase Method in Psychophysics," *Am. J. Psychology*, Vol. 75, No. 3, Sept. 1962, pp. 485-491.
17. G. Stigmar, "The Effect of Blurred Visual Stimuli on Vernier and Stereo Acuity," *Acta Ophthalmologica*, Vol. 49, No. 4, Apr. 1971, pp. 364-379.
18. F.C. Crow, "The Use of Grayscale for Improved Raster Display of Vectors and Characters," *Computer Graphics* (Proc. SIGGRAPH), Vol. 12, No. 3, Aug. 1978, pp. 1-5.
19. W.J. Leler, "Human Vision, Anti-Aliasing and the Cheap 4000 Line Display," *Computer Graphics* (Proc. SIGGRAPH), Vol. 14, No. 3, July 1980, pp. 308-313.
20. J. Kajiya and M. Ullner, "Filtering High Quality Text for Display on Raster Scan Devices," *Computer Graphics* (Proc. SIGGRAPH), Vol. 15, No. 3, Aug. 1981, pp. 7-15.
21. M. Wertheimer, "Experimentelle Studien uber das Sehen von Bewegung," *Zeitschrift fur Psychologie*, Vol. 61, 1912, pp. 161-265.
22. A. Korte, "Kinematoskopische Untersuchungen," *Zeitschrift fur Psychologie*, Vol. 72, 1915, pp. 194-296.
23. W. Neuhaus, "Experimentelle Untersuchungen der Schein-Bewegung," *Archiv fur Gesamte Psychologie*, Vol. 75, 1930, pp. 315-478.
24. G. Sperling, "Movement Perception in Computer Driven Visual Displays," *Behavior Research Methods and Instrumentation*, Vol. 8, No. 2, Feb. 1976, pp. 144-151.
25. D.C. Burr, "Motion Smear," *Nature*, Vol. 284, No. 5752, Mar. 13, 1980, pp. 164-165.
26. D.C. Burr, *On the Visibility and Appearance of Objects in Motion*, doctoral dissertation, Cambridge Univ., Cambridge, UK, 1979.
27. G. Westheimer and S.P. McKee, "Visual Acuity in the Presence of Retinal Image Motion," *J. Optical Soc. America*, Vol. 65, No. 7, July, 1975, pp. 847-850.
28. A.B. Watson, A. Ahumada, and J.E. Farrell, "The Window of Visibility: A Psychophysical Theory of Fidelity in Time-Sampled Visual Motion Displays," *J. Optical Soc. America A*, Vol. 3, No. 3, Mar. 1986, pp. 300-307.
29. I. Newton, *Opticks*, Dover Publications, New York, 1952, p. 347.
30. H.B. Barlow, "Temporal and Spatial Summation in Human Vision at Different Background Intensities," *J. Physiology*, Vol. 141, 1958, pp. 337-350.
31. K. Koffka, *Principles of Gestalt Psychology*, Harcourt, Brace and World, New York, 1963.
32. R.L. Gregory, *Eye and Brain*, McGraw-Hill, New York, 1966.


**James A. Ferwerda** is a senior technical advisor in the Program of Computer Graphics at Cornell University. His research interests include human and machine vision, realistic image synthesis, and cognitive aspects of interactive computer graphics. His current work includes the design of a laboratory to allow comparison of the physical and perceptual aspects of synthetic images with real scenes.

Ferwerda received a BA in experimental psychology in 1980 and an MS in computer graphics in 1987, both from Cornell University.

**Donald P. Greenberg**'s biography and photograph appear on p. 40.

The authors' address is Program of Computer Graphics, 120 Rand Hall, Cornell University, Ithaca, NY 14853.