

IMAGE QUALITY IMPROVEMENT IN COMPUTED VISUAL SCENE SIMULATION

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INTRODUCTION

When a simulation or training application requires simulation of visual scenes, a number of techniques can be used. Wide use has been made of pictures—both still and movies—and of models, with optics alone and with servoed television cameras for display on raster-scan devices. During the past decade Computer Generated Images (CGI) have seen increasing application to this requirement.

With CGI the scene exists as stored numbers in the system memory. If standard TV rates are used, the computer generates 30 new scenes per second, based on the simulated relationship between the environment and the observer for each scene. It immediately follows from this basic concept that the operator or trainee has no constraints on his path or rates of motion or acceleration. Multiple moving models in the scene can be accommodated. Special effects, such as blinking or directional lights, limited visibility simulation, explosion and disappearance of a target, etc., can be included.

The importance of these features is such that significant work with valid results has resulted from scene generation with very limited pictorial realism. Calligraphic techniques, in which objects are depicted by vectors or strokes on a display device outlining the objects and significant features or faces of the objects, have been applied and are still being used. The features are recognizable, just as are the figures in a child's coloring book prior to being colored. When shown with proper perspective and motion, they provide valid visual cues.^{1, 2} The illusion of realism is, however, quite limited with such systems.

Realism is greatly enhanced by a process conceptually equivalent to coloring the scenes in the coloring book. The faces defining the objects and surfaces are filled in with their designated colors. Figure 1 shows a scene from such a system. Only recently have advancements in available hardware complexity and display generation algorithms reduced the cost of such systems to the point where they can be considered for a wide range of applications. Past difficulties are indicated by the fact that only a half-dozen or so such systems are currently in existence.

Figure 1 is representative of the highest image quality currently available in real-time systems. By "real-time" is meant a system in which an operator can control his simulated aircraft, automobile, or ship, and see the scene respond just as if it were real.

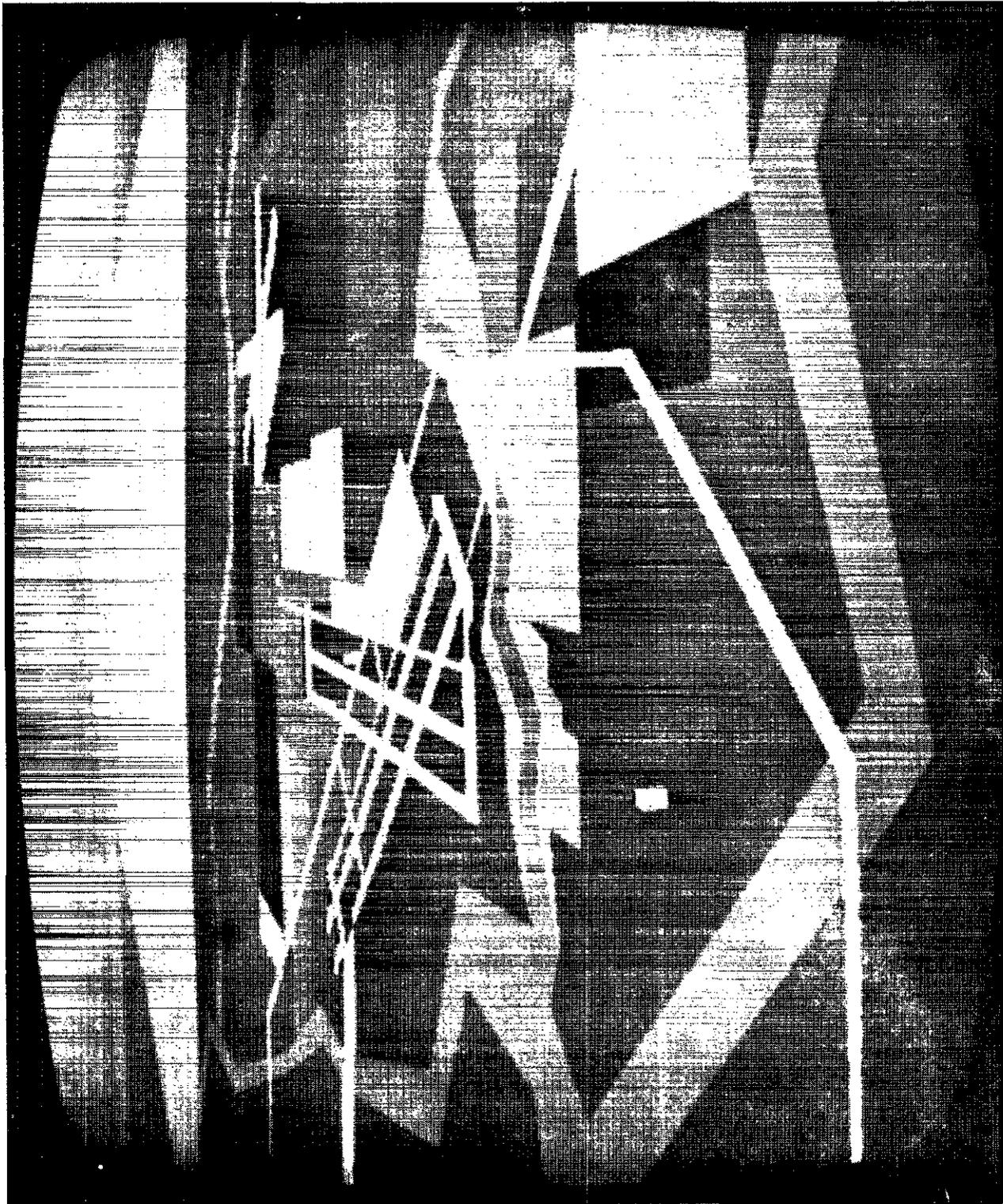


Figure 1. Scene from Current CGI System

For all except the very slowest rates of linear and angular motion, this requires scene computation and display at a 30-per-second rate. The term "Image Quality Improvement" in the title is with reference to the current status as represented by Figure 1.

FACTORS AFFECTING IMAGE QUALITY

Edge Capacity

Realism is increased by the ability to produce more complex scenes, and to model objects with greater fidelity to the shapes of real objects. Scene complexity is generally expressed in terms of the number of edges in the displayed scene. The "edges" are the line segments bounding the faces of the scene. The highest capability real-time system currently operational is at the Naval training facility at Kingsville, Texas. It can display up to 500 edges on a single scene, although the total environment complexity can be far greater. A system currently being built for the Air Force will have 2000-edge display capacity, from an 80,000-edge gaming area. The current status in regard to edge capacity is that as many edges as required can be provided—but system cost tends to grow linearly with edge capacity. The beneficial results have been fully verified by generation of highly complex scenes in non-real-time, in which there is no limitation to the time which can be applied to handle the resulting computational complexity.

Curved Surface Simulation

Straight edges and flat faces are used for environment definition in CGI systems. Since straight lines remain straight under a projection transformation, the mass of equations which must be solved at high speed for scene generation are linear equations. For greater accuracy in showing objects with curved surfaces, a greater number of edges and faces can be used in modelling them. In addition, the technique of incrementing color linearly between vertices along the image of an edge, and of incrementing linearly between edges along a scan line, renders interior edges invisible and greatly enhances the illusion of curvature.^{3,4} The results of applying this technique have been evaluated from a large number of scenes generated in non-real-time, and it has been further verified by real-time implementation in the GE laboratory system. Current status: Being incorporated in system now being built for the Air Force. Available for application to any system in which the benefits justify the added cost.

Display Element Size

CGI systems compute the video for each scan line of the scene being simulated as numbers representing the color at each of the computed display elements along the scan line. In the Kingsville system mentioned above, which is based on conventional television standards, 512 scan lines are computed to represent each scene, with 512 elements computed per line.

The expression of element size which best indicates its significance is in terms of its angular size at the observer's eye. This is a function of numbers of lines and elements, and of the angular dimensions of the entire display at the eye. This unit of measure does not have the immediate significance to most people of such numbers as 36, 24, 36. Insight can be gained by considering that at a viewing distance of 10.3 feet from a television set with a 10-inch high display, the distance between scan lines appears as one arc-minute at the eye. The display height is approximately 8.3 degrees.

At something on the order of one arc-minute, individual picture elements become indiscernible to the eye and resolution is then limited only by the characteristics of the eye itself. It would thus be desirable to approach this goal as closely as possible.

In the Kingsville system, the display dimensions are 180 degrees horizontal by 60 degrees vertical; 60 degrees by 60 degrees for each of three juxtaposed displays. Distance between scan lines is thus about 8 arc-minutes. Computation and display of 4000 scan lines, each with 4000 elements, would achieve one arc-minute element size. This would be a 64-fold increase in video element rate, the square of the linear dimension reduction ratio. The current 10 MHz rate would have to be increased to 640 MHz—and many portions of the system cost increase linearly with this number.

In summary, the image quality improvement of decreased element size can be achieved in a straightforward manner; it has been fully verified by non-real-time simulation, but it can be quite costly. The Air Force system being built will compute 1000 scan lines of 1000 elements each, for each of its 14 displays. The decision, as in most matters, must be based on a careful evaluation of results versus cost.

Display System Considerations

Many factors associated with the display system have an effect on image quality. Display system resolution, brightness, monochrome or color, spatial and color matching at boundaries, projection or collimated optics, eye relief, etc., are all important.

The Navy system at Kingsville uses rear projection by color light valves onto three juxtaposed screens. Cockpit motion and position are sensed. The resulting change in viewer eye location is provided to the image computation system so that the image on the retina of the eye behaves as though the scene were at an infinite distance. This constitutes a form of synthetic collimation which can accommodate quite large variations in the eye position relative to the screens—essential when the scenes are fixed and the viewer is on a moving platform.

The Air Force system will have a platform-mounted display system arranged as seven segments of a dodecahedron practically surrounding the pilot. Thirty-six inch diameter monochrome cathode ray tubes, with pancake-window collimated optics systems, will be used.

Some very promising work in new display system concepts is currently under way. This area is, however, not within the scope of this paper.

Quantization Effects

The set of image phenomena categorized as quantization effects have significant negative impact on image quality. The combination of concepts, algorithms, and hardware to eliminate these effects has only recently been successfully developed. The effect of this elimination on the effective resolution of a displayed scene is of great significance. This entire area has been covered in the literature in only a very preliminary manner. The topics of quantization effects, their elimination, and consequences of this elimination will therefore constitute the bulk of this paper.

QUANTIZATION EFFECTS DESCRIPTION

CGI systems compute a number representing color, grayshade, or video level, for each of a large number of display elements. A logical approach for determining color for each element is to consider a ray from the viewpoint through the center of the element, determine which face of the scene it strikes first, and select the color of that face for the element. This approach led to some very efficient algorithms which could be implemented with earlier integrated circuit complexity. Systems designed on this basis have proven valuable tools; nevertheless the effects discussed below have been distracting, and extensive effort has been applied to eliminate them.

Step Effect

Step effect is one of the more noticeable of quantization effects. It is illustrated on Figure 2. Figure 2(a) shows an edge separating a black (video level 0) face below it from a white (video level 100) background above it. The computed display elements for scan lines 1, 2, and 3 are shown. An "x" indicates the black face contains the ray through the center of an element.

This edge will appear on the display as shown on Figure 2(b). The origin of the term "step effect" is obvious.

Figure 2(c) shows the video for scan lines 1 and 2 resulting from the configuration of (a), and giving the result shown in (b).

In a dynamic situation these steps move around on the display and can be very distracting.

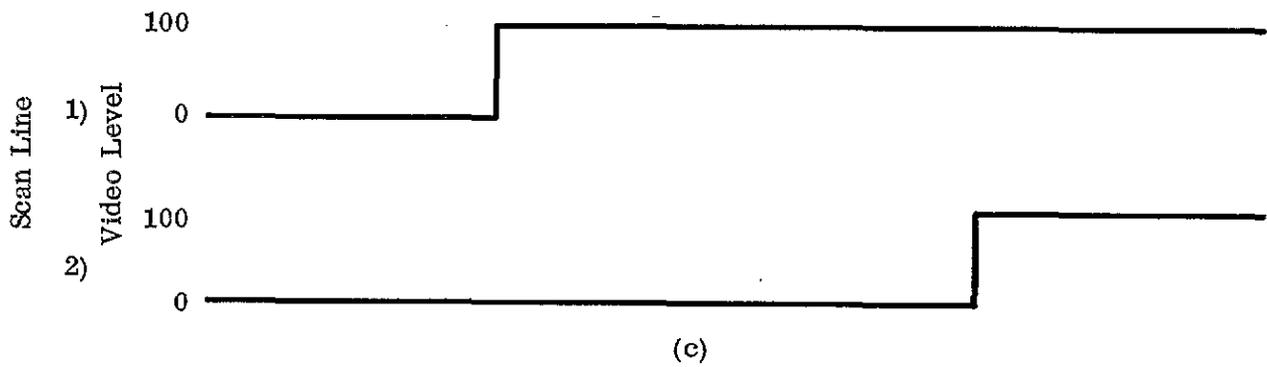
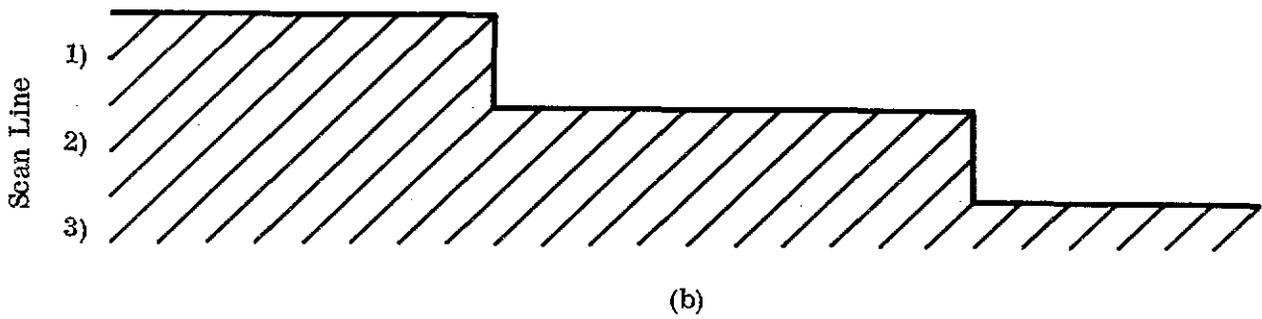
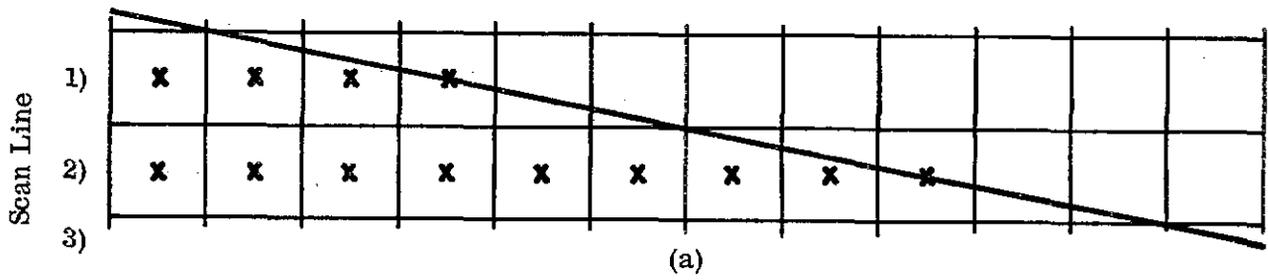


Figure 2. Illustration of Step Effect

Face Breakup

The phenomenon of face breakup is shown on Figure 3. Again, the face is black and the background white. The (a), (b), and (c) portions of Figure 3 have the same significance as the corresponding parts of Figure 2. The result is to display a continuous narrow face as a set of disjoint segments. In a dynamic simulation the segments move around and change in size.

Face Crawling

Figure 4 shows a one-scan-line slice of a vertical bar which is 2.4 elements wide. The bar is moving slowly to the right, and the slice is shown as it would appear on eleven successive frames. The left column shows the exact mathematical image of the bar. The right column shows the quantized version as displayed. The effect is that it successively advances to the right, then recedes from the left. It appears to be crawling, rather than smoothly moving.

Face Blinking

If the bar of Figure 4 were 0.5 element in width and moving to the right, it would in some positions cover the center of an entire column of elements and in other positions cover the center of none. When it covered none, it would disappear completely. It thus will blink in and out on the display.

Combination Effects and Resolution

Figure 5(a) is the image of a white numeral "1" on a gray runway. Figure 5(b) shows the result of quantization on the scene. The numeral in the display is of variable width, alternating between two and three elements wide along its length. It would not be invalid to call the "variable width effect" an additional quantization effect. It is fully explained, however, by the application of the step effect explanation to both the left and right edges.

The topic of resolution will be introduced in connection with Figure 5. Resolution is normally expressed in terms of the smallest details which can be resolved by a system (line pairs per mm. for example). If actual displays corresponding to Figures 5(a) and (b) are seen, there is no question that (a) has far better resolution than (b), even though there are no small features in the scene. The significance of satisfactory resolution in simulated scenes might be expressed in terms of accurate recognition of moderately small features (the numeral "1"). Or, it might be in terms of locating a specified portion of a scene feature. On Figure 5(a) the middle of the right edge of the numeral is accurately located at 0.4 element past the start of element 478. On (b) it would be precisely at the start of 478.

Assume the numeral moves 0.15 element to the right. Now the middle will be at 0.55 element into 478 on (a), and at the beginning of element 479 on (b)—a full element jump on (b).

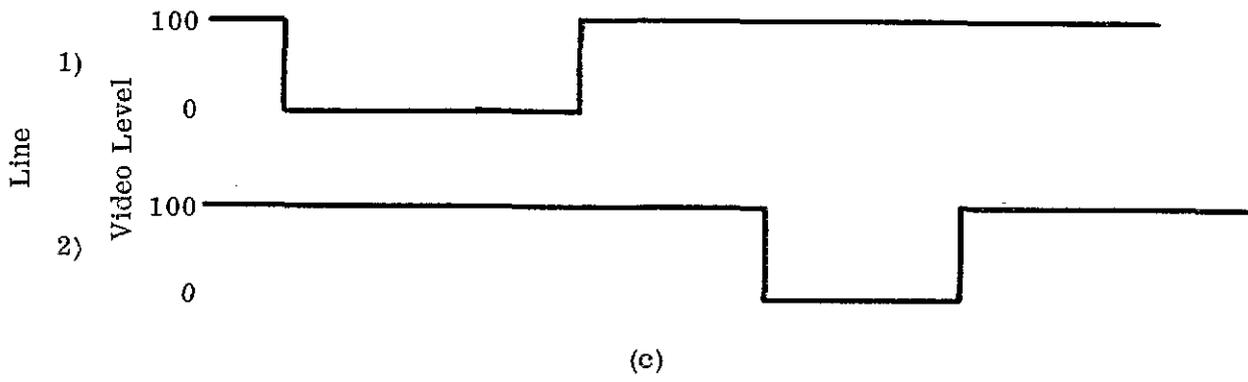
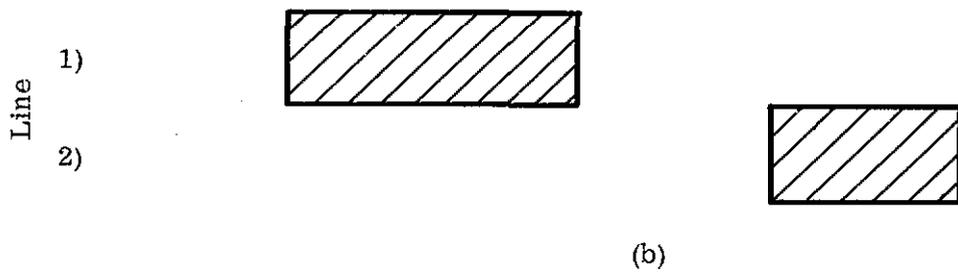
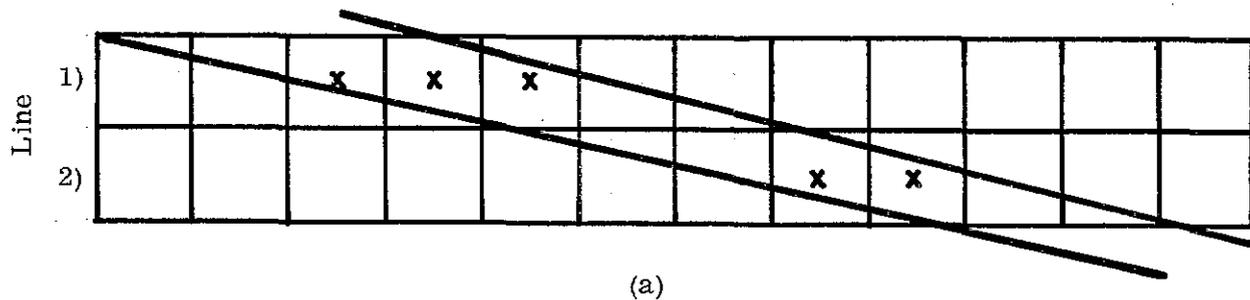


Figure 3. Face Breakup

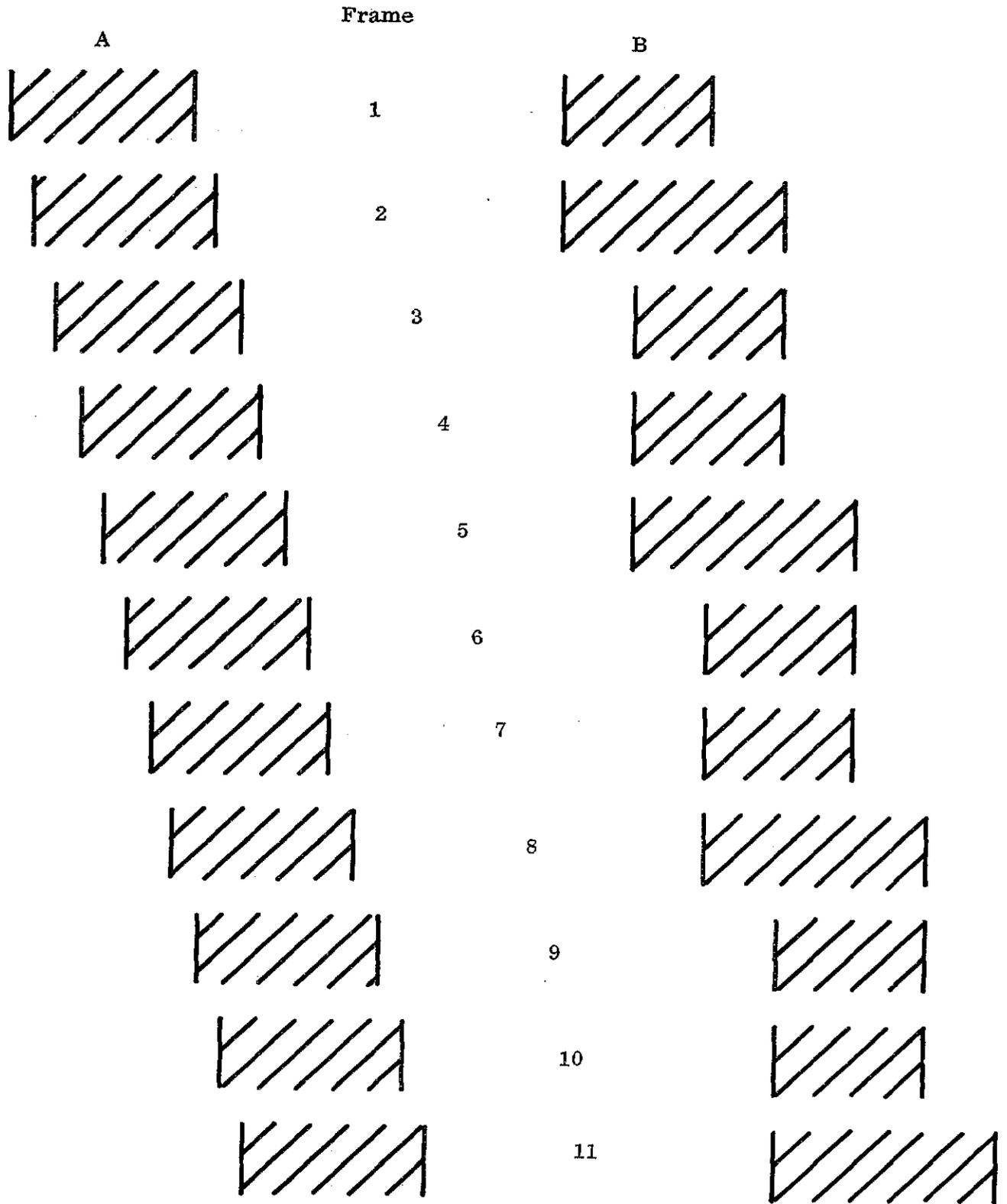
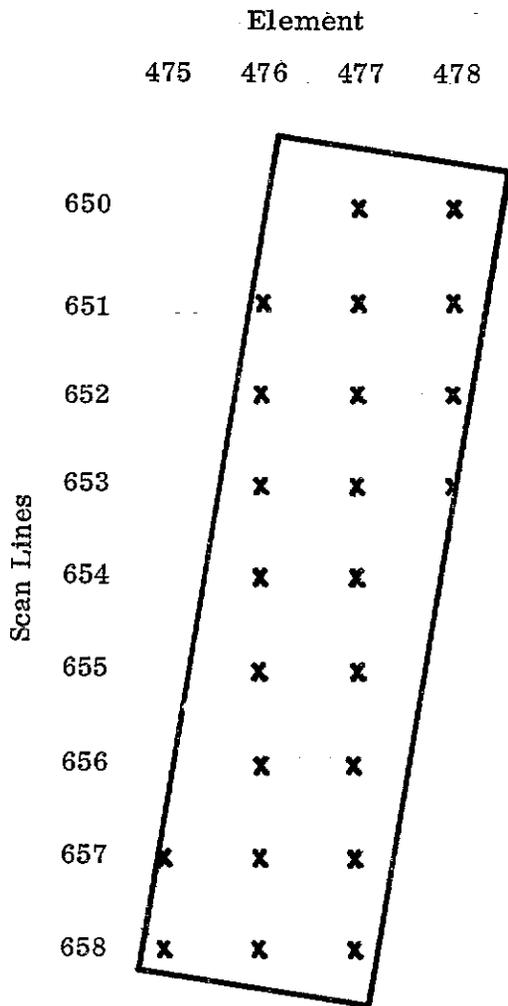
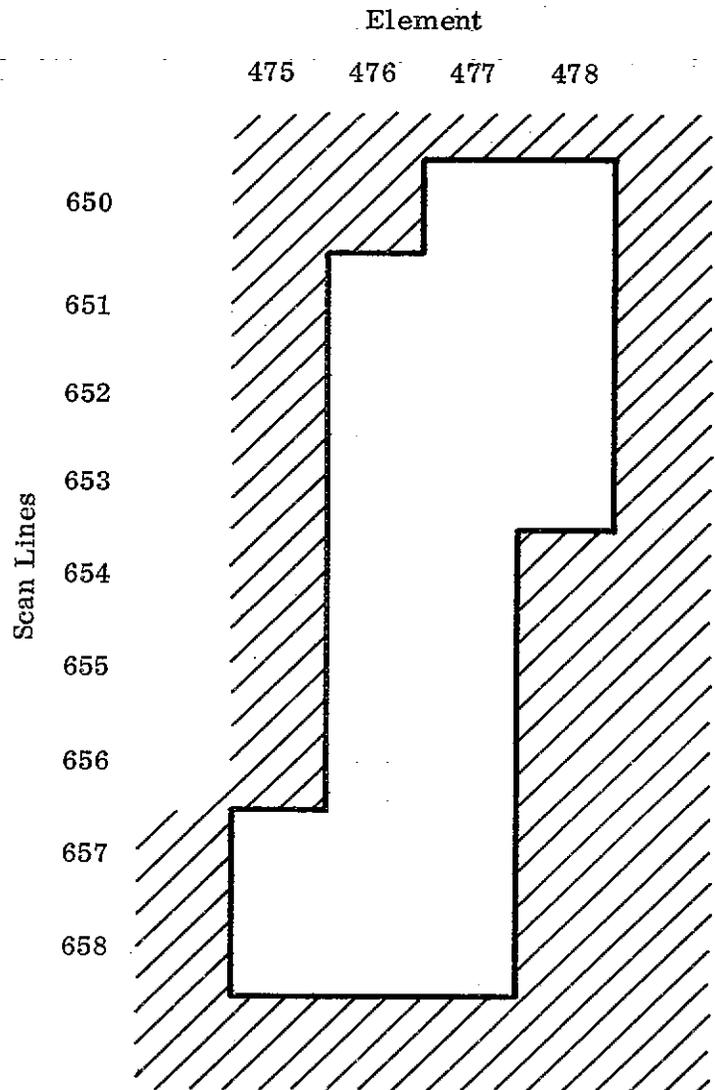


Figure 4. Face Crawling



(a)



(b)

Figure 5. Variable Width Effect

As an additional factor of significance, note that even if the edges of the portrayal of (b) were absolutely sharp, and those of (a) were fuzzy over a region of some portion of an element, (a) would still be far superior to (b) in terms of recognizability and detail location—in effective resolution.

Partial Solution of Quantization Effects

The question might be raised at this point whether systems which exhibit the quantization effects discussed above have any value at all. The answer is that they have proven quite valuable.

One reason is that many steps can be taken to minimize the effects. In the selection of face colors, contrast across edges is minimized, making the effects far less apparent. In the modelling, small faces subject to blinking and breakup are avoided wherever possible. A technique known as "level of detail control" substitutes alternate versions of a model as it becomes more distant. Simulated fog or haze causes distant—and hence small—faces to fade from view at distances where they would otherwise exhibit objectionable effects.

An additional factor is that a trainee concentrating on a landing tends to concentrate on the visual cues associated with his task and ignore extraneous effects. It has frequently been noted that observers standing at the side will comment on some such effect, and that the individual in the cockpit has not noticed it at all.

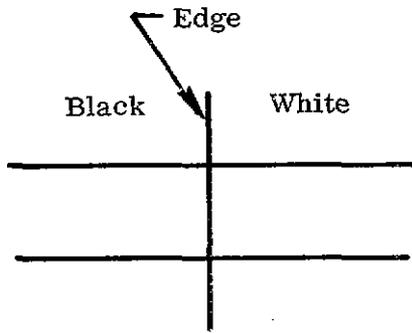
Systems with the quantization effects have been quite valuable. Nevertheless, the effects are serious and to eliminate them will without question greatly improve results.

QUANTIZATION ELIMINATION CONCEPT

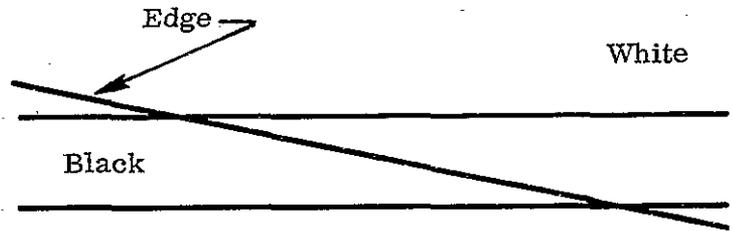
Clues to techniques for solving the above problems can be gained by considering standard television. Quantization effects exist in television*, but they are far less noticeable and serious than those discussed above.

Note the vertical edge separating black and white regions on Figure 6(a). The computed CGI video is as shown by (b) using the dashed lines in the transition region. Actually, some rather subtle effects are coming up for discussion, so it would be better to switch to a closer approximation of the analog video as it appears at the display device, considering video amplifier bandwidth and device limitations. A transition time equal to one display element time closely approximates this. This is shown as the solid line of (b).

*Fink, Television Engineering Handbook, pg. 8-19: "Because of the raster line structure, it is possible for a given system of longitudinal bars to be resolved in one position but to fail to be resolved when bodily shifted a fraction of the raster pitch distance in the transverse direction".



(a) Scene



(d) Scene



(b) CGI Video



(e) CGI Video



(c) TV Video



(f) TV Video

Figure 6. Video Generation

Figure 6(c) shows the video as it would be created by a television camera, even without consideration of bandwidth limitations. The spot size in the camera is adjusted to be slightly greater than the interline spacing. It is circular with Gaussian distribution of intensity. Thus as it moves across an edge separating black from white, the video changes during an interval determined by the width of the spot. A very close approximation to actual television video shape results if we assume a moving square spot equal in size to a display element, and this greatly facilitates analysis.

Figures 6(b) and (c) show identical shapes, with a one-half element shift to the right on (b). As long as this shift is the same over the entire display it is a trivial difference of no concern.

Figures 6(d), (e), and (f) show the difference between the two video waveforms which lead to a step-like representation of the edge with CGI, and a valid representation with television.

As an elementary approach to eliminating step effect, we might consider starting the voltage transition at the element where an edge enters a scan line, and controlling the transition time by the slope of the edge. This technique is quite easy to implement and was applied in early evaluation to validate the concept. When this was done for a sloping edge, the subjective effect was of a straight sharp edge with no steps.

The transition-time technique does not offer a practical approach to solving the problem. It does nothing for step effect of near-vertical edges. It offers no guidance when several edges from several faces are present in a single element.

The action of a television camera can also be expressed as follows: At any time, the video output is determined by a composite from all faces having any portion in the area covered by the spot. Using the approximation of equating the scanning spot size and shape with the CGI display element, and assuming within an element there are images of n faces, and that face i has brightness G_i , then element brightness G_e is:

$$G_e = \sum_{i=1}^n A_i G_i$$

where A_i is the portion of the element covered by face i . This "area times color" rule, when implemented in CGI, proves to be the key to complete elimination of quantization effects. Verification of this statement can come only from evaluation of test scenes made by application of the concept; however, further insight can be provided by considering further details descriptively or analytically.

Even after the concept is applied, there is one rather fundamental difference between a scan line of video from a television camera and that computed by a CGI system.

The television video is not quantized horizontally—a transition can start at any point along the scan line. With CGI transitions can be initiated only at discrete element points. If one envisions the television camera spot proceeding across the scan line in steps one element in dimension, taking zero time to move, and defining a video level for an element following each step, this would be a close approximation to the CGI result of applying the area times color rule.

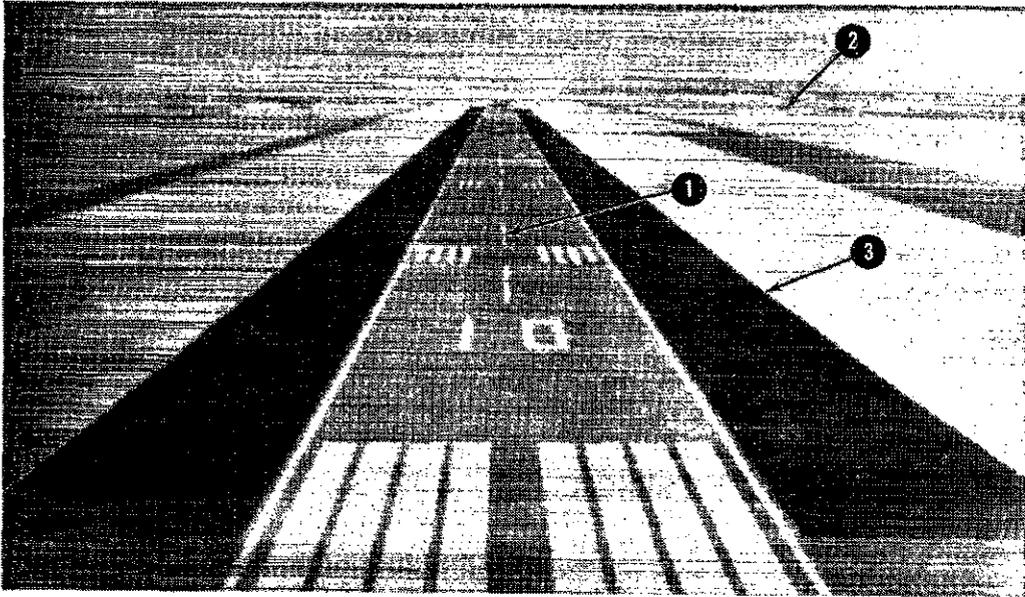
Zenith and Burroughs have recently done some work in investigating the feasibility of the plasma display technique for television. Each dot of the plasma is fixed in location, corresponding to the CGI display elements. Each dot thus has a value of video associated with it, derived from the TV signal in very close approximation to the hypothetical technique just discussed. When the author recently has an opportunity to view the results at the Argonne Workshop on Computerized Graphics in November 1972, he was particularly alert to detect any hint of quantization effects resulting from this type of display. There was none! This provided further verification of the applicability of the area times color rule to CGI.

Figure 4 showed face crawling resulting from quantization. The same figure could also be interpreted as the result of quantization at successive scan lines of a sloping face 2.4 elements wide. In either case, Figure 7 shows the video corresponding to (A) the result of a television camera producing the video and (B) the application of the area times color rule to CGI. The correspondence is not exact—as was mentioned above, actual evaluation must be based on test scenes. However, the video clearly shows a gradual movement to the right, rather than the earlier stepwise results.

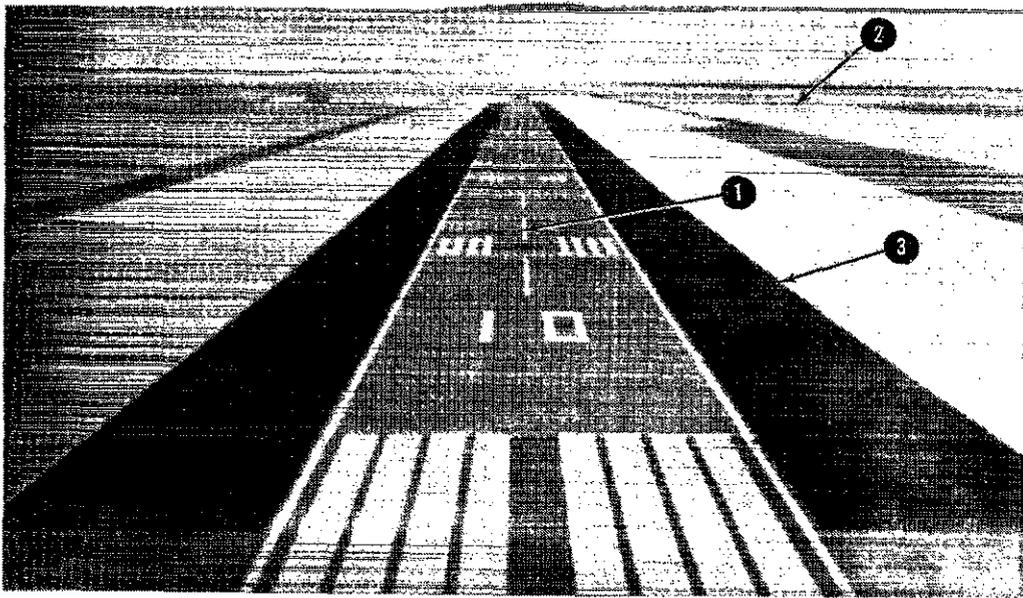
Concept Validation

Figure 8 shows a pair of evaluation scenes made some time ago in non-real-time during the concept verification phase of this effort. The top view exhibits most of the effects discussed earlier, and the bottom shows their elimination. Step effect is present throughout the top scene and absent in the bottom. In the upper right portion of the scene, broken-up white and dark faces appear in the top—they are seen properly in the bottom picture. The hangar to the left of the far end of the runway is quite distorted by quantization in the top, but recognizable in the bottom scene.

Now note the numeral "1" in the runway number. This was earlier shown in Figure 5 and was discussed. It can clearly be seen that the lower version corresponds quite closely to that shown in Figure 5(a), although the computed element size is the same in both parts of Figure 8. In any meaningful sense, the resolution of the bottom scene is far better than that of the top scene. It seems valid to say that only when the quantization effects are eliminated is the resolution capability of a given element size attained—the quantization effects seriously degrade the resolution.



Unsmoothed



Smoothed

Figure 8. Effect of Quantization Effects Elimination on Airport Scene

Essentially the statement is being made that we can locate the horizontal position of a point on the numeral to within a fraction of the computed element dimension. On the face of it this seems impossible. Certainly a far more detailed investigation is in order, not only to further validate that statement, but to determine rules for the limits of application of the technique. How large can the elements be, for example, before this result is no longer achieved.

Hypothesis I

The following hypothesis is presented, not as proven, but as a statement which explains all observed effects of the area times color technique for quantization elimination.

Assume that the element sizes are sufficiently small so that their images on the retina are comparable to the distances associated with the mutual inhibition effect of lateral neural interaction. If there is a transition from gray to white, with an intervening element shown light gray between these shades, as shown on Figure 9(c), the subjective effect will be very nearly the same as that diagrammed in Figure 9(d), with the gray-to-white transition occurring midway in the light-gray element. If this transition element is colored closer to the gray, shown as medium gray in Figure 9(e), the subjective spatial transition will occur closer to the gray region, and comparably as in Figure 9(g) and (h) if the color is very light gray, closer to the white.

The response characteristics of the eye have been simulated with a computer model and applied to this situation in an analytical investigation to add to the knowledge obtained from evaluation of test scenes.

MODELLING EYE RESPONSE

The model of eye response is based on the measurements made on the eye of the limulus (horseshoe crab).⁵ In brief, this work established that the response of a given receptor is proportional to the stimulus to that receptor, but is inhibited by amounts proportional to the magnitude of response of surrounding receptors, with the inhibition effect a function of the distance of the inhibiting receptor. That is:

$$r_i = s_i - \sum_{j=1}^n k_{ij} r_j, \quad j \neq i$$

This is a simplified formulation which ignores some threshold effects. Further, in the model used for this work, k_{ij} is taken as a function only of the retinal distance between receptors i and j .

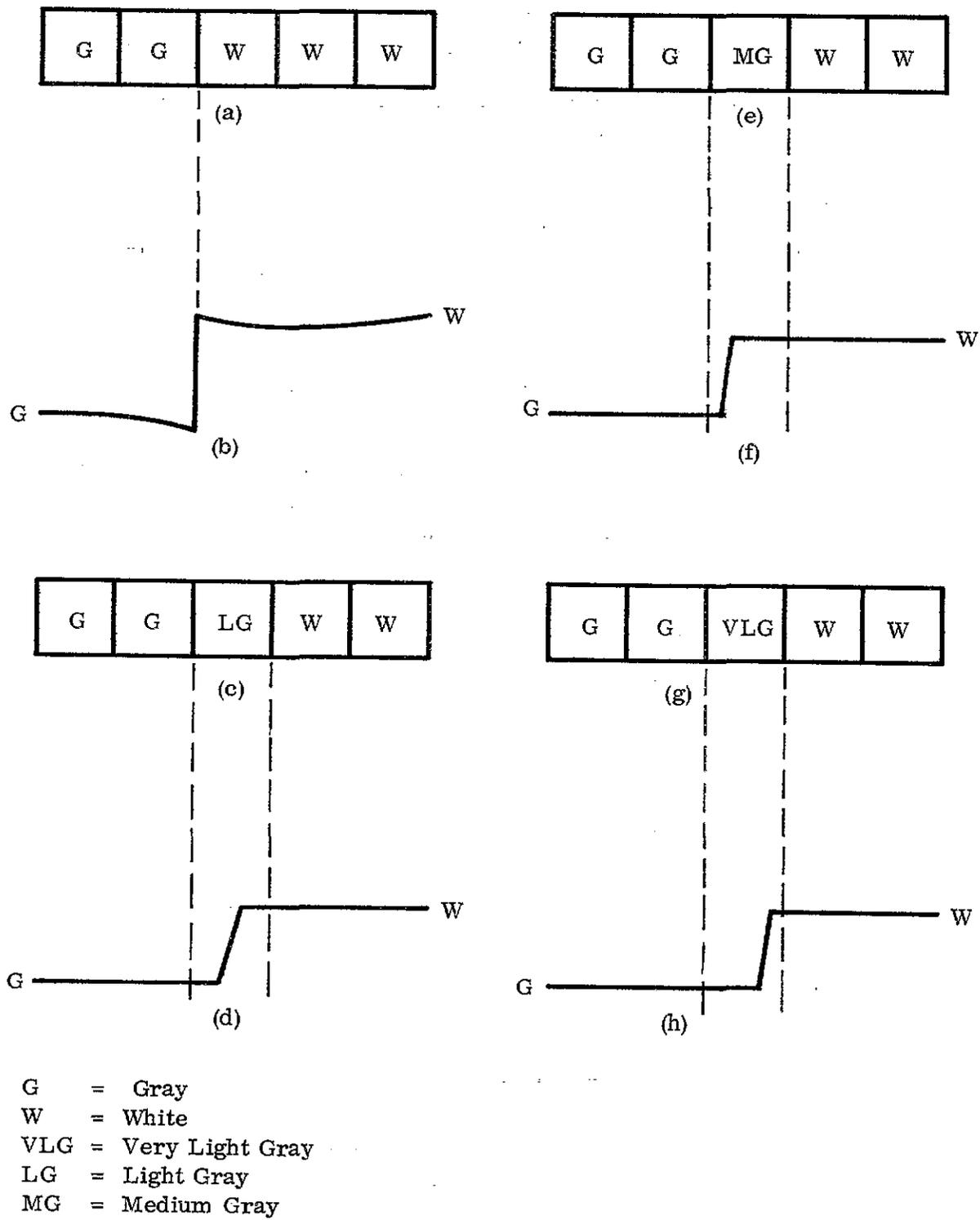


Figure 9. Illustration for Discussion of Hypothesis Explaining Quantization Smoothing

The k_{ij} were selected to give results consistent with the author's observations of the first order Mach effect. When two regions are adjacent, each of uniform brightness but differing from each other, the darker of the two appears darker near the boundary than in the body of the region; similarly the brighter of the two appears brighter near the boundary. This is diagrammed in Figure 9(a) and (b) for a gray region adjoining a white region. Figure 10 illustrates the effect (it is hoped the illustration will still be effective after the printing process).

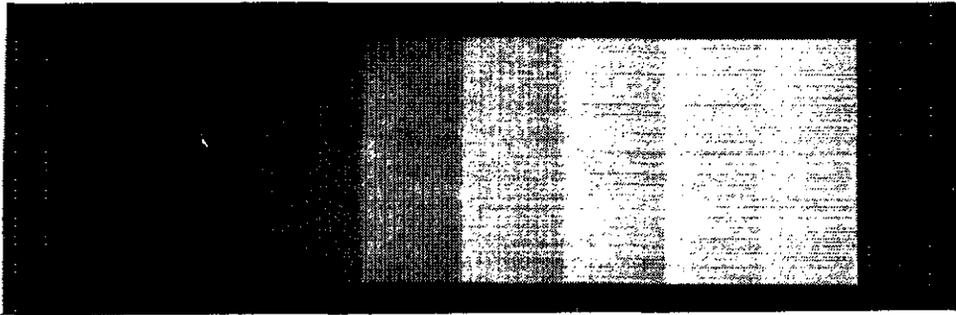
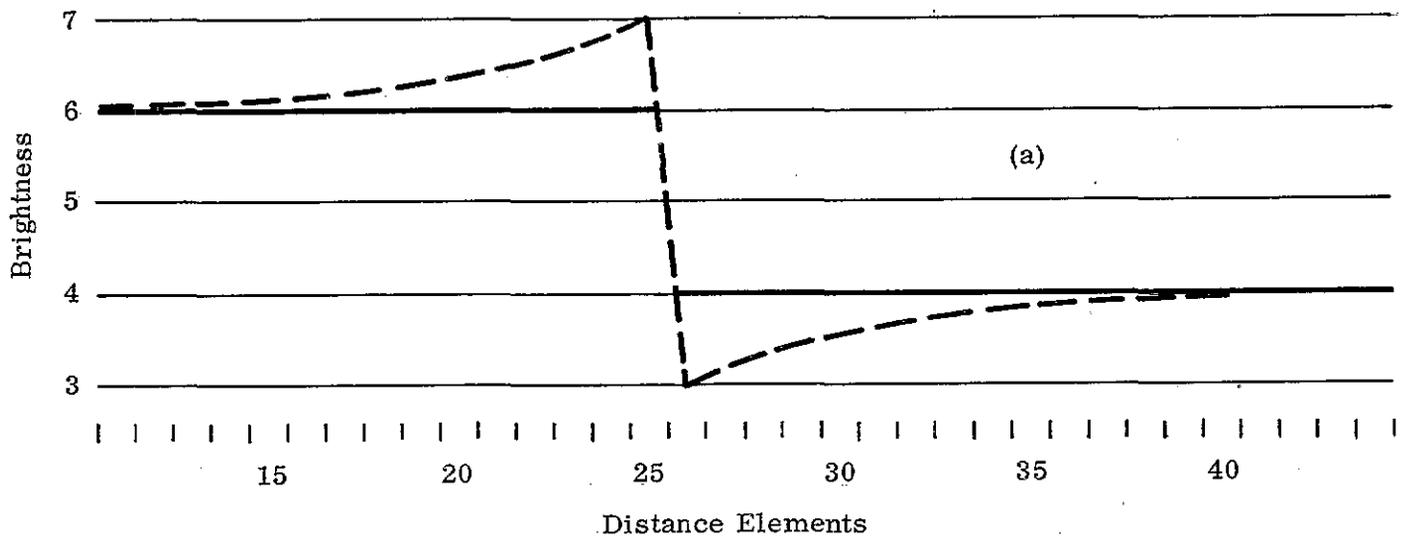


Figure 10. Mach Effect Illustration

The result of the simulation for a situation where brightness changes abruptly from level 6 to level 4 is shown in Figure 11(a). The "distance elements" identify the points used in the computation. The inputs to the model are the values of the stimulus at the centers of the distance elements, and the program computes the values of response at these same locations. The subjective input used in determination of the k_{ij} was that the departure of subjective brightness from that of the uniform portion of the region followed an approximate exponential decay. We might speak of a "distance constant", paralleling the familiar time constant, as the distance required for the initial difference to decay to $1/e$ of its value. For this model, the distance constant is equal to five distance elements. This model was then applied to situations with differing relations between the CGI element size and this distance constant.

There is a second order Mach effect which applies when there is no discontinuity of brightness, but where a discontinuity of the first derivative of brightness exists. This effect is less striking than the first order effect, and no attempt is made to illustrate it. For model verification, the model was applied to a brightness configuration known to produce this effect, and the results as shown on Figure 11(b) agree with subjective observations of the effect.

This model, verified to the extent discussed above, will now be applied to Hypothesis I.



— Stimulus
 - - - Response

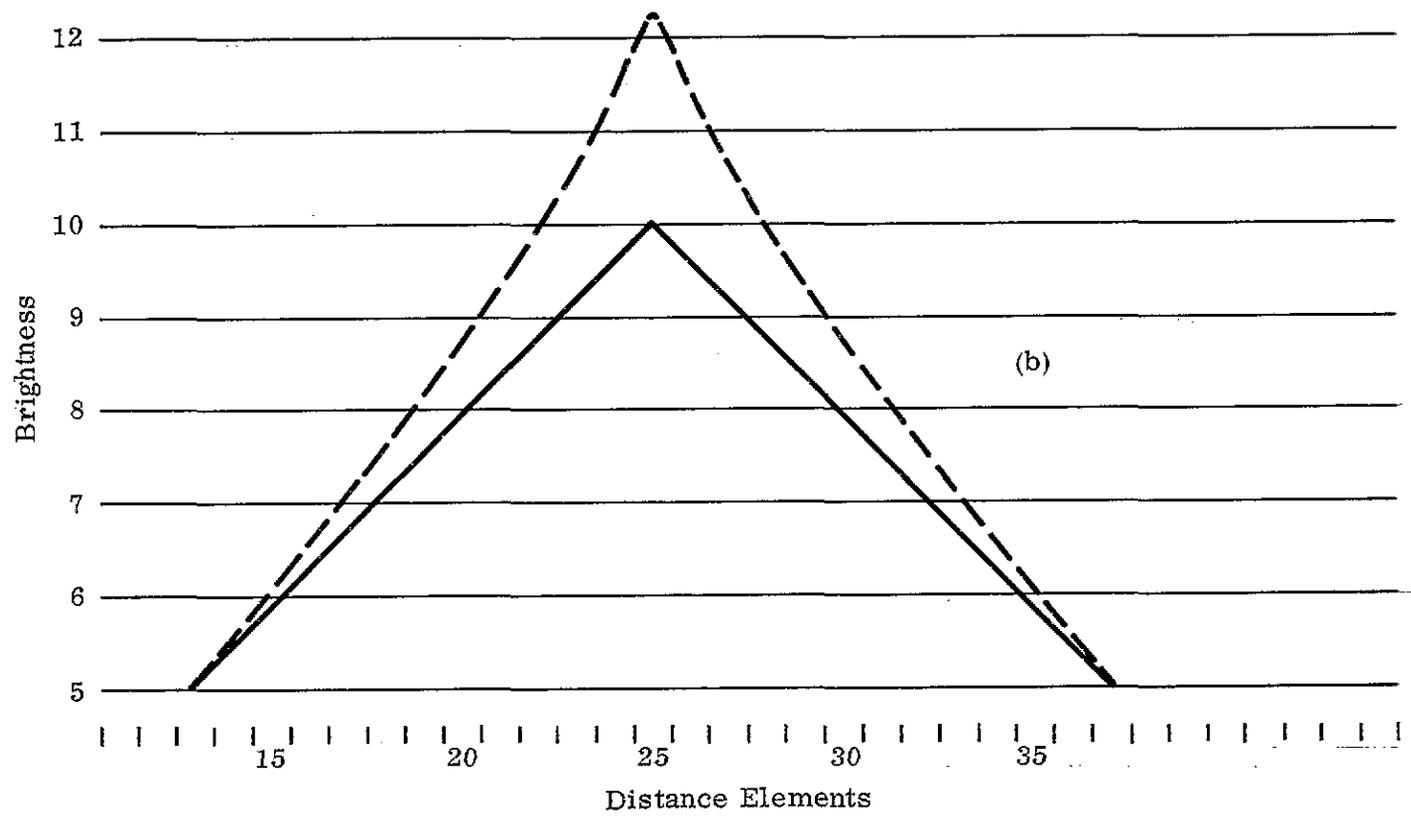


Figure 11. Eye Model Applied to Mach Effect Simulation

EYE MODEL APPLICATION TO CGI

Figure 12(a) shows a situation similar to that of Figure 9(c) and (d), with display element size set to one distance element. Stimulus is 6 through element 24, it is 5 at element 25, and is 4 starting at element 26. The dashed line shows the computed response for this stimulus. A question now arises: At what point does the eye interpret the change from 6 to 4 as taking place?

Hypothesis II

When a change from one brightness level to another takes place in a non-zero distance, the subjective effect is that it takes place at the point where the brightness passes the midway point of the two regions involved. This is subject to restrictions on magnitude of distance over which change occurs, linearity in region of change, etc.

In defense of this hypothesis—it is in general agreement with observations. It will therefore be used for discussion purposes in the following.

The subjective transition between 6 and 4 on Figure 12(a) takes place at the midpoint of element 25, or at distance 25.5.

Figure 12(b) has element 25 at brightness level 5.5, and the transition point is at distance 25.8. In Figure 12(c), element 25 is at 4.5, and transition is at distance 25.2. These results provide verification for the illustration of Hypothesis I as shown on Figure 9.

Now let's examine the situation if we make the display elements equal to two distance elements. Proceeding as above, we get the results shown on Figure 13. No attempt will be made to attach meaning to these results. Rather, we will examine our approach. Recall in an earlier portion of this paper the discussion regarding limitation of video bandwidth such that transition time approximates one element time. Figure 13 results would apply only for an infinite bandwidth case.

Figure 14 shows the case of one display element equal to two distance elements, computed in a manner which validly simulates CGI operation. On Figure 14(a) the stimulus is 6 through display element 9. It changes linearly to 5 at the end of display element 10, then to 4 at the end of display element 11, after which it remains 4. For (b) and (c) the values at the end of display element 10 are 5.5 and 4.5. Transition times are: (a) 26; (b) 26.7; (c) 25.3. Results continue to be consistent with Hypothesis I.

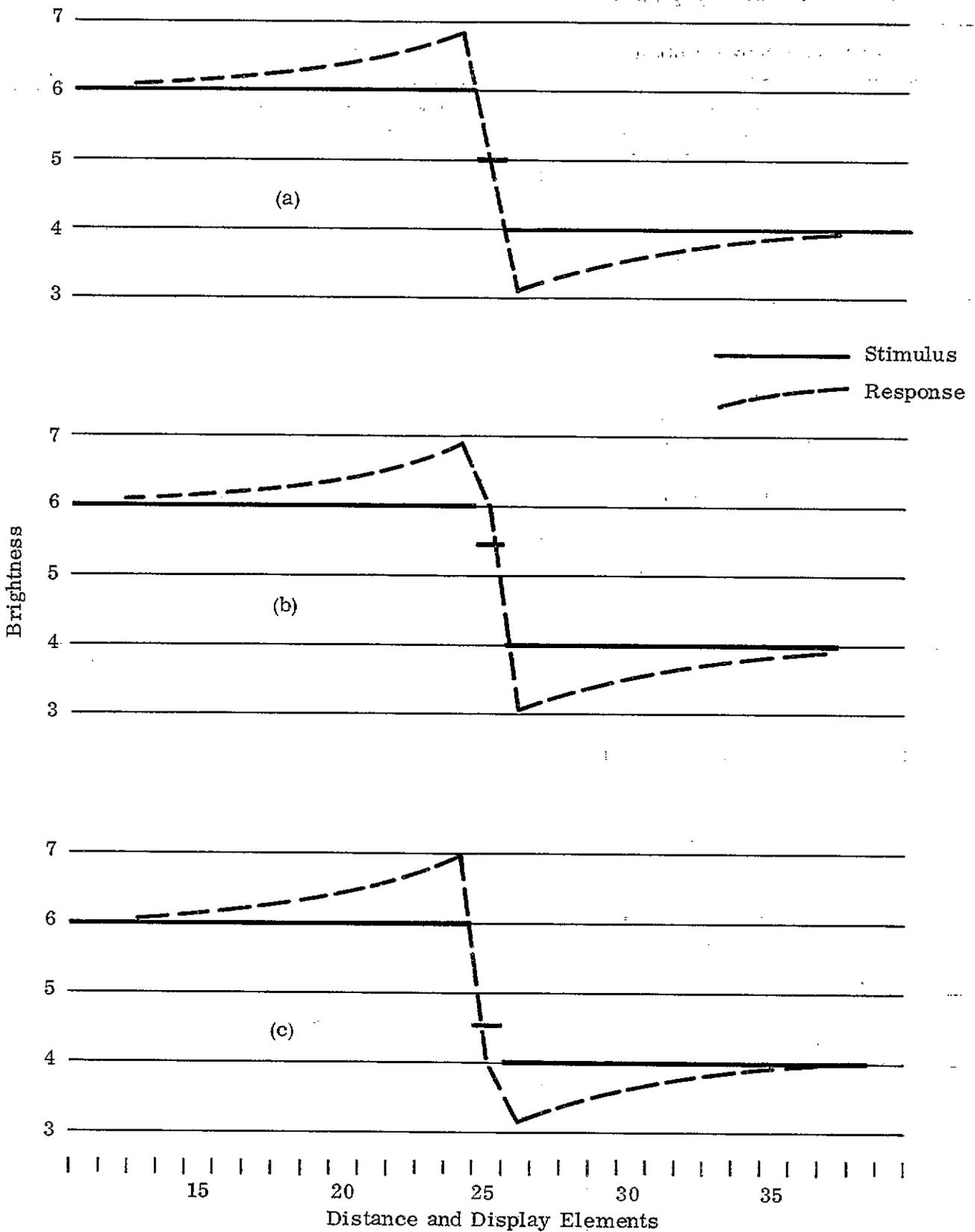


Figure 12. Eye Model Applied to CGI. Display Element = 0.2 Distance Constant

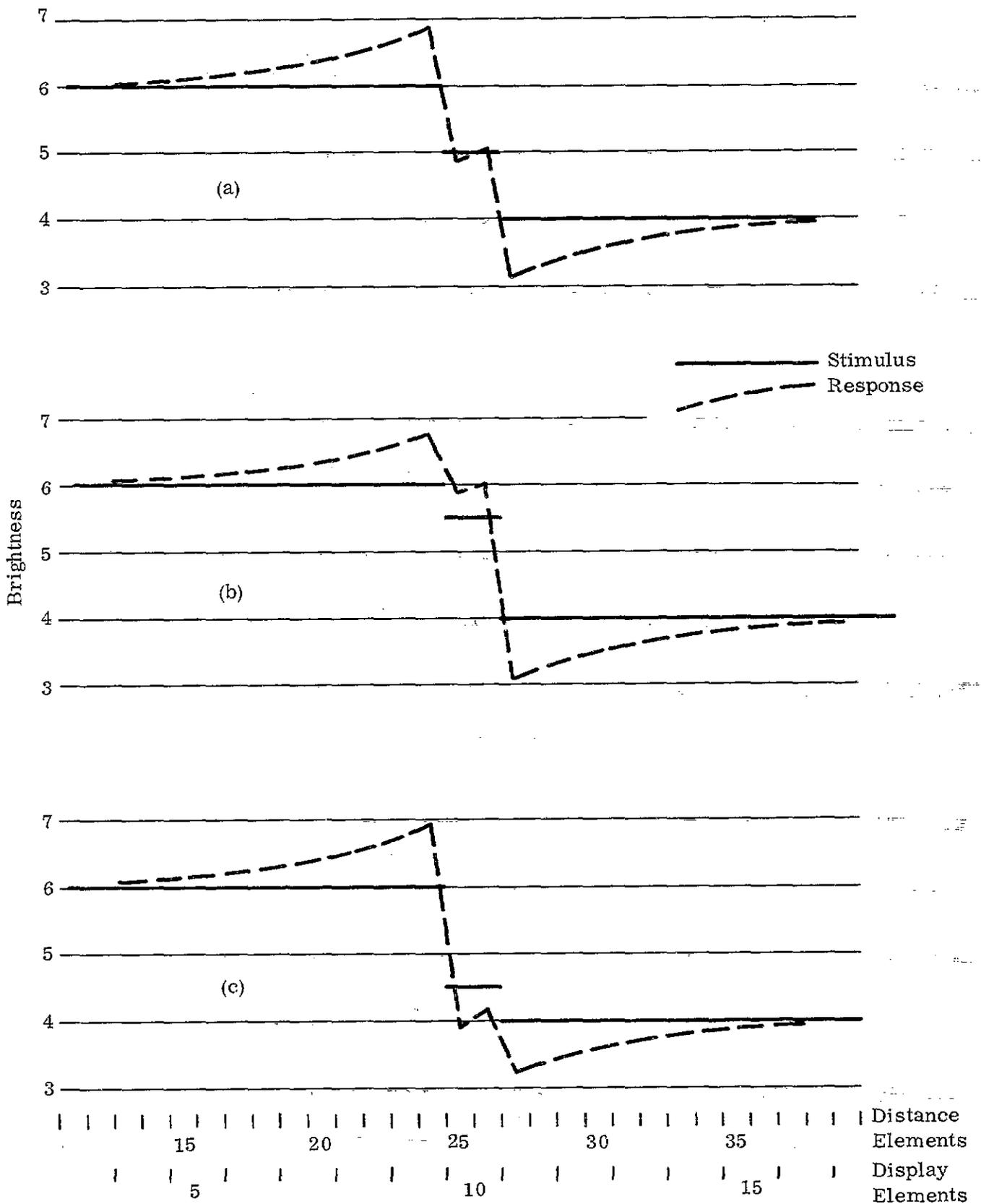


Figure 13. Invalid Eye Model—CGI Simulation for 0.4 Distance Constant Display Element

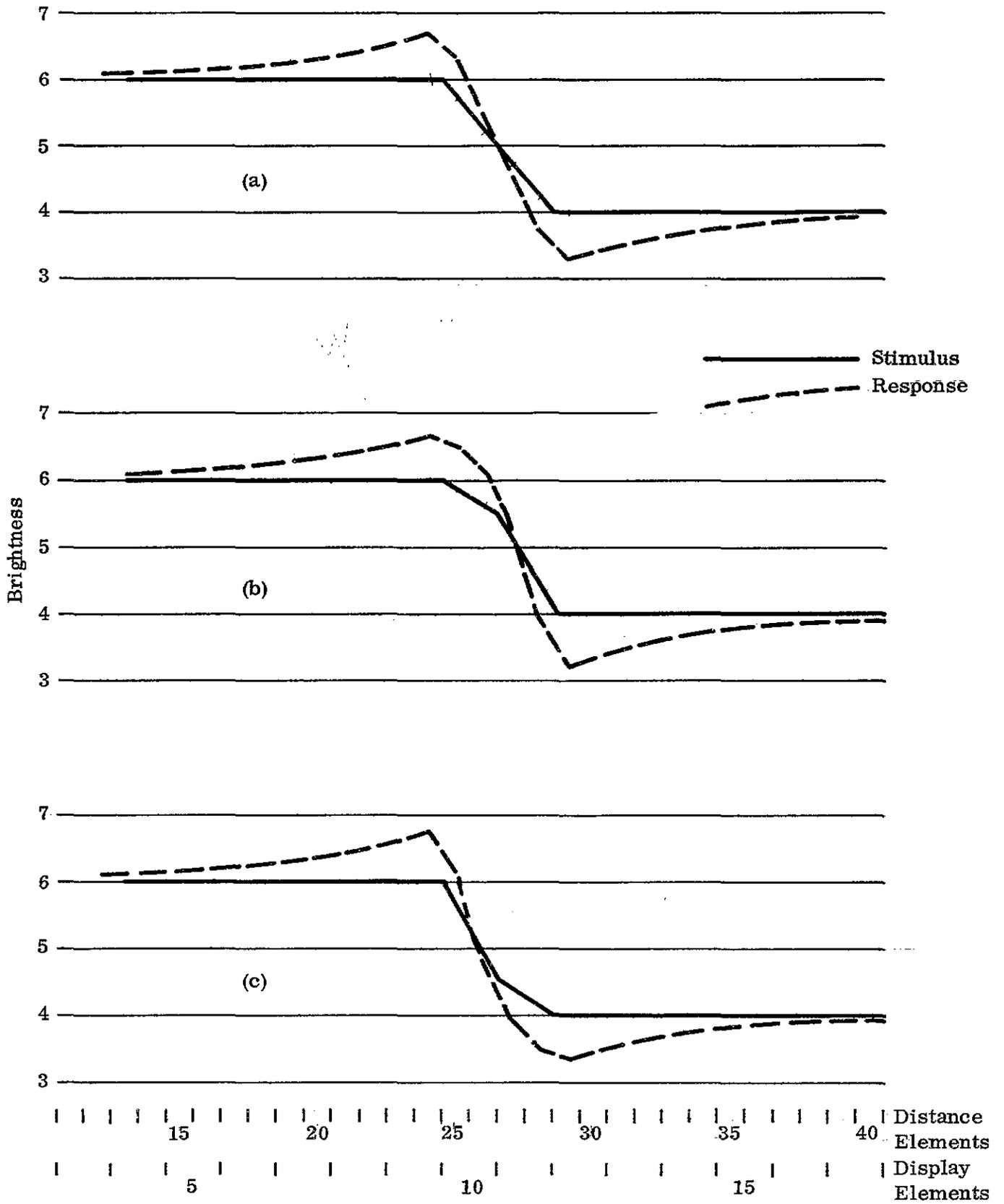


Figure 14. Valid Simulation of 0.4 Distance Constant Display Element

Suppose the value of stimulus at the end of display element 10 had been 6. This corresponds to the CGI situation of an edge being coincident with the element boundary. This is shown in Figure 15. Tabulating information from Figures 14 and 15:

<u>Element 10</u> <u>Brightness</u>	<u>Transition</u>
4.5	25.3
5	26
5.5	26.7
6	27

We achieve a smooth subjective movement of the transition point, in small fractions of a display element.

Is there any limit to the size of display element for which this will be effective? A close look at Figure 15 as compared with Figure 14(a) will show that the transition is less steep on 14 than 15. Thus, if the sizes are such that the eye can distinguish the difference, the transition will appear less sharp when the edge bisects an element than when it is at a boundary. It appears that this, rather than any breakdown of validity of the hypotheses above, is the limiting factor.

As an aside, prior to pursuing this topic, it might be noted that had there been any doubt regarding the practice of limitation of video bandwidth to conform with element time, an examination of Figures 13 and 14 should dispel them.

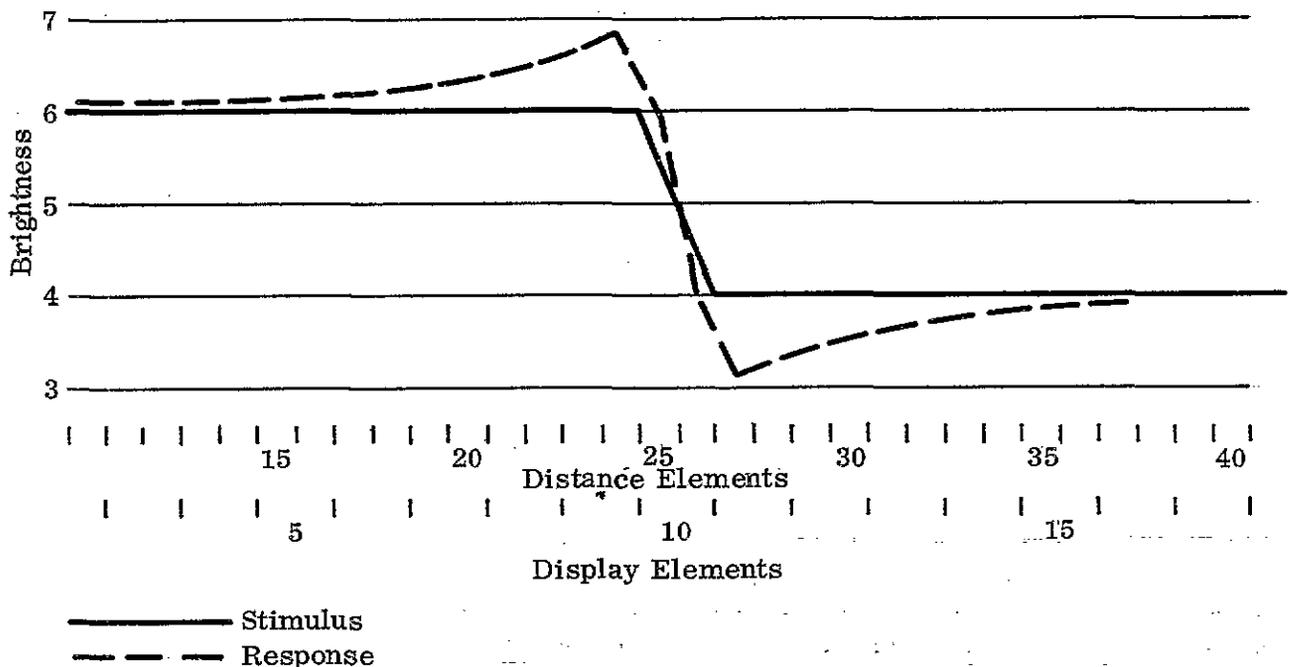


Figure 15. Simulation of Case with Edge Coincident with Element Boundary

Figure 16 shows the results when the display elements are made equal to five distance elements or, expressed in a more fundamental sense, equal to one distance constant. The transition point moves from 25.5 to 28, then to 30.5, in steps of one-half display element. The nature of the transition is, however, quite different for the middle case, corresponding to a CGI edge bisecting an element.

Figure 17 is a picture of a display in which the element size has purposely been made so large that this variable sharpness effect can be seen. It might be noted that even in this extreme case, the results are far superior than when quantization elimination is not applied.

This technique has recently been implemented on a real-time system. Additional evaluation is under way to determine guidelines quantitatively relating element size and effectiveness of the simulation.

As an aside, it might be mentioned that this technique has been applied to raster-scan display of vectors, and provides equally striking results in improving the appearance.

DISPLAY DEVICE SPOT SIZE

When focus is adjusted on a cathode ray tube, the spot is generally adjusted to as near point size as possible. Similar practices are followed when adjusting light valves or other display devices.

It has been noted experimentally that adjusting spot size to something larger than the minimum provided an apparent improvement in the display. The reaction has frequently been, "Sure, if you defocus, you mask the defects. Now let me get it properly focussed".

On the other hand, it would seem that adjusting the display spot size to approximate the scanning spot size on which the computation is based would not be invalid. Some very valuable insight into this area was provided by a paper at the Society For Information Display 1973 Symposium.⁶ The author presented a slide which showed a map formed by a raster-scan display. The words "NATIONAL GEOGRAPHIC" were on the order of 2 or 3 scan lines high. They could not be said to be readable. They could be deciphered. Similar comments applied to many other features of the map. The author then had the operator of the projector defocus the slide rather severely. Now the words could be read and the entire map information became clearer. The author explained this as follows.

The raster structure itself on the focussed picture has a very high signal-to-noise ratio. However, this entire structure is "noise" to the information content of the scene which thus has a very low signal-to-noise ratio. When the picture is defocussed, the signal-to-noise ratio of the raster structure decreases much faster

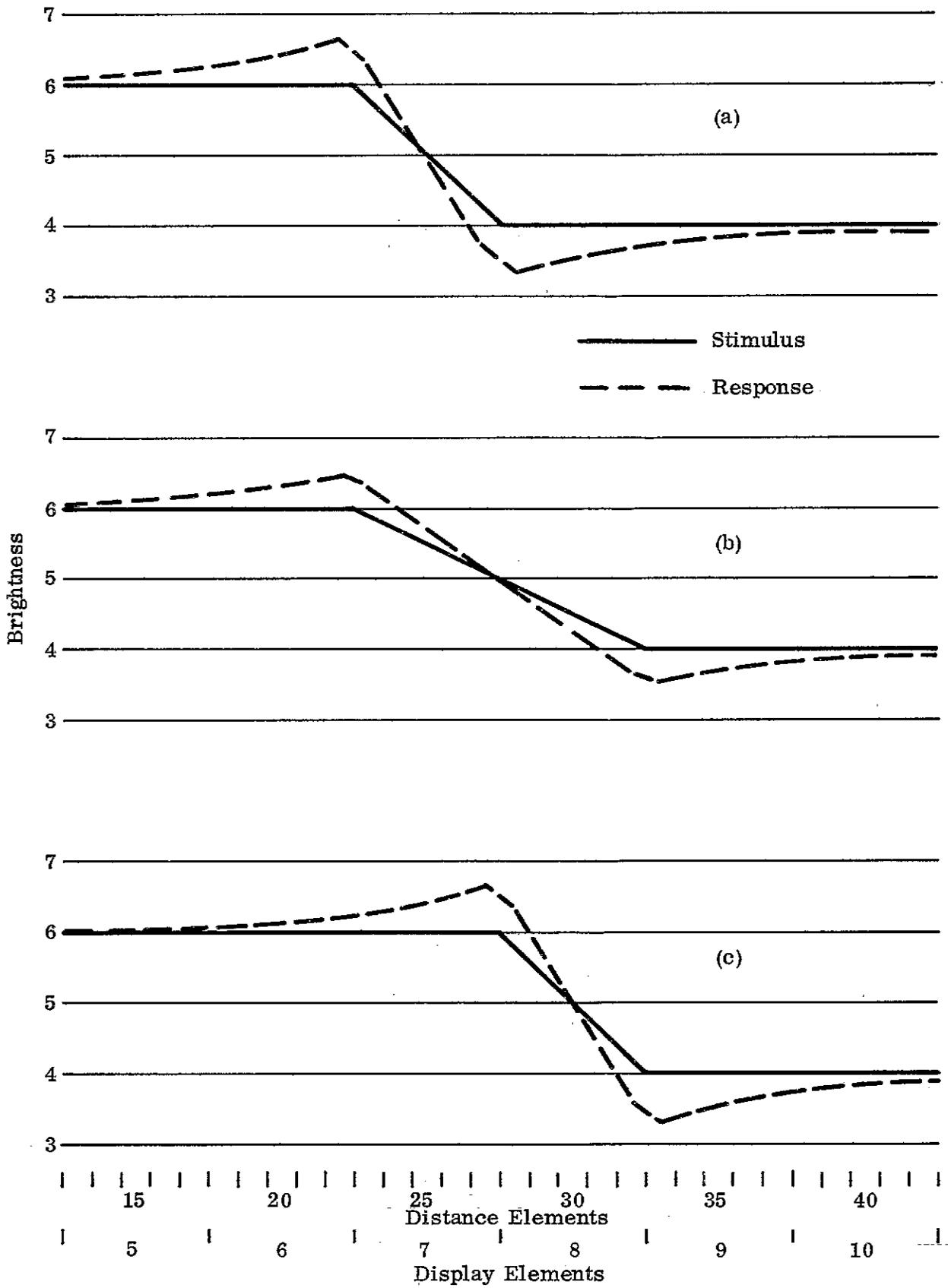


Figure 16. Display Element Equal to One Distance Constant

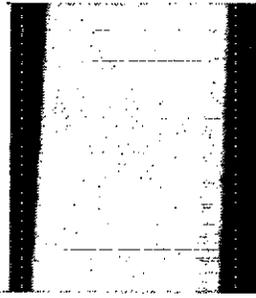


Figure 17. Display Elements Too Large

than that of the picture information--thus the information signal-to-noise ratio improves. He presented additional experimental and analytical evidence that optimum display results on a raster-type display require that the information on a scan line cover the full inter-scan-line distance. Thus, CGI image quality can be improved by revising focus adjustment procedures on display devices to achieve this. Some gains come easily.

CONCLUSION

The area of image quality improvement for Computer Generated Images has been an extremely active one for the past several years. Techniques and algorithms have been developed to solve all fundamental problems associated with such systems. Quite high levels of realism, with freedom from distracting side effects, can now be provided with moderate hardware complexity and cost. Continuing effort is further improving this situation.

The improvements have been largely based on evaluation of results of different techniques. In some cases analytical and theoretical investigations have shown the basis of the improvement and provided additional insight and guidance in application of the techniques.

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