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THE RESOLUTION AND PERFORMANCE EFFECTS OF THREE-DIMENSIONAL DISPLAY ROTATION ON LOCAL GUIDANCE AND SPATIAL AWARENESS MEASURES

BY

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B.S., United States Air Force Academy, 1996

THESIS

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To my family and friends.

You know who you are.

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1. Introduction

Recent technology has made electronic maps possible. The potent graphical capability and processing speed of computers have made it possible to represent map information in a myriad of ways. No longer is the user a slave to the conventional paper map. The computer map has several advantages compared to conventional maps (Wickens, Liang, Prevett, Olmos 1996):

1. dynamic depiction of current user location
2. easy updating of the digital data base underlying the map as conditions change
3. ability to "declutter" and customize the map for particular users or situations
4. providing a framework for the addition of other hazard information such as terrain, traffic, and weather.

Thus, computer technology has made it possible for the traditional paper map to be replaced with a realistic, three-dimensional, easily updated picture of the world. Possibilities abound as to exactly how this new computer map should be designed and implemented for use in aviation. What kinds of tasks should such a map support? Should the map depict the pilot's viewpoint or should the aircraft be viewed from a distance? If from a distance, how far and from what angle should the ownship be presented? In the present research we intend to give insight to the answers to some of these questions by investigating manipulations of two important properties of three-dimensional displays (their elevation and azimuth angle), and assessing how these manipulations influence performance or interact across aviation relevant tasks. We will begin by describing three categories of navigational tasks. Next, we will describe a general model of three-dimensional space and the biases created by perspective viewing, and will continue with a review of the research that has addressed these subjects.

1.1 The Three Tasks of Navigation:

Navigation through any medium may be characterized by at least two basic tasks: global awareness and local guidance (Wickens & Prevett, 1995; Wickens, 1996). A third task, navigational checking, is also relevant when the traveler must compare the forward field of view with a map, a display, or even one's memory of directions (Wickens, Schreiber, & Renner, 1994; Hickox & Wickens, 1996; Schreiber, Wickens, Renner, & Alton, 1996). This paper will primarily discuss the first two tasks of navigation, since these apply for all navigation situations.

1.1.1 Global Awareness:

It is important for pilots to have a general understanding of the location of objects and other hazardous entities (e.g., bad weather) in the airspace around them so that if an unexpected event arises within that airspace, they will have all the information available to them to make an informed decision on how to maneuver. High global awareness is characterized by an accurate and comprehensive knowledge of where things are in the 3-dimensional space, with respect to one's momentary position and orientation (Wickens and Prevett, 1995). Thus, as shown in Figure 1.1, global awareness involves an understanding of an enormous volume of space, 360 degrees around the aircraft (Wickens, 1995A). This understanding should include not only the location and movement of aircraft or hazards in the immediate area ahead of ownship, but also other hazards which may not have a direct or certain impact on the flight given its planned trajectory. Such information can occasionally be just as important for flight as the hazards near the intended path, which clearly will influence the flight. The importance of such unexpected hazards is clearly evident in the large amount of accidents due to controlled flight into the terrain (CFIT), which was the largest cause of air carrier accidents between 1979 and 1989 (Kuchar and Hansman, 1993; Bateman, 1990). As an aircraft moves through the three-dimensional volume of space, global hazards may evolve to become critical factors in local guidance.

1.1.2 Local Guidance:

Local guidance involves the movements required to stay on the navigational path while traveling from one location in 2 or 3-dimensional space to another (Wickens and Prevett, 1995). Such guidance can be defined as “local” because it requires awareness of information about a limited area through which the aircraft is projected to pass, i.e. "local awareness" (Davenport, 1997). Although the area of perceived importance for local awareness is generally confined to that space in front of the aircraft, objects behind or to the side may also be significant if they will affect the pilot's control of the aircraft along the flight path. Figure 1.1 illustrates how the local spatial awareness region, though smaller than the global spatial awareness region, may still include airspace to the side of the aircraft. Effective local guidance is made more complex because the bounds of the local area are determined not only by space, but also by a temporal component. While most pilots (and controllers) operate with a spatial model of the local area forward of the ownship (similar to that displayed by Figure 1.1), new systems such as TCAS (Traffic alert and Collision Avoidance System) that are based on temporal algorithms may better represent the true local area important for guidance. These temporal models may be superior because they indicate time-to-contact, the most critical functional variable when aircraft must navigate through hazardous airspace. Such temporal models, however, can be confusing for pilots and controllers because they are difficult to meaningfully visualize, due to the added dimension of time (Pritchett and Hansman, 1997). Instead of the typical three-dimensional “hockey puck” of safety envisioned by pilots and controllers and supported by the regulations, temporal models require the pilot/controller to integrate such factors as speed and acceleration into the algorithm for determining safe operating zones. Not only do these factors differ for each conflict, but humans are inherently poor at making judgments in this fourth dimension.

The task of local guidance is characterized by the psychology of tracking (Wickens, 1996; Wickens, 1986; Poulton, 1974). Tracking is the continuous process of choosing spatially defined outputs in response to spatially defined input (Wickens, 1996). Thus, it involves the loop of action and feedback which alters future action. Pilots use local information as well as internalized goals to guide their control movements to stay on their intended flight path or trajectory. Because external events and the pilot's own actions are continually changing the situation, local guidance is much more complex than merely being aware of or identifying global information. The researcher must attempt to understand not only what the pilot perceives (i.e. local awareness), but also how that perception will affect the pilot's actions.

1.1.3 Navigational Checking

A third task in aviation navigation, navigational checking, refers to the comparison of features on a map with features of the outside world to determine one's position in space (Hickox and Wickens, 1996). This task, characteristic of flight in a visual environment (i.e., visual meteorological conditions, or VMC), will not be specifically examined in this experiment, but has been looked at by several researchers (Aretz 1991; Wickens, Schreiber & Renner, 1994; Hickox & Wickens, 1996; Schreiber, Wickens, Renner, & Alton, 1996). Examination of the display parameters for navigational checking by these investigators has some relevance for the three-dimensional display concepts discussed below.

The research we review examines the particular map biases and parameters that affect both local guidance and global awareness, in order to understand how these constructs influence pilots' navigational performance in instrument meteorological conditions (IMC). In the following pages we outline the general model of perception in three-dimensional space and how this model is manifest in the numerous biases associated with viewing a three-dimensional world on a two-dimensional screen. The basic viewing parameters are then summarized and it is explained how these parameters influence the biases for a given map representation. Next, we describe how performance on local guidance and global awareness tasks may be differently affected by these biases and parameters and how these performance effects have been revealed in previous studies. Finally, we indicate how the present research will improve understanding of three-dimensional display design by explaining some of the areas left unclear by the research to date.

1.2 General Model of Perception in 3-D Space

The challenge inherent in the design of any three-dimensional map or display is how to depict 3-D space in a 2-D format. Although virtual reality techniques, using 3-D display surfaces, offer some hope for resolution of this problem, the current technology constrains the designer to dealing with the issue of collapsing three dimensions onto a two-dimensional viewing surface. Such a two-dimensional representation of the world requires the user of the map to mentally reconstruct the 3-D world. The reconstruction of the world can be hindered or facilitated by the designer based on the selected parameters of the representation. Most current aviation displays and maps are presented in a top-down, two-dimensional view. Although these displays lack vertical (altitude; Y-axis) information, they faithfully represent the horizontal (X and Z-axis) information in relation to the aircraft. In other words, the horizontal information is not distorted or compressed in any way. This type of 2-D display would be adequate if vertical (altitude) information was less important. However, this is not the case in aviation, where maneuvering is accomplished through movement in all three dimensions, and vertical deviations are often more critical than lateral ones. Research has shown that users tend to under-utilize the vertical dimension when conventional 2-D displays are used, as evidenced by horizontally biased avoidance maneuvers of traffic (Ellis, McGreevy, and Hitchcock, 1987; McGreevy and Ellis, 1986; Ellis, McGreevy, and Hitchcock, 1984; Smith, Ellis, and Lee, 1984). These biases were eliminated when altitude information was explicitly presented either as an integrated 3-D display (Ellis, McGreevy, and Hitchcock, 1987) or in a co-planar display, which gives a top-down view as well as a side view (Merwin, O'Brien, and Wickens, 1997).

1.3 Three-Dimensional Mapping Biases

In theory, three-dimensional displays have made it possible for aviators to simultaneously have information about all three axes of their world. By providing an integrated representation, three-dimensional displays have allowed for a more "natural" depiction of the environment possibly supporting a more realistic perception of the spatial relationships of objects in the environment (Hendrix and Barfield, 1995; Yeh and Silverstein, 1992). However, since display screen projection is ultimately only two-dimensional, the representation of these three axes requires that at least two, or, depending on the viewing parameters, possibly all three, of the axes be compressed. The amount of compression, represented with depth cues such as linear perspective, size-distance invariance, and height in the visual field, is one of the few ways humans can estimate location along a third dimension in a low fidelity artificial environment. This compression, which occurs uniformly across the entire compressed viewing plane or axis, increases as the viewing plane is rotated to approach the line of sight, and decreases to zero when the viewing plane is orthogonal to the line of sight (Barfield, Hendrix, and Bjorneseth, 1995). Figure 1.2 demonstrates this point. In the Figure, the three line segments AB, AC, and AD are all an equal 4 units in length. However, only the line segment AD, which is orthogonal to the viewer's line of sight, would be uncompressed and perceived as its actual 4 units. Line segment AC, and any information contained within that segment, would have a reduced resolution and would be seen as less than 3 units in length. Line segment AB, which is parallel to the line of sight, is fully compressed and the viewer would see it only as a dot, yielding no information about the actual length of the segment. Thus, compression of a given axis or dimension leads to reduced resolution for that axis which can be said to be due to its rotation away from orthogonality relative to the line of sight. The present research will refer to the relation of compression with rotation as the "Resolution Through Rotation (RTR)" model of effects. The RTR model effects do not influence the properties and relationships of the objects which are located along the compressed dimension, but only make it more difficult to ascertain information along that axis by decreasing the resolution, as compressed distances are represented by fewer pixels and a smaller visual angle (Boyer and Wickens, 1994).

One possible factor that might magnify the effects of compression is that compressed axes may require increased cognitive effort to mentally transform the compressed dimension back to its uncompressed status in order to accurately estimate distances and positions (Barfield, Hendrix, and Bjorneseth, 1995), through what we may refer to as "mental stretching". For example, envisioning vector AC in Figure 1.2 as four units in length, despite the fact that it is represented by many fewer screen pixels than vector AD, may require cognitive effort to stretch or rotate the vector to the orthogonal orientation of vector AD. Under such a model, accuracy in position estimation might be degraded by imperfect rotation of points to their location in the uncompressed plane. Furthermore, such a mental rotation of the axis would take not only effort, but time. Such an effect on time, however, with the exception of the Yeh and Silverstein study (1992) and perhaps the Hickox and Wickens (1996) study, has generally not been documented by the 3-D display research to date. Indeed, Wickens, Liang, Prevett, and Olmos (1996) noticed that spatial judgments in 3-D displays were actually faster (but less accurate) than those made with 2-D displays. At present, we will predict that the decreased performance for a compressed axis is characterized only by the loss of resolution. If judgments which are made along compressed dimensions take more time, however, we would conclude that the compressed axis must be mentally transformed to its uncompressed state.

Position estimation for a 3-D display, like any decision, can be described as a decision based upon uncertainty (i.e. it will have a mean and a variability around that mean; Wickens, 1992). Since the visual acuity of the operator is constant, the distribution of estimated decision points, and thus, the error, in the actual dimension varies in size depending on the amount of compression of that dimension. In other words, when an axis is compressed, the distribution of perceived position stays the same, but then encompasses a greater amount of actual distance in the displayed volume of airspace, causing the viewer to lose accuracy in defining the actual position of points along the compressed dimension. Figure 1.3 shows how the limited visual acuity of the viewer can encompasses a greater amount of actual units in the compressed line segment AC (as compared with AD), resulting in the possibility of greater position estimation error along that segment. It must be remembered, furthermore, that the explanation of compression as a result of rotation as described by the RTR model can be applied not just to line segments, but to all vectors in the simulated 3-D world.

As a vector approaches and finally becomes aligned with the line of sight, the linear information visible within the vector is reduced until it becomes a single dot. Thus, at the extreme, one can not tell the extent of the vector nor whether the vector is indeed a vector, or is a point somewhere along the line of sight. Line segment AB in Figure 1.3 is one such example of an ambiguous vector caused by its orientation exactly along the line of sight. This problem is known as ambiguity along the line of sight (McGreevy and Ellis, 1986). The line of sight ambiguity problem has been confronted by designers since they first started making 3-D displays (Gregory, 1977). Since then, this problem has been observed in numerous experiments (Wickens and Prevett, 1995; Boyer, Campbell, May, Merwin, and Wickens, 1995; Wickens, Liang, Prevett, and Olmos, 1996) and is often attributed as the cause of poor performance in three-dimensional displays.

Another effect which results from displaying 3-D environments on a flat surface is slant underestimation (Perrone and Wenderoth, 1993). Perrone and Wenderoth describe slant underestimation as the tendency for people to underestimate the angle of a slant in relation to the screen (see Figure 1.4). In other words, as shown in Figure 1.4, they perceive the slanted surface to be shorter and more parallel to the viewing screen (like segment AB) than it actually is (segments AC, AD, and AE). This effect is increased as the amount of depth cues available becomes more limited.

Different researchers have different names for the effects which occur in three-dimensional maps. Barfield, et al. (1995) have conducted several experiments investigating the "compression effect." McGreevy and Ellis (1986) have described the problems "line of sight ambiguity" can cause. Perrone and Wenderoth (1993) have examined the effects of "slant underestimation." However, as Figure 1.4 displays, these seemingly different phenomenon are actually only slightly different symptoms of the RTR model effects, caused by the geometric foreshortening of vectors due to their rotation in the three-dimensional world. The compression effect is manifest as a bias of distance estimation, while slant underestimation is a bias of angle estimation, and ambiguity along the line of sight is a bias in position estimation. The distinction among these effects is blurred since they all interact and affect each other and can take place together (as seen in Figure 1.4). In any task, we might predict that these biases will be enhanced to the extent that required judgments are to be made parallel to the line of sight, and reduced to the extent that these are orthogonal to it (Wickens, 1995B). The biases will also be more pronounced when the display has relatively few depth cues. Although the problems discussed can be remedied to some extent with the addition of gridlines, droplines, shadows, texture gradient, or other graphic mediations (Wickens, 1995B; Hendrix and Barfield, 1995; Ellis, Tyler, Kim, McGreevy, and Stark, 1985), these can never truly eliminate the problems inherent in displaying a three-dimensional world on a two-dimensional screen.

Another bias which is similar to the biases due to compression of one of the three axes is the virtual space effect (McGreevy and Ellis, 1986). The virtual space effect, like the other biases, is related to resolution. However, unlike the other biases, the virtual space effect is not a consequence inherent in the depiction of a 3-D scene and does not directly relate to the RTR model. Instead, it is the result of attempting to increase or decrease the geometric field of view (GFOV, as referred to later) of the display to compensate for differences in viewpoint distance, as explained as follows.

A close-up display with high resolution, like that through a telephoto lens or binoculars, may suffer from the problem of displaying only a small part of the world at one time, known as the "keyhole effect" (Woods, 1984). For aviation displays, this effect can be especially harmful for global spatial awareness (Wickens and Prevett, 1995). A display that views the world from afar (i.e., a wide-angle view) can facilitate global awareness, at the cost of reducing resolution and negatively affecting local guidance. To counter the keyhole effect on the one hand or the loss of resolution on the other, researchers have attempted to expand through wide angle minification, or contract through telephoto magnification the amount of world that is displayed on the screen (Wickens and Prevett, 1995). The problem encountered by these corrections is that they create a distorted picture of the spatial relationships among all the items depicted, especially those further from the center of the field of view. This problem, known as the virtual space effect (McGreevy and Ellis, 1986), is a consequence that is often worse than the original problems of keyhole effect and resolution loss.

1.4 The Viewing Parameters

The biases discussed above can all be influenced by the viewing parameters of a 3-D display. In general, four viewing parameters may be manipulated in 3-D display design: elevation angle, azimuth angle, tether distance, and geometric field of view (GFOV). The influence of all of these has been examined in a number of experiments. In understanding the effects of the four parameters, the viewpoint for depicting one's aircraft (ownship) in relation to the rest of the world can be represented as a camera. This camera is attached to the ownship by a tether. Figure 1.5 illustrates the four viewing parameters and the axes within which they are manipulated. Display elevation angle (DEA) refers to the angle above or below one's aircraft (ownship) from which ownship is viewed (see panel A of Figure 1.5). Thus, the display elevation angle involves viewpoint changes along the y/z axis plane. Given a camera which is directly behind the ownship, as the display elevation angle increases toward 90 degrees, the y-axis is compressed according to a cosine function. Thus, as Figure 1.6a shows, a map displayed from a 0 degree display elevation angle would have no compression for the y-axis and a resolution of 1, or 100% vertical resolution. Similarly, a 2-D, top-down map displayed from a 90 degree display elevation angle would have zero y-axis resolution, and the information about object identity, distance, and relative position, would be fully compressed and unavailable except in regards to relative size. While the y-axis resolution is reduced according to the cosine function as the elevation angle increases toward 90 degrees, the z-axis is expanded according to the sine function as the display elevation angle increases toward 90 degrees. Therefore, a 0 degree display elevation angle yields 0 resolution for the z-axis and a 90 degree display elevation angle yields a full z-axis resolution of 1. As long as the display has no azimuth offset, the resolution effects will remain consistent for manipulations of the display elevation angle.

Display azimuth angle (DAA) is similar to elevation angle but refers to the angle left or right of the longitudinal axis or fuselage of ownship, from which the visual scene is displayed (see panel B of Figure 1.5). Therefore, changes in the display azimuth angle occur along the x/z axis plane. Given a display elevation angle of 0 degrees, as the display azimuth angle increases toward 90 degrees in either direction from the view directly behind ownship, the x-axis becomes compressed, and the z-axis is expanded. As shown in Figure 1.6b, this compression corresponds to the compression created by increasing the display elevation angle and incurs the same effects, except along the orthogonal axes. Namely, as the display azimuth angle approaches 90 degrees, the x-axis resolution decreases according to the cosine function, and the z-axis resolution increases according to the sine function. As long as the display elevation angle is zero, the resolution will be consistently affected by changes in the display azimuth angle.

Up to this point, we have described the effects of different display elevation angles or display azimuth angles as they occur independently of each other. However, the resolution effects are more complex when a display contains both a non-zero display elevation angle and display azimuth angle. For example, if a display has an elevation angle of 45 degrees, changes in the display azimuth angle will not have their full effect on the resolution of the x or z-axis because resolution loss has been shared with the y-axis, which already has lost some of its resolution due to the 45 degree display elevation angle. The present research intends to investigate this geometric property to illustrate how the effects of changing both the display elevation angle and display azimuth angle are apparent in local guidance and spatial awareness tasks.

As the above analysis suggests, resolution for a given axis (x, y, or z) can be calculated based on its display elevation angle and display azimuth angle. The parameters of display elevation and azimuth angle are similar in that change in either the display elevation angle or display azimuth angle affects the z-axis resolution and makes the display line of sight less parallel to the forward field of view of the aircraft. These two variables will be manipulated in the present experiment.

As the view of the ownship is taken further away from the ownship (as in panel C of Figure 1.5), the hypothetical camera tether distance increases, resulting in a greater amount of real world depicted on the display. Decreasing the tether distance results in less of the world being shown, but the display of ownship and the world is larger, with better resolution. The immersed field of view, equal to what one would see in the forward field of view, is the endpoint of the continuum in which tether distance is zero.

Closely related to tether distance is the parameter of geometric field of view, GFOV. The GFOV is "the angle depicted by the display image from a hypothetical point where all light rays would converge" (Wickens, Todd, and Seidler, 1989). The GFOV determines the amount of the actual world presented to the viewer on the screen at a given tether distance (see panel D of Figure 1.5). As we noted above, one can increase the GFOV to show more of the world (imposing a loss or resolution) or decrease the GFOV to show less of the world (imposing a keyhole effect). The tether distance and GFOV work together to determine the resolution and amount of world shown on the display. However, care must be taken in manipulating the tether distance and GFOV to avoid the virtual space effect, as described above. The similar parameters of elevation angle and azimuth angle, and the wedded parameters of tether distance and GFOV all influence the biases in estimating the location and orientation of information in a 3-D display. The studies we review below have investigated the effects of these parameters across different tasks. The present experiment intends to extend the information and conclusions generated by those studies

1.5 Spatial Awareness Studies

In examining the use of three-dimensional displays, one class of studies has required static judgments of elevation, azimuth, or distance between the reference item (e.g. "ownship") and a target item. We refer to the two angles formed between these items as the Target Elevation Angle (TEA) and the Target azimuth angle (TAA), to distinguish them from the formerly mentioned display angles (display elevation angle and display azimuth angle). Correct judgments of this type would reflect more accurate spatial awareness of the environment.

Several studies have looked at this aspect of spatial awareness while manipulating the parameters of display elevation angle, display azimuth angle, or target location.

McGreevy and Ellis (1986) conducted some of the early three-dimensional display research which sought to test how target direction judgment varies in perspective displays as a function of the target location. In the experiment, subjects used round dials to indicate the judged elevation and azimuth angles of target cubes relative to a fixed reference cube at the center of the screen (see Figure 1.7). Although McGreevy and Ellis did not vary the display azimuth angle or display elevation angle, they did vary the placement of the target throughout the simulated world. The results showed that accuracy of judged target azimuth angles (TAA) was highly affected by the actual azimuth of the target in relation to the reference cube and the viewing line of sight for the display. Error in azimuth estimations of the target varied sinusoidally with respect to the angle to that target's location. This occurred such that the sine function of the error was at a maximum when the target cube was aligned with the viewing line of sight, and was at a minimum when the target azimuth angle was orthogonal to the line of sight. This effect would be expected because a sine curve would explain the resolution of the vector that connects the reference and target cubes. As this vector becomes more and more orthogonal to the line of sight, resolution for the vector increases along with performance. As the vector becomes more parallel to the line of sight, resolution and performance decrease.

Yeh and Silverstein (1992) performed a similar experiment to that of McGreevy and Ellis in which they had subjects judge which of two objects were higher above the surface, and which were closer to the viewer. The researchers measured latency of judgment and found that z-axis depth judgments were faster with a 45 degree display elevation angle than a 15 degree display elevation angle, and altitude judgments were faster at the 15 than the 45 degree display elevation angle. Accuracy of judgment was not reported for this comparison. The judgment latency reversal of effectiveness for the 15 and 45 degree display elevation angles can be attributed to the larger compression and lower resolution of the y-axis, or vertical dimension, at 45 degrees display elevation angle, and of lower z-axis resolution at 15 degrees display elevation angle.

In another study examining estimation of angles between cubes in a perspective display, Hendrix and Barfield (1994) used a paradigm similar to McGreevy and Ellis (1986) and found that increasing the vertical dimension compression by increasing the display elevation angle to 75 degrees, resulted in significantly poorer vertical judgments than were found for smaller display elevation angles of 15 or 45 degrees, which were not found to be significantly different from each other. They also found that judgments made for images orthogonal to the viewing vector were superior to judgments made when the target cube was parallel to the line of sight. Later work by Barfield, Hendrix, and Bjorneseth (1995) revealed similar results. Consistently, higher elevation angles increased the magnitude of elevation estimation errors between the cubes, and elevation angles between 15 and 45 degrees continued to provide for the best overall spatial judgment performance by minimizing elevation and azimuth judgment errors.

Some recent aviation-related experiments comparing spatial awareness supported by 3-D vs. 2-D co-planar displays are also relevant for examining performance with compressed dimensions. As mentioned before, the 2-D display is merely an extreme case of the 3-D display where the display elevation angle would be at 90 degrees. Although the vertical (Y) axis information is fully compressed and unavailable, the (X) and (Z) lateral axes are displayed orthogonal to the line of sight, resulting in zero compression and full resolution for the two displayed dimensions. For co-planar 2-D displays, the two different 2-D views of the same visual scene allow all three axes to be presented in one view or the other without compression. Thus, distinguishing between 2-D and 3-D maps for judgment along any given axis enables a comparison between a compressed and uncompressed axis.

Wickens, Liang, Prevett, and Olmos (1996) compared the effectiveness of 3-D vs. co-planar maps for indicating the relative position of probed features of the environment. Their 3-D display was represented from an elevation angle of 30 degrees. The results showed that the 2-D display facilitated more accurate vertical judgment. This result would be expected by the RTR model as the decreased resolution for the vertical dimension in the 3-D display made position judgments more challenging. Though less accurate, the 3-D display did result in more rapid judgments of vertical position, indicating a speed-accuracy trade-off probably due to the increased cost of scanning between the two views imposed by the 2-D co-planar display (Wickens, 1993; Wickens, 1992B).

Davenport (1997) also examined spatial judgment of relative intruder location as pilots used a 3-D or a co-planar display. The 3-D display was presented with a 30 degree elevation angle and an 8 degree azimuth angle. The results showed that judgment of intruder altitude was significantly more accurate with the co-planar display than with the 3-D display, whose altitude was, of course, compressed. Judgment of relative distance from ownship to the intruder was also more accurate with the co-planar display. These results are consistent with the resolution model because the 30 degree elevation angle and 8 degree azimuth angle reduce the resolution for the vertical and horizontal axes, resulting in the difference in judgment accuracy. Figure 1.8 graphically depicts the general findings of Davenport and the previously discussed studies as performance for a given axis is related to the resolution for that axis.

O'Brien and Wickens (1997), Merwin and Wickens (1996), Jasek, Pioch, and Zelter (1995) have all found similar advantages for the co-planar display in studies examining performance in air traffic displays. Although these studies did not explicitly manipulate target elevation angle or target azimuth angle, the compression of one or more of the three axes resulted in ambiguity of position. This ambiguity was found to have a larger cost than the cost to scan between the two parts of the co-planar display.

Recent research by Hickox and Wickens (1996) is also relevant here. Although Hickox and Wickens did not examine the spatial awareness task, they did vary elevation angles and model how judgments of navigational checking are affected by loss of resolution parallel to the line of sight. Figure 1.9 shows how Hickox and Wickens describe the resolution of features in a scene as influenced by the sine of the display elevation angle from which the scene is presented. In this study, the participants were tasked with making same/different judgments based on a comparison of the "world" and the map. The experimenters varied the elevation angle from which both the world and the map were presented. The data revealed several findings relevant to the present research. First, the navigational checking performance functions were best described by the sine of the angular disparity between the actual world and map views, rather than the actual angular disparity between these two views. This finding suggests that 2-D projection on the image plane, as captured by the sine angle, was playing a role in judgment. Furthermore, the fact that increasing angular disparity between the two images caused reduced accuracy and increased latency, seems to support the RTR model and provides evidence that rotation of the scene is taking place. This finding supports the previously discussed "mental stretching" theory that participants may actually mentally rotate a compressed axis to orthogonality to better determine the information for that axis. Finally, the results indicated some hint that overall, the 45 degree map display elevation angle was best across all disparities. The nature of trigonometric fact might explain this result, since the 45 degree display elevation angle is the one that minimizes overall disparities or distortions in both the y and z-axes.

Other studies have also examined spatial awareness while manipulating tether and GFOV (McGreevy and Ellis, 1986; Hendrix and Barfield, 1994; Prevett and Wickens, 1995). These parameters, though not involving the three-dimensional compression of an axis as the manipulations to be imposed in the present experiment, do have relevance for loss of resolution and its affects on spatial awareness. The direct manipulation of tether distance while holding GFOV constant changes only the resolution of a given portion of the world. As tether distance increases, a larger part of the world is revealed on a screen of constant size, with the result that the same world is then displayed with less resolution (see panel C of Figure 1.5). In this way, changing the tether distance reduces or increases the resolution for all three axes, rather than only two at a time. Changing the GFOV at a given tether distance can also alter the resolution. However, when the GFOV is altered from its undistorted, natural state for that given viewing distance, the change results in the virtual space effect, as previously discussed (McGreevy and Ellis, 1986; Wickens et al. 1996). Because of this, the studies investigating spatial judgment tasks which have altered the GFOV away from the undistorted GFOV based on the center point (McGreevy and Ellis, 1986; Hendrix and Barfield, 1994; Prevett and Wickens, 1995) are difficult to evaluate because the effect of the resolution change is experimentally confounded with the virtual space effect.

As the above review suggests, numerous studies have looked at the effects of parameter manipulations on spatial judgments for perspective displays. However, few experimenters have made an attempt to explain the underlying cognitive mechanisms and display geometry responsible for the effects. Several experiments have examined the target elevation angle and target azimuth angle and all have found that compression and resolution influence either the speed or the accuracy of spatial judgments. Other experiments have investigated the display elevation angle and display azimuth angle and these also have found that changes in resolution can affect the ability to make spatial judgments and thus, influence the ability to maintain spatial awareness. However, no experiment has examined spatial judgments while manipulating all four (display elevation angle, display azimuth angle, target elevation angle, and target azimuth angle) of these parameters. Furthermore, even those studies that did examine a subset of these parameters together did not simultaneously explore local guidance. Only the aviation studies (e.g. Wickens, Liang, Prevett, and Olmos, 1996; Davenport, 1997) examined both local guidance and spatial judgments, and these studies considered only two levels of display elevation angle (i.e. 30 and 90 degrees). Therefore, despite the consequences documented in the literature concerning the implications of resolution effects for spatial awareness, it is still unclear how these effects will influence local guidance.

1.6 Local Guidance and Tracking

While the studies reviewed above explored spatial awareness, a class of studies we address now has examined the effects of perspective display viewing parameters on closed-loop control, or tracking, as errors are represented in three-dimensional space. The tracking paradigm (Wickens, 1986; Poulton, 1974; Warren and Wertheim, 1990) describes the continuous process of choosing spatially-defined outputs in response to spatially-defined inputs

(Wickens, 1996). The tracking task contains an element that is similar to spatial awareness, especially if tracking is broken down as a continuous set of discrete judgments, as sample data models presume (Wickens, 1977). These judgments require a decision on the control action to implement based on one's actual estimated position in relation to the estimated intended position (i.e., the error vector). The individual judgments or estimations of position and error are very similar to those involved in spatial awareness. Although the underlying 3-D display problems of compression and ambiguity that affect the spatial estimations of position and distance still exist for tracking, the additional interacting factors that go into closed-loop control may alter the effects of these variables (as addressed in Figure 1.10, discussed below). These interacting factors, which will be discussed more fully below, include attention allocation, value and urgency differences between axes, the control to display error misalignment, as explained by stimulus/response incompatibility, and the possibility that error may be perceived differently in a dynamic than in a static task. These factors make tracking more complex and the effects of display parameters more difficult to predict.

As we have discussed above, the geometry of projection dictates that errors of a given size (in true meters of 3-D space) will be represented as smaller (in pixels) on the display screen for dimensions that are compressed. However, just because the errors are represented as smaller and there is more ambiguity about their actual size, does not necessarily mean that they will be corrected less efficiently in a multi-axis closed-loop tracking task.

Researchers have done extensive research on simple tracking tasks and have been relatively successful in modeling this type of task (Wickens, 1992). However, the modeling is greatly complicated when one takes into account the competing demands of axes in multi-axis tracking. Flying is an example of a multi-axis task in which the pilot must sometimes maneuver through all three axes of the world. A pilot can bank and roll through the x-axis, climb and dive through the y-axis, and accelerate or decelerate through the z-axis. These maneuvers must sometimes be performed simultaneously, requiring a difficult division of attention among the multiple axes.

1.6.1 Multi-Axis Tracking

The pilot engaged in multi-axis tracking must have a mental algorithm of when to transfer attention and effort between the relevant axes. One way to model when this transfer will take place is based on the perceived urgency of each axis (Onstott, 1976). The urgency for an axis takes into account the pilot's perceived importance of that axis and the amount of error perceived in that axis. Especially when flying close to the ground, a pilot may be more likely to correct a relatively small deviation in flight path altitude than a larger deviation in lateral position. Therefore, for multi-axis tracking tasks, the size of the error is not always the most important factor. Even if we can predict the error in pilot perception using the RTR model, the values and urgency of the pilot may result in different performance.

Performance prediction for multi-axis tasks is further complicated by the limited resource capacity of pilots. Pilots have a threshold of error tolerance and usually will not, or can not, correct every error, particularly in a multi-axis, time-sharing environment. In the extreme, this may result in the pilot correcting only the most urgent deviation and accepting all others, eliminating any effect of loss of resolution for the un-corrected axes. However, resolution differences may still be important if urgency between two axes is nearly equal and the lack of resolution leads pilots to ignore an axis that needs to be corrected.

Another effect of tracking that complicates the application of the RTR model involves the complex mechanisms humans have for correcting errors. One model which attempts to explain how aggressively humans will correct deviations is the Crossover model (McRuer and Krendel, 1959; McRuer and Jex, 1967; Wickens, 1992). The Crossover model states that correction velocity will be proportionate to the momentary error size. Large errors will be corrected very aggressively (i.e., with greater velocity) and small errors more slowly. For instance, a pilot may perceive large lateral deviation from the flight path and will then aggressively correct it. As the pilot samples the size of the error again, the deviation should be smaller and he or she will slow down his or her correction velocity. Because of this, lack of resolution may affect the velocity of correction more than the amount of correction. Therefore, the small amount of error added through reduced resolution should make less and less of a difference as the error is corrected.

An additional reason closed-loop control in a 3-D world is so complex is that a control movement which does not line up with the displayed error vector brings about stimulus-response compatibility effects (Fitts and Seeger, 1953; Wickens, 1992). In other words, if the displayed view of the target's fore-aft movement axis is re-oriented to the side (i.e., with a non-zero display azimuth angle), without corresponding displacement or rotation of the control (i.e., joystick) axis, a situation arises such that movement of the control does not coincide with the viewed movement of the target. This visual-motor misalignment between the viewing and control axis brings about its own effects which may differ from the effects due to the RTR model.

All of these factors make multi-axis tracking a very complex task for examining the variables affecting perspective displays. The following studies will examine the complex tracking paradigm and review how display axis rotation has been found to affect performance in previous experiments.

1.6.2 Tracking Studies

One of the first studies to examine how tracking was influenced by the perspective parameters was conducted by Ellis, Tyler, Kim, McGreevy, and Stark (1985). In the second part of this study, the researchers manipulated the display azimuth and elevation angles used in a three-dimensional tracking task. The subjects used two 2-axis joysticks to track a cursor moving irregularly through three dimensions. First, the researchers varied the display elevation angle while holding the display azimuth angle at a constant 0 degrees relative to the center of the fore-aft control axis of the depicted grid system. They found the best overall performance (lowest vector error) at 45 degrees of display elevation angle, with increasingly poorer performance as angles increased or decreased from this optimum angle. The researchers conducted two more experiments testing several display azimuth angles while holding the display elevation angle at a constant 45 degrees. The results revealed the best tracking performance to take place at 0 degrees of display azimuth in relation to the center of the grid system along the primary fore-aft axis and the axis of control displacement, with little effect of increasing azimuth on performance until the display azimuth angle exceeded 50 degrees. The error then increased to a maximum at 135 degrees of display azimuth angle.

Ellis, Tyler, Kim, and Stark (1991) continued this line of research on three-dimensional tracking with a perspective display and also investigated the effects of visual-motor alignment in which the control axis angle was aligned or mis-aligned with respect to the viewing axis or display azimuth angle. In the experiment, subjects used a two-axis joystick to track a diamond that moved irregularly in the 3-D world. The world was displayed with a consistent 45 degree display elevation angle and the display azimuth angle was rotated through nine different angles relative to the axis of control. Consistent with the findings of Ellis, et al. (1985), the results revealed that tracking was best at a display azimuth of 0 degrees, with few detrimental effects noted at display azimuth angles below 50 degrees. Also consistent with the previous Ellis, et al. study, the researchers found that above 50 degrees, the errors increased to a maximum at 125 degrees and decreased again as the display azimuth angle approached 180 degrees. The experimenters found that much of the tracking error was due to the control/viewing misalignment, since rotation of the control axis to alignment with the viewing axis greatly reduced the detrimental effects of increasing display azimuth angles. This accounts for the results in which the maximum tracking error occurred at 125 degrees instead of 90 degrees, indicating that mental rotation may be a factor in the control mis-alignment effects (Shepard and Metzler, 1971; Cooper and Shepard, 1978). Ellis et al. postulate that subjects mentally rotate the display view to align it with the control but that at some point (e.g., 125 degrees) it becomes simpler to reverse it and then rotate the other direction. Such a reversal strategy has been documented in other studies of mental rotation (Aretz, 1991).

Despite the large effects, control/viewing mis-alignment did not describe all the variance in tracking performance in the Ellis, et al. (1991) experiment. Even when the control axis was rotated to alignment there was found to be a purely visual component accounting for some of the tracking error. In particular, it was found that the visual component of the tracking error along each axis was minimized when that axis was viewed from an orthogonal direction, and that the tracking error for control/viewing aligned conditions was proportional to the sine of the angular deviation from that ideal orthogonal view. This finding is congruent with the earlier described resolution effects (as seen in Figure 1.6), which described how resolution was at 100 percent for displayed axes which were orthogonal to the line of sight, and decreased to zero according to the sine of the angular deviation from the orthogonal view.

Hence, this study provides strong support for the RTR model and the belief that performance along a given axis will be influenced by the resolution of that axis.

In contrast to the "generic" 3-axis task used by Ellis et. al. (1991), Barfield, Rosenberg, and Furness (1995) sought to examine the effects of manipulations of the display elevation angle on an aviation tracking task. For this experiment, subjects flew a simulated F-16 aircraft through a computer-generated world. The world was presented from either a 30 degree or 60 degree display elevation angle. Elevation and speed of the aircraft were held constant and subjects were scored only according to their lateral root mean square (RMS) error from the ideal flight path. The experiment revealed that the 60 degree display elevation angle resulted in more accurate lateral tracking than the display presented from a 30 degree display elevation angle. Despite the fact that z-axis tracking (speed) was not measured, the results indicate that the increased compression of the z-axis at 30 degrees was still detrimental to lateral tracking. This is likely due to the fact that in aviation tracking, lateral correction depends heavily on prediction (i.e., what is the future--along the z-axis). To the extent that the z-axis is compressed, resolution loss for that axis will make prediction estimation more difficult, which will have cascading effects on lateral deviations in tracking.

The previous studies by Ellis et al. (1985, 1991) and Barfield et al. (1995) all generally demonstrate the effects that would be expected due to the RTR model. Furthermore, with the exception of the addition of control/viewing misalignment effects, the local guidance results mirror the results found for position judgments.

Wickens, Liang, Prevett, and Olmos (1996) conducted two experiments with aviation-related tasks manipulating fixed versus rotating maps (i.e., north-up vs. track-up) and two-dimensional versus three-dimensional maps presented from display azimuth angles of either 0 or 30 degrees. In both experiments, subjects controlled an aircraft using a joystick with two axes of control. With airspeed held constant, subjects followed a predetermined flight path and were evaluated according to their horizontal and vertical RMS error as they deviated from the flight path. One finding from the first experiment was that lateral tracking performance, using the 3-D display in the fixed North-up map was worse for east-west legs than for north-south legs. This finding indicates that the relatively reduced resolution of the z-axis of the display compared to the x-axis made lateral tracking more difficult when the lateral flight axis was compressed into the z-axis depth dimension (i.e., on the east-west leg). Some aspect of this effect could also have been due to viewing/control axis misalignment, since pilots here would be required to move the flight control stick in a left-right axis, to control z-axis motion on the display. Results for the 0 degree versus 30 degree display azimuth comparison showed little performance difference between the two conditions. This effect replicates other research which also found very little effect on tracking performance until display azimuth angles exceeded 50 degrees (Ellis, Tyler, Kim, McGreevy, and Stark, 1985; Ellis, Tyler, Kim, and Stark, 1991).

As with the review of spatial awareness studies, numerous studies have also been conducted comparing tracking performance for 2-D co-planar versus 3-D displays. Much of the recent research using co-planar displays has found these displays to generally be superior to exocentric 3-D displays for tracking performance (Davenport, 1997, Merwin and Wickens, 1996; Wickens, Liang, Prevett, and Olmos, 1996; Wickens and Prevett, 1994; Rate and Wickens, 1993; Andre, Wickens, Moorman, Boschelli, 1991; Olmos, Wickens, and Chudy, 1997). Again, this superiority can be attributed to the undistorted, unambiguous presentation of information afforded by the co-planar display. Only when considerable efforts are undertaken to diminish 3-D ambiguity problems (as in Olmos, Liang, and Wickens 97, and Olmos, Wickens, and Chudy, 1997, experiment 2) does the 3-D display approach equivalence.

As the previous review suggests, the effects of resolution loss due to display azimuth angle or display elevation angle rotation are apparent not only for spatial awareness tasks, but also for local guidance tasks. However, unlike the effects on position judgments, the RTR model effects do not seem to significantly alter local guidance performance until the display azimuth angle (or display elevation angle) exceeds approximately 45 or 50 degrees relative to the control alignment axis. Furthermore, mis-alignment between the viewing and control axes seems to have an additional effect which may even overshadow the resolution effects when this control/viewing axis misalignment exceeds 50 degrees. Though it is clear that the RTR model is useful for examining both spatial localization judgments and tracking tasks, it is not yet clear if performance for the two tasks will be altered correspondingly.

Tether distance and GFOV have also been manipulated for tracking tasks. Kim, Ellis, Tyler, Hannaford, and Stark (1987) conducted one of the few studies varying tether distance independent of GFOV. The results reveal the effects of compression and resolution loss, un-confounded by the virtual space effect. The results, as expected due to the influence of resolution loss, indicated that increased tether distance led to increased tracking error (as measured in world units, not pixels). Kim et al. also manipulated GFOV from 8 to 64 degrees for a given tether length, and also revealed that larger GFOVs (minification) resulted in greater error in world units, due to resolution loss. In the first experiment of the previously discussed study by Ellis, Tyler, Kim, McGreevy, and Stark (1985), the experimenters varied tether distance, while changing the GFOV so that the amount of actual world displayed in each display remained constant. This study followed the expected results due to resolution loss except that the smallest tether distance led to much greater error than would normally be predicted according to its resolution. Experimenters speculated that the unusually large error for the smallest tether distance was due to the large 119 degree GFOV, which seemed to distort the scene enough that the virtual space effect overshadowed any advantage due to increased resolution.

Wickens and Prevett (1995) also manipulated GFOV and tether distance, and found that changing the GFOV may have had a similar effect of introducing the virtual space effect. In this study, four tether distances, O feet, 10,000 feet, 25,000 feet, and 70,000 feet, were examined for their effectiveness in facilitating tracking. The GFOV for each display was manipulated in compensatory fashion so that each display showed approximately an equal amount of the actual world. The results for horizontal mean absolute error (MAE) from the flight path generally showed increased tracking error for further distances, as would be expected due to loss of resolution. The deviation from such expectation occurred for the short tether distance of 10,000 feet, which led to considerably greater vertical error from the flight path. At this distance the GFOV was set at 120 degrees, nearly the same as the 119 degree threshold found by Ellis et al. that severely degraded performance due to the virtual space effect. Another interesting finding was that the mid-exocentric position of 25,000 feet resulted in the lowest tracking error overall. This result too can be explained because this distance provided the greatest resolution without exceeding the critical point at which the virtual space effect may have overshadowed any advantages afforded by resolution.

As one can see, many aspects of tracking appear to follow the same trends as spatial judgments, when viewing parameters are varied. Namely, with all other variables held constant (eliminating the virtual space effect), resolution loss for a given axis leads to reduced tracking performance for that axis. Still, applied aviation studies such as Wickens, Liang, Prevett, and Olmos (1996), Wickens and Prevett (1994), and Barfield, Rosenberg, and Furness (1995) reveal that guidance performance in the aviation realm can often be complex and difficult to predict. More research needs to be done on aviation tasks to examine the complex effects of resolution and display biases as they are influenced by 3-D display parameters and are jointly manifest in the tasks of local guidance and spatial judgment.

1.7 Summary of Viewpoint Parameters

In general, the research seems to indicate fairly consistent trends in effects of compressing the various axes through manipulation of the elevation and azimuth angle. As would be predicted from the "Resolution Through Rotation" model, the more an axis is compressed, due to the greater angle its axis is rotated from orthogonal, the greater is the loss of resolution and the more performance seems to suffer for both spatial awareness and tracking tasks. Similar effects have been observed for loss of resolution due to increasing the tether distance and increasing the GFOV, although some of the latter effects have been found to be greatly influenced by the distortion caused by the virtual space effect.

Despite the related tasks of local guidance and spatial awareness, few studies have examined both together as they are affected by the different viewing parameters. Also, no study to date has varied both the elevation angle and the azimuth angle at the same time. Since both of these parameters influence resolution of the z-axis as well as the x or y-axis, it is important that they be manipulated simultaneously to determine if they interact. The present study will investigate these important aspects of three-dimensional displays by examining local guidance and spatial awareness through simultaneous manipulations of the display azimuth angle and display elevation angle. Our tests of spatial awareness of targets relative to ownship will also manipulate target azimuth angle, target elevation angle, and target distance over the full 3-D display range. By employing both tracking and spatial awareness tasks to examine the effects of changes in both elevation and azimuth angles, the present research intends to more clearly separate the effects of these variables for the purpose of understanding the effects of perspective viewing on display design. By examining the extent to which effects of viewing parameters on spatial judgments and tracking performance are congruent or incongruent, we hope to gain insight as to the separate contributions of RTR and axis alignment to tracking performance.

2. Methods

2.1 Participants:

Twenty-five members of the aviation program at the University of Illinois participated in the experiment. All participants had a minimum of 35 hours of flight experience, and ranged in age from 19 to 42. Each participant was tested for approximately 1.5 hours, receiving payment of $7.00 per hour.

2.2 Apparatus:

The experiment was conducted on a Silicon Graphics IRIS workstation with a 16 inch diagonal screen. A two-degree-of-freedom joystick with a trigger in the front and button on top was attached to the right arm of the participant's chair. The joystick used standard aviation control to direct the lateral and vertical control of the aircraft. Forward or back stick pressure controlled the pitch, while side-stick pressure altered the roll rate. Turn rate was directly proportional to the roll angle, which was held to a maximum of 80 degrees. True flight dynamics were used with pitch cross-coupled with roll such that rolling the aircraft would result in a simultaneous pitch down of the aircraft. Aircraft velocity was held constant at 260 kts.

2.3 Display:

The display depicted a 3-D representation of a simulated world as used in previous experiments (see Figure 2.1). Participants flew along a final approach flight path to landing (see path C of figure 2.1). The map was continuously viewed in a track-up format such that the position of the aircraft remained centered in the display and the map rotated when ownship heading was changed. The viewpoint of ownship was fixed from a common distance of 25,000 feet across all trials. This distance provided the best performance for guidance and spatial awareness tasks as demonstrated by Wickens and Prevett (1994). The GFOV was set such that horizontal and vertical dimensions were represented equally and undistorted, relative to the viewing distance of the participant's eyes to the screen. Participants were seated approximately 16 inches from the screen at the approximate station point. Display viewpoint elevation and azimuth angles were manipulated from 15 to 75 degrees as independent variables for the experiment.

Several augmentations to the display were maintained from the previous experiment by Wickens and Prevett (1994). First, the cardinal directions were depicted on the world terrain with a large white arrow and the corresponding direction, N, S, E, or W. Next, a directional predictor extended from the nose of the aircraft so participants could better judge their future position in both the lateral and vertical axes. Both the end of the predictor extension, the center of the ownship, and the intruder aircraft were connected to the ground by droplines, thereby giving more vertical as well as lateral information to the user. An additional augmentation which was unique to this experiment was the addition of elevation tick marks along the droplines. Small marks indicated 2,640 feet (one half mile) of elevation and larger tick marks depicted 5,280 feet (one mile) of elevation. Finally, an attitude display indicator (ADI) was positioned at the top center of each display to help stability in tracking along the flight path. The ADI was configured such that the aircraft symbol banked to show roll movement while the pitch bars moved to show pitch inputs.

2.4 Experimental Design:

The experiment was carried out with the following independent variables:

1. Display elevation angle, relative to the orientation and velocity vector of ownship fuselage, randomly assigned over five trials at 15, 35, 45, 55, and 75 degrees (within subjects)

2. Display azimuth angle, relative to longitudinal axis of the aircraft (ownship), was varied at angles of 15, 35, 45, 55, and 75 degrees (between subjects)

3. Lateral azimuth angle to the target: randomly positioned at 10 degree intervals from 0 to +-180 degrees.

4. Vertical elevation angle to the target: randomly positioned at 10 degree intervals from 0 to +-90 degrees vertically.

5. Distance to the target: randomly positioned at .1 mile intervals from .5 to 1.3 miles.

Display azimuth angle was manipulated between subjects for the experiment, and display elevation angle was manipulated within subjects. Not all possible target position combinations of variables 3, 4, and 5 were necessarily sampled. Instead, a quasi-random uniform distribution of 12 target positions per trial was chosen. Each participants flew the entire path at one assigned display azimuth angle. At this angle, the display elevation angles were varied using a Latin square design such that all five display elevation angles were seen over the five trials in a counter-balanced order. During each trial participants performed the spatial judgment task of identifying the azimuth angle, elevation angle, and distance to 12 randomly positioned intruder aircraft, relative to ownship.

2.5 Procedures:

Upon arrival, participants were given a short demographic questionnaire to record their age, gender, and flight experience. Participants were then given instructions for performing the tasks of the experiment and queried for any questions they had. Next, participants performed a short practice trial in which they saw all possible display elevation angles, viewed from the same azimuth angle that they would be using in the experiment. During this practice trial the participants were allowed to ask the administrator any questions they wanted. After participants completed the practice trial, the administrator left the room and participants continued the experiment alone. Each flight was initiated by the participants so they were given the opportunity to rest between all of the five recorded flights, each of which took approximately 12 minutes to complete.

In a given trial, subjects started at the beginning of the flight path. Participants were given the task of guiding their ownship along the curved final approach flight path. Upon appearance of intruder aircraft along the way, the screen was frozen to ensure all participants saw the same intruder location and to maintain consistency of judgment conditions. Upon detection of the intruder, participants pushed the trigger, initiating the appearance of a slider scale for which participants used the left/right cursor keys to estimate the azimuth angle to the intruder relative to the ownship heading. When participants were satisfied with their answer they pushed a black button on the top of the joystick, which brought about the appearance of the elevation angle slider scale. Participants then used the up/down cursor keys to move the slider to the estimated elevation angle from the position of ownship to the intruder. Again, participants pushed the black button upon completion, initiating appearance of the distance slider scale. Participants used the left/right cursor keys to position their estimate of the actual vector distance from ownship to intruder expressed in units of grid block distance, and pushed the black button upon completion. Participants were instructed on the importance of both speed and accuracy for all of the judgments of intruder position. When the participants were ready to continue their guidance along the flight path, they pushed the trigger, allowing them to continue flight from their former position and heading. This was continued until participants completed all 12 intruder position estimation tasks. Participants then continued along the last portion of the flight path, which had no intruders, and followed it until landing.

After completion of all trials, participants were given a post-test to evaluate their perception of the overall difficulty of both the guidance and spatial awareness tasks. Participants were also asked to comment on their perception of the effects induced by the different display elevation angles and intruder positions.

2.6 Performance Measurement:

2.6.1 Local Guidance: Performance was recorded using RMS (Root Mean Square) error in terms of horizontal deviation, vertical deviation, and actual deviation from the flight path. This was recorded both for the entire flight path, and for the portion of the flight path following the last intruder event, the pure tracking portion of the trial.

2.6.2 Spatial Judgment: Participants were evaluated for their spatial judgment ability for a given combination of display parameters based on the accuracy of their estimation of intruder location. The accuracy was assessed by finding the difference between the actual azimuth angle to the intruder and the participants' estimated angle, the difference between the actual elevation angle to the intruder and the participants' estimated angle, and the difference between the actual distance in miles to the intruder and the participants' estimated distance.

3. Results

The data were analyzed using the statistical computer program SPSS for UNIX, motif interface. The results are reported in two primary sections: local guidance measures and spatial awareness measures. All error bars reported indicate 2 standard errors from the mean.

3.1 Local Guidance Measures:

Results were recorded using the root mean squared error (RMSE) from the flight path, as averaged over the final "pure tracking" portion of each trial, in which no intruders were present. A log transformation was carried out on the data prior to analyses due to its skewness. Both lateral and vertical RMSE log data were subjected to a 5 (display elevation angles) x 5 (display azimuth angles) mixed model ANOVA with repeated measures over azimuth angles. A correlation analysis was also performed for lateral and vertical RMSE versus display elevation angle and display azimuth angle.

3.1.1 Vertical RMSE:

Figure 3.1 shows the vertical error from the flight path for the five conditions of display elevation angles. The figure reveals that higher display elevation angles, creating lower vertical resolution, resulted in a higher vertical RMSE. The repeated measures ANOVA testing this result revealed a significant effect of display elevation angle on log vertical RMSE, $F(4,80=44.77, p<.001)$. No significant effect was found for the between-subject variable, diplay azimuth angle, on log vertical RMSE, $F(4,20=2.08, p>.12)$. However, the univariate ANOVA for interaction effects revealed that the interaction between display azimuth angle and display elevation angle was significant, $F(16,80=1.93, p<.03)$. Figure 3.2 shows the vertical RMSE for the five elevation conditions by the five azimuth conditions. This figure indicates that the interaction found by the ANOVA is due to the "fan effect" of the results, such that the negative effects on vertical RMSE of higher display elevation angles is found to be stronger if the display azimuth angle is smaller. Alternatively, at higher display azimuth angles, the detrimental effect of increasing the display elevation angle is diminished. This "fan effect" will be discussed more fully later. A correlation analysis was also performed on these data and it was found that the vertical RMSE was positively correlated with the display elevation angle (N=125, r=+.51, p<.001), and negatively with the display azimuth angle (N=125, r=-.30, p<.002). As seen in Figure 3.2, this latter effect is only in evidence at the higher elevation angles. Thus, although no effect of display azimuth angle was found in the ANOVA, a small effect for display azimuth angle was found in the regression analysis, a difference in significance reflecting the greater statistical power of the regression anlaysis for revealing the effect of a monotonically ordered variable.

3.1.2 Horizontal RMSE:

Figure 3.3 shows the horizontal error from the flight path for the 5 different azimuth angle conditions. The repeated measures ANOVA testing the effects of display azimuth angle on log lateral RMSE was found to be non-significant, F(4,20=1.46, p>.25). Despite this finding of non-significance (which may be due to the low power of the between-subject variable for this repeated measures design), the figure indicates a possible step function in which display azimuth angles of 55-75 degrees provide worse horizontal performance than that for display azimuth angles of 15-45 degrees. Indeed, the data points of 45 degrees and 55 degrees are separated by approximately four standard errors. Figure 3.4 displays the horizontal RMSE as a joint function of display elevation and azimuth angle. The ANOVA test for effects of display elevation angle on log horizontal RMSE was found to be significant, F(4,80=8.75, p<.001). The direction of this effect, as shown in Figure 3.4, suggests reduced lateral error at higher display elevation angles, although as we see below, this effect was itself moderated by display azimuth angle. As with the data for vertical RMSE, there is again evidence for a "fan effect" in which larger display elevation angles seem to reduce the apparent negative effects of display azimuth angles greater than 45 degrees. This interaction, though less clearly visible in Figure 3.4 than in Figure 3.2, was found to be signigicant, F(16,80=2.00, p<.03).

3.1.3 Local Guidance Correlations:

A regression analysis was performed to examine the correlation effects. Again in contrast to the ANOVA, the regression analysis did reveal a significant but small correlation between the horizontal RMSE and the display azimuth angle ($N=125$, $r=+.20$, $p<.03$), capturing the general positive slope of the data in Figure 3.4. The correlation between horizontal RMSE and the display elevation angle also revealed a small but significant negative correlation ($N=125$, $r=-.28$, $p<.001$), replicating the ANOVA finding (i.e., smaller horizontal error at higher display elevation angles.

3.1.4 Summary of Local Guidance Measures:

Thus, the results indicate a consistent pattern of results. Along both axes, increasing the viewing angle increased compression in a way that increased error (higher display elevation angles = higher vertical error; higher display azimuth angles = higher horizontal errors). In neither case, however, did these effects appear linear, only emerging at the higher viewing angles; and in both cases the error cost of the higher viewing angles was greatly reduced by increasing the viewing angle on the other axis.

3.2 Spatial Awareness Measures:

Six variables were examined for the spatial awareness measures: target Vertical angle Judgment Error (VJE), target Horizontal angle Judgment Error (HJE), target Distance Judgment Error (DJE), Vertical angle Judgment Time (VJT), Horizontal angle Judgment Time (HJT), and Distance Judgment Time (DJT). VJE is defined as the absolute difference between the actual vertical angle from the ownship to the target, and the judged vertical angle to the target indicated by the participant. HJE is defined as the absolute difference between the actual horizontal angle from the ownship to the target, and the judged horizontal angle to the target indicated by the participant. DJE is defined as the absolute difference between the actual vector distance from ownship to the target, and the judged distance to the target as indicated by the participant. Finally, VJT, HJT, and DJT are defined as the time from when the respective elevation, azimuth, or distance judgment gauge appeared to the time when the participant pushed the button indicating their judgment on the corresponding variable was complete. All six dependent variables were subjected to a 5 (display elevation angles) x 5 (display azimuth angles) mixed model ANOVA with repeated measures over azimuth angles. A correlation analysis was also performed for the six dependent variables versus display elevation angle and display azimuth angle.

3.2.1 Vertical Judgment Error:

Figure 3.5 displays the VJE for the five display elevation angle conditions. As with the local guidance measures, reduced vertical resolution caused by high display elevation angles reduced performance for vertical judgments. This effect was evident both in the significant effect of the ANOVA (F,4,80=15.39, p<.001) and the correlation between these two variables (N=1500, r=.15, p<.001). The ANOVA analysis for effects of display azimuth angle on VJE was non-significant (F,4,20=.68, p>.61) and the correlation between these two variables indicated no significant correlation (N=1500, r=-.03, p>.20). Figure 3.6 shows the measure of the vertical judgment error (VJE) as a joint function of both display elevation angle and display azimuth angle. The ANOVA testing the interaction effects of display elevation angle and display azimuth angle on VJE revealed a significant interaction, F(16,80=2.29, p<.01). This interaction, however, does not appear to reveal any monotonic trend.

Figure 3.7 shows the joint effects on vertical judgment time (VJT) of both display azimuth angle and display elevation angle. Though the graph indicates a trend for quicker judgments at 45 degees display azimuth angle, neither the effect of azimuth error (F,4,20=1.52, p>.23), nor the effects of the other variables were found to significantly effect vertical judgment time.

3.2.2 Horizontal Judgment Error:

Figure 3.8 displays the horizontal judgment error (HJE) for the five display azimuth angle conditions, and Figure 3.9 shows the HJE based on the joint levels of both display azimuth angle and display elevation angle. The ANOVA test for the effects of display elevation angle on HJE was found to be non-significant (F,4,80=.09, p>.95), as was the correlation between HJE and display elevation angle (N=1500, r=-.01, p>.60) and the interaction between display elevation and display azimuth angles F(16,80=.89, p>.58). The repeated measures ANOVA testing the effects of display azimuth angle on HJE was found to be non-significant, F(4,20=.53, p>.713), as was the correlation between HJE and display azimuth angle (N=1500, r=.004, p>.85).

The non-significance of the HJE/display azimuth angle ANOVA and correlation is not unexpected. Unlike the vertical judgment error, both of the primary axes affected by changes in display azimuth angle (x and z axes) are equally important in determining the target azimuth angle. Since targets were balanced across all lateral locations, the advantage to changing display azimuth by reducing compression on one axis (x or z) would be offset by the cost of increasing compression on the other axis (z or x, respectively). Instead, the target position resolution was affected more by relative target location than by the display azimuth angle. Therefore, a more telling variable for influencing the HJE would be the extent to which the judgement must be made along the line of sight (i.e. the relative bearing between the display azimuth and target azimuth). This will be examined in section 3.2.4.

Figure 3.10 reveals how horizontal judgment time (HJT) was lowest at 45 degrees of display azimuth angle, as was seen for vertical judments in Figure 3.7. As with the former trend, however, no significant effects were found in the ANOVA for display azimuth angle (F,4,20=1.29, p>.30) nor any of the other variable effects on horizontal judgment time.

3.2.3 Distance Judgment Error:

Figure 3.11 displays the distance judgment error (DJE) for the five levels of display azimuth angle. As can be seen, the results seem to indicate that a display azimuth angle of 45 degrees supports the best judgment of distance. Also, excluding the 45 degree data, there appears to be a slight trend for increasing display azimuth angles supporting less acurate distance judgments. Despite these apparent effects, the effect of display azimuth angle on DJE was not found to be significant in the ANOVA (F,4,20=.39, p>.80), although the correlation analysis did reveal a very small but significant correlation between the two (N=1500, r=.08, p<.005), reflecting the slight monotonic increase of DJE with increasing display azimuth angles.

Figure 3.12, which shows the DJE for the five conditions of display elevation angles, also seems to show the superiority in DJE for the mid-range display elevation angles. The ANOVA testing the effects of display elevation angle on DJE revealed a marginally significant effect (F,4,80=2.20, p<.08). This finding gives evidence for the possibility that vector distance judgment is best when resolution for the axes are equal, preventing confusion from the task of disambiguating several unequally compressed axes. Figure 3.12 also indicates a slight trend for higher display elevation angles to result in more accurate distance judgment, a trend found to be significant though with a very small negative correlation (N=1500, r=-.06, p<.03). Figure 3.13 shows the joint effects on DJE of both display elevation angle and display azimuth angle. The ANOVA testing the interaction between display elevation angle and display azimuth angle revealed no significant interaction, F(16,80=.90, p>.57).

Figure 3.14 displays how the distance judgment time (DJT), similar to the elevation and azimuth judgment times, was quickest for display azimuth angles of 45 degrees. This finding, similar to those found for VJE and HJE may give further evidence for the superiority of mid-range, 45 degree angles. Perhaps more important, however, is the effect of display elevation angle on DJT, depicted in Figure 3.15, plotting the same data points as Figure 3.14, but with display elevation angle as the x-axis. The decrease in DJT at higher display elevation angles was found to be statistically significant in the ANOVA, F(4,80=3.05, p<.025) and in the correlation analysis (N=1500, r=-.13, p<.001). This result may be due to the placement of the targets which, though fairly uniformly distributed around the ownship, was slightly skewed toward greater horizontal than vertical distances in order to prevent targets from being underground. Thus, since a greater proportion of the distance to the targets was in the horizontal plane, it makes sense that participants would perform their distance judgment more quickly and accurately (as indicated by the significant correlation between display elevation angle and DJE) when the display elevation angle was higher, resulting in greater lateral resolution.

3.2.4 Line of Sight Effects:

To further examine the effects of display resolution on the dependent measures, VJE, HJE, and DJE, we assessed the effect of the target's proximity to the display line of sight. The line of sight parameter was measured as the absolute value of the difference between the display azimuth angle or display elevation angle, and the target azimuth angle or target elevation angle. Thus, at the 45 degree display azimuth angle condition, a target that was 45 degrees left of the ownship's forward vector was considered to be directly along the horizontal line of sight, with a resulting value of 0 degrees. A target that was 5 degrees to the right of the ownship, then, would have a horizontal line of sight value of 50 degrees. Values over 90 degrees were not possible since they would then be considered in relation to the line of sight in the opposite quadrant.

LOS Measures: Figure 3.16 plots the vertical judgment error (VJE) as a function of the vertical line of sight angle. As the figure shows, VJE was not significantly correlated with the vertical line of sight angle ($N=1500$, $r=-.04$, $p>.10$). The VJE did, however, have a small negative correlation with the horizontal line of sight angle (1500, $r=-.10$, $p<.001$), such that the greater the azimuth line of sight difference, the lower the VJE. Figure 3.17 portrays the effect of this resolution. As the figure shows, most of this effect can be accounted for by the large value of VJE when the target was precisely along the horizontal line of sight (i.e., LOS angle=0). The correlation between HJE and vertical line of sight angle was found to be small but significant (1500, $r=-.05$, $p<.04$). Though Figure 3.18 indicates that the trend was not consistent, the HJE was slightly smaller when the vertical line of sight angle was large, allowing for better resolution to view the lateral vector between ownship and target. Figure 3.19 shows the HJE as a function of the horizontal line of sight angle. The correlation between these two measures was not found to be significant ($N=125$, $r=+.11$, $p>.23$), although Figure 3.19 shows that the HJE directly along the horizontal line of sight (angle=0) appears to be negatively affected in a way very similar to the way the VJE was affected in Figure 3.17. The high standard error in this particular condition suggests that certain targets were very poorly resolved. These targets tended to be those that also had a 0 degree line of sight angle on the vertical axis (as seen in Figure 3.18). This would be expected according to the literature on ambiguity along the line of sight (McGreevy and Ellis, 1986).

Figure 3.20 displays the DJE as a function of both the vertical and horizontal line of sight angles. The figure reveals that the DJE is greatly increased when the target is directly along both the vertical and horizontal line of sight (ie., the left uppermost point in the graph). In this case, the vector distance is extremely ambiguous since resolution of the vector connecting the ownship and the target is minimized and the only information available for the viewer is based on size difference.

An important finding for all the line of sight measures is that even a small offset in either axis is sufficient to render the judgments as accurate as larger offsets on either or both axes. Figure 3.21 indicates this was <u>not</u> the case for all the measures of judgment time as a function of the line of sight. The horizontal line of sight displacement was found to be significantly negatively correlated with both horizontal judgment time ($N=1500$, $r=-.06$, $p<.02$) and vertical judgment time ($N=1500$, $r=-.08$, $p<.003$). As indicated by the figure, larger displacement from the line of sight resulted in progressively quicker judgments. Thus, although the judgment error measures did not follow the continuous function expected according to the RTR model, the horizontal and vertical judgment reaction time measures do seem to show that greater resolution improves performance. The correlation between horizontal line of sight displacement and distance judgment time was not found to be significant ($N=1500$, $r=-.02$, $P>.55$), although Figure 3.21 does indicate that the longest judgment time occurred along the horizontal line of sight.

3.3 Correlational Analyses:

In order to determine the extent to which local guidance effects are influenced by the same display variables as spatial awareness effects, it is necessary to examine the correlation between these two measures.

3.3.1 Horizontal Correlation Measures:

The horizontal RMSE was found to be significantly positively correlated with the horizontal judgment error (HJE), ($N=25$, $r=.45$, $p<.025$). The fact that this correlation exists at all, given the inconsistency of the main effects across the two dependent variables, as shown in Figures 3 and 8, indicates that much of this correlation effect may be due to the interaction of display elevation angle, which seems reasonable according to the RTR model. The correlation also seems to indicate that, despite the imperfect correspondence between horizontal guidance and spatial judgments, the two are similarly affected by resolution to a certain extent.

3.3.2 Vertical Correlation Measures:

As would be expected by the similarity of Figures 1 and 5, a significant correlation was also revealed between the vertical RMSE and the vertical judgment error (VJE), ($N=25$, $r=.60$, $p<.003$). This correlation reveals an association between guidance and spatial awareness in the vertical axis that is closer than that in the horizontal axis.

3.3.3 Distance Correlation Measures:

Distance Judgment error (DJE) was found to be significantly correlated with the Horizontal RMSE ($N=25$, $r=.58$, $p<.003$). This correlation would also be expected since both measures showed trends toward the best performance at 45 degrees of display azimuth angle and slightly better performance at higher display elevation angles.

3.3.4 Summary of Correlation Measures:

The results seem to indicate that display resolution, as explained by the RTR model, and directly affected in the spatial awareness measures, does account for much of the effects on local guidance. As the graphs and correlations indicate, however, resolution can probably not account for all the effect on local guidance. In the Discussion we will examine where the two tasks seems to be affected the same by display resolution and where there is a disjunction of effects, indicating either that the resolution effects are being played out differently for these two tasks, or that different mechanisms are responsible for the difference. Furthermore, we will attempt to explain more fully the Resolution Through Rotation model, and how this model can explain the results from the present experiment.

4. Discussion

The current thesis set out to examine the tasks of local guidance and spatial awareness and how manipulations of the display viewing elevation and azimuth angle affected performance of these tasks. We hope to develop a better understanding of the effects of perspective viewing on display design. In order to do this, the experiment required subjects to perform both local guidance and spatial judgment tasks as they navigated through a simulated three-dimensional world. We manipulated the display elevation and azimuth angles, as well as the location of intruder targets along the flight path. As it turned out, the local guidance, or tracking data were the easiest to interpret, and so we discuss these first, before turning to the data for the spatial awareness measures.

4.1 Local Guidance:

As Figures 3.1 and 3.3 indicate, tracking for a given axis seems to be greatly affected by the resolution of movement along that axis, caused by its given display elevation (3.1) or azimuth (3.3) angle. Increasing the display azimuth angle, which correspondingly decreased the horizontal (x-axis) resolution, resulted in larger horizontal deviations from the flight path. Increasing the display elevation angle, consequently decreasing the vertical (y-axis) resolution, resulted in greater tracking error for the vertical axis. The effect was especially robust for vertical guidance, where tracking was generally poorer than for horizontal guidance and was more greatly affected by changes in the display orientation. The effects of display resolution on horizontal guidance may have been diminished by the relative ease of tracking along the horizontal axis. This is probably due in large part to the display augmentation of the dropline connecting the ownship to the ground which, used in conjunction with the shadow of the flightpath, allowed for a clear and unambiguous view of horizontal error (a corresponding dropline to a vertical surface was not available for vertical tracking). However, this dropline was maintained for the present experiment because it has become a standard feature in all such flight displays (Ellis, et. al., 1985, 1991; Barfield, et. al., 1995; Wickens and Prevett, 1995; Wickens, et. al., 1996).

As shown in Figure 3.3, in addition to the loss of performance at high display azimuth angles, horizontal guidance also seems to reflect a step function between 45 and 55 degrees, which is not apparent for vertical guidance. The apparent disparity between performance from display azimuth angles of 15 to 45 degrees and those from 55 to 75 degrees is likely partially due to the effects of viewing/control misalignment (i.e., stimulus-response incompatibility), as discussed earlier. In other tracking studies this effect has consistently resulted in sharp drops in performance beyond 45-50 degrees (Ellis Tyler, Kim, McGreevy, and Stark, 1985; Ellis, Tyler, Kim, and Stark, 1991).

One of the primary hypotheses for this experiment was that display axis resolution has an important effect on performance for a given axis. The Resolution Through Rotation model attempts to explain how display azimuth angle and display elevation angle alter axis resolution and subsequent performance within that axis. Since display geometry dictates that the display elevation and azimuth angle have a non-linear (as seen in Figure 1.6) and interacting effect (as shown in figure 4.1, which will be discussed more fully below) on resolution, it was predicted that performance would show a corresponding effect. As expected, the interaction between display azimuth angle and display elevation angle was found to be significant for both vertical and horizontal tracking performance. As seen in Figures 3.2 and 3.4, both horizontal and vertical tracking seem to exhibit an ordering as well as a "fan effect" to the data. For example, while increasing values of one angle hurt performance for a given axis, increasing values of the other angle generally improve performance for that same axis, and particularly restore performance where it was most degraded. In other words, high compression on one axis hurts that axis, but can be offset by increasing the angle on the other. Furthermore, the data seem to indicate that the "fan effect" is especially strong for the vertical axis, in which increasing values of the display azimuth angle have more and more of a positive performance effect as the display elevation angle increases. All of these effects can be explained by the RTR model.

To facilitate this understanding, imagine the actual three-dimensional world of the display as a cube with x,y, and z-axis lengths such that the z-axis corresponds to the axis of the fuselage (and to the forward velocity vector of flight). If each axis is represented by a side of length 1, the displayed length of each axis can be approximated as the resolution for that given axis. Thus, viewing that cube with no azimuth or elevation angle would yield the full length, or resolution value of 1, for the x and y axes but 0 resolution for the z-axis (see Figure 4.1A). If we were to then change the view of the cube to an elevation angle of 45 degrees, the x-axis resolution would remain at 1, and the y-axis resolution would change to .707 (the cosine of 45 degrees), while the z-axis resolution would be equally compressed to .707 (the sine of 45 degrees) (see Figure 4.1B). Similarly, if the elevation angle was held at 0 and the azimuth angle was changed to 45 degrees, the y-axis resolution would remain at 1, the x-axis resolution would change according to the cosine of 45 degrees to .707, and the z-axis resolution would be transformed according to the sine of 45 degrees to .707 (see Figure 4.1C). When manipulated in this way, the mere sine or cosine of the elevation or azimuth angle can be easily used to predict the x,y, and z-axis resolutions. If we examine the horizontal axis, for instance, we also find that the loss of resolution from 0 degrees azimuth to 45 degrees azimuth (1 -.707= .293) is considerably less than the loss of resolution from 45 degrees to 90 degrees (.707 - 0=.707). Thus, these computations can explain the non-linearity of the present experiment's data.

A similar, though more complex effect than the one above, describes an axis' resolution value when both elevation and azimuth viewing angles are present. Figure 4.2 displays the results of this effect, which can explain the "fan effect" witnessed in Figures 3.2 and 3.4. The bold rectangle in Figure 4.2 represents a cube which, like that in Figure 4.1B, is presented from 0 degrees azimuth angle and 45 degrees elevation angle. When the viewing azimuth angle of this cube is rotated 45 degrees to the right, we see the lighter cube in the figure, which is now presented from a 45 degree azimuth angle and 45 degree elevation angle. As the figure reveals, the x-axis resolution has decreased, the z-axis resolution has increased, and the y-axis resolution has stayed the same. These changes are as would be expected from the earlier explanation of the effects of azimuth or elevation angle manipulations. However, due to the existing elevation angle displacement, the effects of azimuth rotation are greatly reduced from what they would be if no elevation angle was present. This reduction in effects exists because the y-axis resolution is reduced due to the elevation angle, and the missing resolution is available for the x and z axes. Therefore, the x and z axes have resolutions greater than .707, which they would otherwise be if no elevation angle displacement existed.

We now explain how these geometric effects can explain the "fan effect" witnessed in Figures 3.2 and 3.4. The present experiment did not directly measure tracking performance along the z-axis, since for aviation tasks the z-axis corresponds with the speed of the ownship, a construct very different than the lateral and vertical error from the flight path. However, the lack of z-axis measures does not mean that the z-axis was unimportant for this task. One aspect of z-axis information which proved very important for tracking was the predictor, which extended from the nose of the ownship. This predictor gave information about where the ownship would pass in the next few seconds, allowing the participant to correct for tracking deviations while they were still small. Thus, the greater the z-axis resolution, the larger was the predictor vector, and the easier it was for participants to quickly correct tracking error from the flight path.

If we examine Figure 3.2 we see that greater display elevation angles (i.e., lower y-axis resolution) resulted in poorer vertical tracking (i.e., greater vertical errror). However, large display azimuth angles were able to reduce this effect greatly. This is due to the greater z-axis resolution and predictor information available for increasing display azimuth angles (as displayed by the greater length of the z-axis in Figure 4.2 at 45 degrees azimuth). The same effect would also account for the fan effect witnessed for the horizontal tracking measures, since the predictor symbol is of importance for both vertical and horizontal tracking.

As we have shown, the RTR model can be an effective tool for predicting local guidance performance. Given that display resolution is affected equally while performing spatial awareness tasks as it was with local guidance tasks, we might expect that spatial awareness would reveal similar results. Furthermore, any lack of correspondence in the results might help explain the separate mechanisms acting on local guidance and spatial awareness.

4.2 Spatial Awareness:

Although we initially expected situation awareness measures to be more easy to interpret than tracking measures, the present experiment revealed that this was not the case. There are two possible reasons for these unexpected results. First, the more ambiguous results of the spatial awareness studies may be the result of the fact that twice as many parameters were involved, as both display angles and target angles were manipulated. Alternatively, the unclear results for spatial awareness measures may simply reflect the operation of different perceptual or cognitive mechanisms. We will discuss both possibilities below.

Situation Awareness measures were assessed from two perspectives for the present experiment: as a function of the display parameters (i.e., display azimuth angle and display elevation angle), and as a function of the target's deviation from the line of sight. Furthermore, judgment time was evaluated for judgments as a function of the display parameters.

4.2.1 Effects of Display Parameters:

Vertical Judgments: As expected by the RTR model, the display elevation angle had a significant effect on vertical judgments. Comparing the main effects for vertical tracking (Figure 3.1) with the main effects for vertical judgment error (Figure 3.5) we see nearly exactly the same nonlinear trend by which higher display elevation angles hurt vertical performance. However, upon inspection of the interactive effects of display azimuth angle on this trend (Figure 3.6), we no longer see the clear "fan effect" evident in Figure 3.2, in which, at high display elevation angles, vertical tracking performance improved with increasing azimuth angles. Instead, Figure 3.6 revealed little consistent or monotonic ordering within the interaction.

Horizontal Judgments: The analysis for effects on horizontal judgment error revealed no significant effects for any of the display parameters. Despite the non-significance,

Figure 3.9 does indicate a hint of the ordering effect (in which lower display elevation angles caused increased horizontal judgment error) at 55 degrees of azimuth angle, as witnessed for tracking measures as predicted by the RTR model. In contrast, the main effect of display azimuth angle on horizontal judgment (see Figure 3.8) bares minimal resemblance to that effect found for horizontal tracking. This lack of correspondence, however, is not surprising when we examine the reasons behind it.

Although vertical tracking can be compared closely with vertical spatial judgments, the comparison between horizontal tracking and horizontal judgments is less suitable. Two reasons exist for this difference. First, in contrast to the 3-D tracking tasks used by Ellis et. al. (1985, 1991), for aviation tasks such as that used here, the horizontal axis is not functionally equivalent to the vertical axis. While movement in the vertical axis is first order, requiring only forward or back stick motion, movement in the horizontal axis is second order, requiring a roll, then subsequent forward or back stick pressure to execute that roll. Also, the spatial judgments that were made in this experiment were made laterally on a 360 degree scale, but vertically only on a 180 degree scale (+/-90). Next, the present experimental design created another difference because the track-up nature of the viewpoint resulted in ownship rotation along the horizontal axis causing a corresponding rotation of the viewpoint. In contrast, however, aircraft rotation in the vertical axis did not create a corresponding vertical rotation of the viewpoint angle. Thus, vertical tracking and vertical spatial judgments were based on a consistent axis system. The horizontal axis system, however, changed based either on the current heading for tracking tasks, or based on the vector from ownship to the target. Therefore, for spatial awareness, the important horizontal axis was based on the target position, not the forward movement vector or fuselage of the ownship. Thus, depending on the position of the target, the displayed z-axis may be just as important as the x-axis for judging the position of an intruder target. Therefore, as discussed earlier in the results, the horizontal judgment data can be more meaningfully examined as a function of the target's deviation from the display line of sight.

Distance Judgments: Since distance judgments involved the vector distance from ownship to the target, and not the distance projected onto any particular axis, we did not expect to find its judgment following the same ordered effects of the display parameters, as for the other axis-dependent judgments. However, though not supported by significant effects in the ANOVA's, Figures 3.11 and 3.12 indicate a trend for distance judgment to be best at the mid-range values of both display azimuth angle and display elevation angle. This effect can be explained by RTR because at 45 degrees of elevation or azimuth angle, the resolution for the affected axes is equal (as seen mathematically in Figure 1.6, or pictorally in Figures 4.1B and 4.1C) and at a maximum value (since the non-linearity of the sine function dictates that angles over 45 degrees incur a greater loss in resolution for one axis than is gained in the other). Thus, these results indicate that if all axes were of equal importance (as they were in the distance judgment task), a display affording equal resolution for all three axes would result in the best spatial judgment performance.

Effects on Judgment Time: In the introduction, it was predicted that the RTR model effects would be evident only in terms of reduced accuracy and that judgment time would not be effected. If it were affected, we would expect it to follow the same trends as accuracy, explained by the fact that the compressed axis would take time to mentally transform it to a form conducive for making the judgment. Instead, we found that judgment time based on the display parameters seemed to follow the same trend evident for distance judgment error. For all three judgments (i.e., horizontal, vertical, distance), displays with a 45 degree azimuth angle resulted in quicker (though not significantly so) judgments. This 45 degree advantage was also evident, but to a lesser extent, for the effects of display elevation angle, which seemed to show a trend toward quicker judgments at the mid-range values only for horizontal and vertical judgments.

In examining the important finding of the 45 degree advantage, we must first dismiss the possibility that this advantage could be an artifact of the response device or the set of chosen stimuli. First, the slider response device that was used was the same for all display viewpoints. Also, the stimuli were uniformly placed throughout the displayed world in a spherical area around ownship. Thus, no viewing angle was afforded a more favorable positioning of the target stimuli, requiring shorter movements of the slider. Therefore, we believe the 45 degree advantage to be an actual and interesting effect that deserves interpretation.

Collectively, these results can be interpreted in one of two ways. First, it is possible that there is something special in the undistorted way that 45 degrees equally represents the two competing axes. This equal representation alone may make spatial awareness in the displayed world less confusing and therefore allow it to be reported more rapidly. A second possibility is that mental rotation is still being performed by the viewer, however, instead of rotating an axis to orthogonality, the viewer may be rotating it to the above-mentioned equal resolution of 45 degrees. Thus, angles further from this 45 degrees must be rotated more, resulting in the longer judgment time. This would indicate that full resolution of an axis is not as important as a clear understanding of the relative resolution for each axis. Much more research needs to be done on this issue to determine exactly what mechanism is being used by the viewer to disambiguate the resolution and why judgment time would follow different trends than judgment error.

4.2.2 Effects of Line of Sight:

Further analysis of the data was carried out based on the position of the target in relation to the display parameters. For this analysis, a target was measured according to its angle from the line of sight afforded by the display. As expected, this analysis did show a large decrement in distance judgment performance when the target was oriented along the line of sight for both the horizontal and vertical axes (as in Figure 3.19). The target's horizontal position in relation to the line of sight also seemed to have an effect on the error of both vertical and horizontal judgments. The disparity from the vertical line of sight, however, had little effects on judgment except for its interaction with horizontal line of sight when targets were directly along the line of sight of both axes, as discussed above. This muted effect of vertical line of sight is likely due to an earlier-mentioned aspect of the experiment whereby the vertical placement of targets was restricted to a certain extent by the presence of the ground. Because of this restriction, the judgments of targets at some angular displacements from the vertical line of sight were more affected by the ground than judgments at others.

Although the judgment accuracy results supported the premise that ambiguity directly along the line of sight degrades spatial judgments (McGreevy and Ellis, 1986), they seemed to indicate that even a little offset on either axis restores judgment accuracy to its full level as much as larger offsets on either or both axes (as seen in Figures 3.17, 3.19, and 3.20). This pattern describes a different trend from that observed in the tracking data, in which performance more continuously improved as the angle between the display axis line of sight and the controlling axis (lateral or vertical) increased (see Figures 3.1 and 3.3). In other words, if resolution was the key factor in making accurate spatial judgments, we would have expected that larger angular deviations from the line of sight along the axis that was not the axis of judgment, would continuously improve in accuracy as this angle increased to 90 degrees, the point at which the vector from ownship to target is orthogonal (i.e., at full resolution) along the decision axis. Instead, the data indicate that only the judgment times follow this trend.

We believe there are two possible explanations for the finding that errors do not increase continuously as the target approaches the line of sight. First, display geometry dictates that the further objects get from the center of the screen, the more they are affected by the virtual space effect (McGreevy and Ellis, 1986). Although care was taken to diminish the virtual space effect as much as possible for this experiment, it is likely that targets nearer the edge of the screen (at large angles away from the line of sight) were slightly more distorted than those near the center. Furthermore, targets near the center are closer, and thus have somewhat greater resolution than those further away. These two effects, which act opposite to the RTR model of effects, may have nullified the slight advantage in resolution caused by the rotation of the judgment axis away from the viewing axis (i.e., higher line of sight angles). A second explanation for these results is that the effects of the RTR model are nearly completely succesfully compensated for in judgment accuracy (only breaking down at the 0 degree line of sight angle), and are instead revealed in the time required to make the spatial awareness judgments. This hypothesis will be discussed more fully in the following sections.

4.3 Integration of Effects on Spatial Awareness and Local Guidance:

In investigating the effects of the display parameters of elevation angle and azimuth angle, and their effects on both local guidance and spatial awareness, the present study has uncovered some interesting findings. Local guidance performance seems to follow closely the pattern of effects that would be expected according to the RTR model. Spatial awareness performance also seems to indicate some trend toward following the RTR model of effects, although this trend is much less clearly defined than that for tracking performance. Particularly, the effects of the interaction between display azimuth angle and display elevation angle seem to be less clear for spatial awareness measures.

Despite the imperfect comparison between horizontal tracking and horizontal spatial judgments, the correlational analysis comparing horizontal tracking and spatial judgments showed indications that the two are to some degree affected similarly by the display parameters. The comparison of vertical tracking and spatial judgments showed a stronger correlation than the horizontal measures, reflecting the greater similarity between the two vertical tasks. Thus, the correlations indicate that the RTR model can explain some of the variance in performance for the two measures, and that at least to a certain degree, the two tasks are affected in a like manner by manipulations of the display elevation and azimuth angle. However, much of the variance in the measures of local guidance is still unaccounted for by the variance in spatial awareness, indicating that the two tasks may also be affected by different mechanisms (i.e., the compatibility of axis alignment in the case of tracking) or be differently affected by the RTR model of effects, a concept we discuss below.

We overviewed in the introduction several inherent characteristics of tracking that did not characterize spatial awareness (i.e., urgency, control/viewing misalignment, and axis attention allocation). These different effects, which are independent of RTR, may account for much of the difference between the spatial awareness and tracking results. However, according to the assumptions of this processing model, we would expect tracking to be the task which less closely follows the RTR effects, because of the greater contribution of non-perceptual response effects. On the contrary, our results indicated that spatial awareness performance seemed to be less easily explained by the RTR model. We offer a possible explanation for this difference by examining the effects of position judgments as they are manifest as error from the flight path for tracking or the position of the target for spatial judgment tasks.

One primary difference between the position judgments required to estimate error from the flight path for tracking, and the judgment of the position of the target relative to ownship, is the amount of time available to make these judgments. In our study, the participants had a few seconds to judge the vertical and horizontal angle, and distance to the target. These precious seconds may be enough time to allow the participant to perform a mental rotation of the screen necessary to disambiguate the axis of importance. This rotation may be performed in a manner to bring the axis to orthogonality (as discussed in the introduction), or to bring all axes to equal resolution, as the judgment reaction time data for the present study suggests. Further evidence for some sort of mental rotation lies in the apparent trend for judgment time, if not accuracy, to follow the expected effects of the RTR model for judgments along the line of sight (i.e., lower resolution resulting in greater time required). In contrast, the tracking task does not afford the participant a few seconds to make a decision. Instead, they must make continuous, real-time corrections based on their perceived error if they intend to stay near the flight path and track it in a stable fashion (McRuer and Jex, 1967; Wickens, 1986). Thus, the viewer may not have time to mentally rotate the screen to a more compatible representation. This explanation would account for the finding that the tracking accuracy data followed more closely the RTR model of effects than did the spatial awareness data. So the tracking error magnitude is perceived more directly as it is projected on the 2-D screen, hence reflecting the resolution loss of the RTR model. This explanation would also illustrate the fact that effects of the RTR model on accuracy were only present for the most extreme ambiguous situations (i.e., 0 degrees line of sight angle), and the effects were instead played out in the judgment times. Further research should be done to examine these hypotheses in order to get a better understanding of exactly how the display parameters affect both local guidance and spatial awareness.

4.4 Conclusions

The goal of this study was to investigate the effects of display elevation and azimuth angle manipulations on local guidance and tracking. In doing so, we hoped to get a better understanding of the underlying constructs affecting three-dimensional performance, and hence provide guidance for the design of 3-D maps and spatial instruments. The general conclusion of the experiment was that the resolution created by viewpoint manipulations (i.e. display azimuth or elevation angle) affects both accuracy of local guidance and speed and accuracy of spatial judgment tasks. However, local guidance and spatial awareness are affected neither completely independently nor completely congruently by these resolution effects. Thus, we are led to believe the mechanisms for performing tracking or spatial judgment tasks may be cognitively different.

The results of this study afford several design implications. Overall, our display indicated a good balance for horizontal and vertical tracking and spatial judgment at 45 degrees of display azimuth and elevation angle. The reaction time of spatial judgments especially, seemed to indicate an advantage for this 45/45 display orientation. However, it was found that the ideal display angle combination depended greatly on which performance axis was being examined. We would predict that the best combination of display elevation and azimuth angle could change depending on the type of task, display augmentations, and relative importance of each axis. Therefore, we believe the most important findings of this study involve understanding the reasons why some display presentations might work better than others, allowing the system designer to custom build the display based on the tasks and axis values that the display should support.

Much is still unknown about the various ways humans disambiguate three-dimensional display information. The current study raised several interesting questions regarding the differing effects of display parameters on tracking and spatial awareness tasks. Future research should examine the reasons for these effect differences and further explore the extent to which, and the conditions under which resolution is a factor in influencing performance.

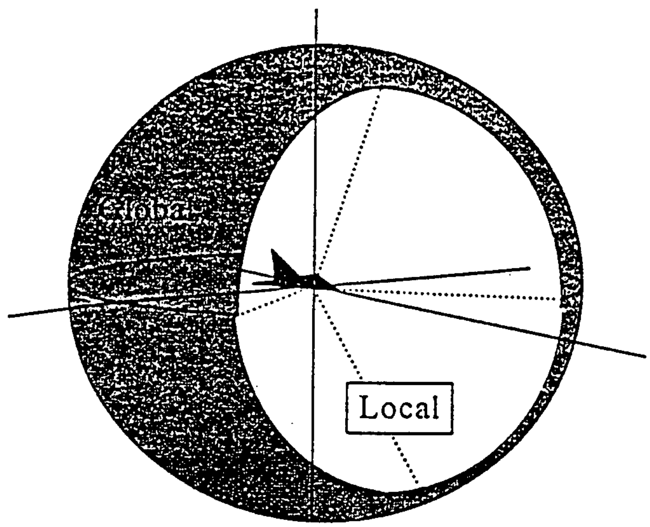


Figure 1.1. Global and local spatial awareness regions (reproduced from Davenport, 1997).

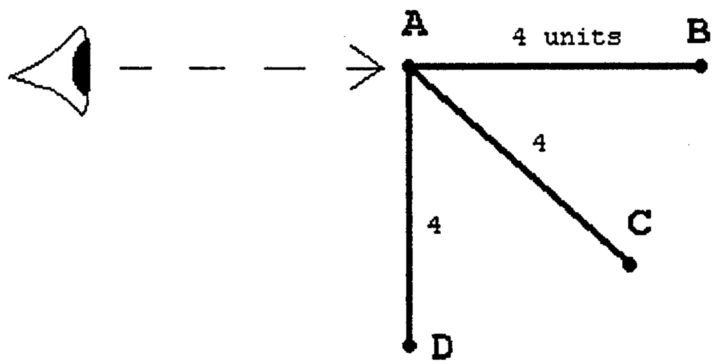


Figure 1.2. Three line segments of equal length but at different orientations, displaying the effects of compression.

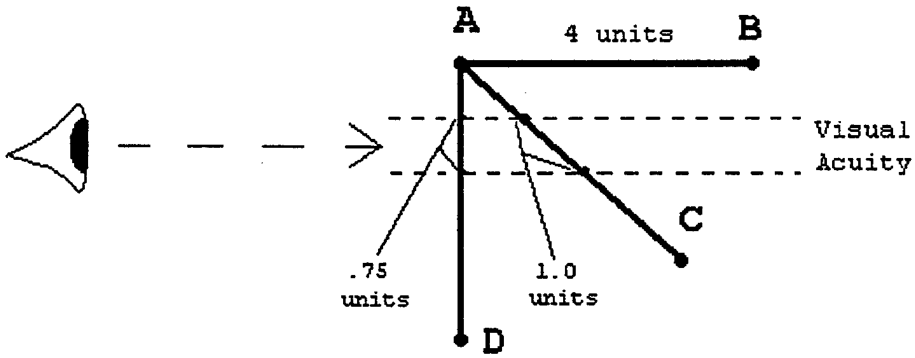


Figure 1.3. Three line segment of equal length but at different orientations, displaying the effects of limited visual acuity when compression occurs.

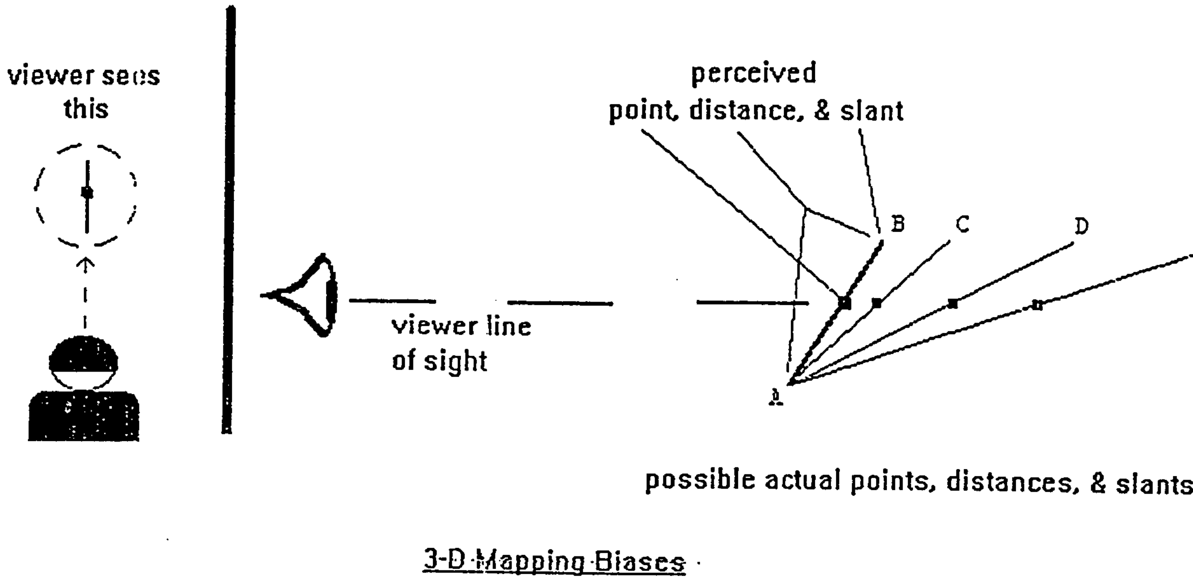


Figure 1.4. Depiction of the similar 3-D mapping biases of compression, line of sight ambiguity, and slant underestimation.

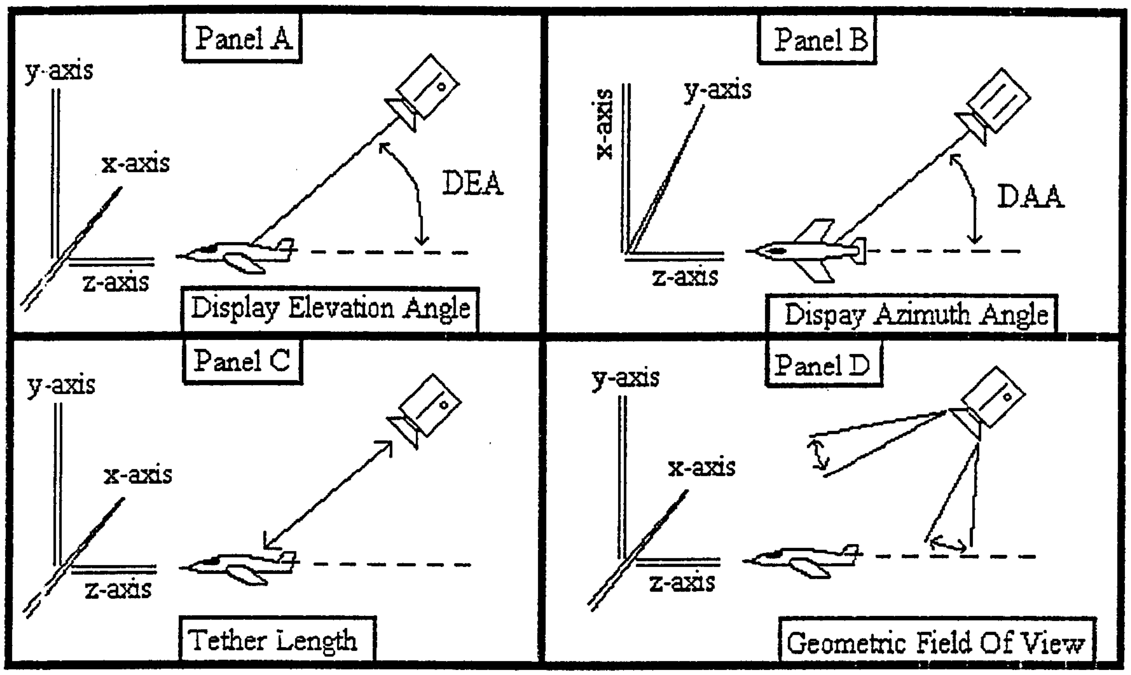


Figure 1.5. The four viewing parameters of 3-D displays.

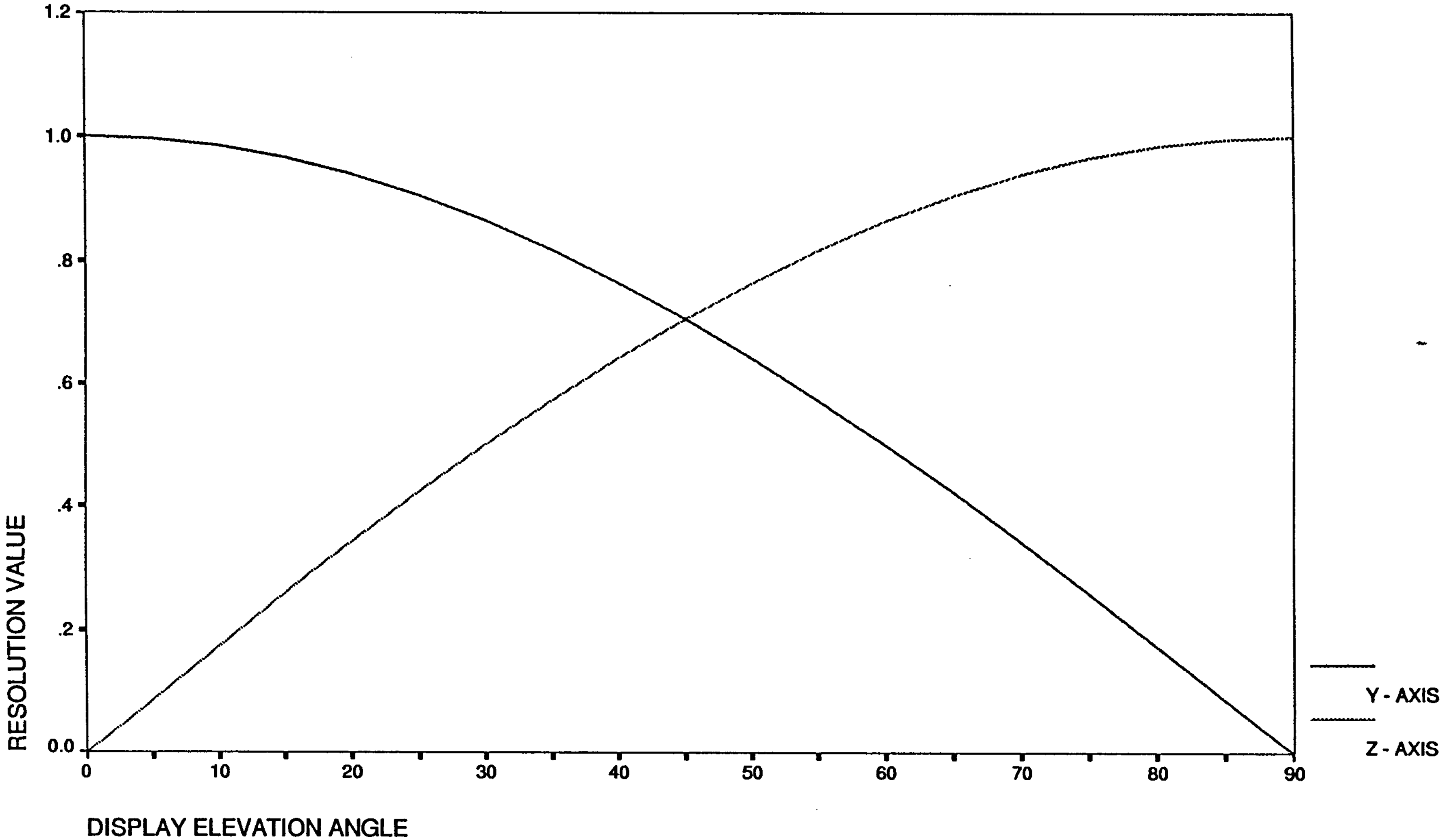


Figure 1.6a. Resolution effects for changes in the display elevation angle.

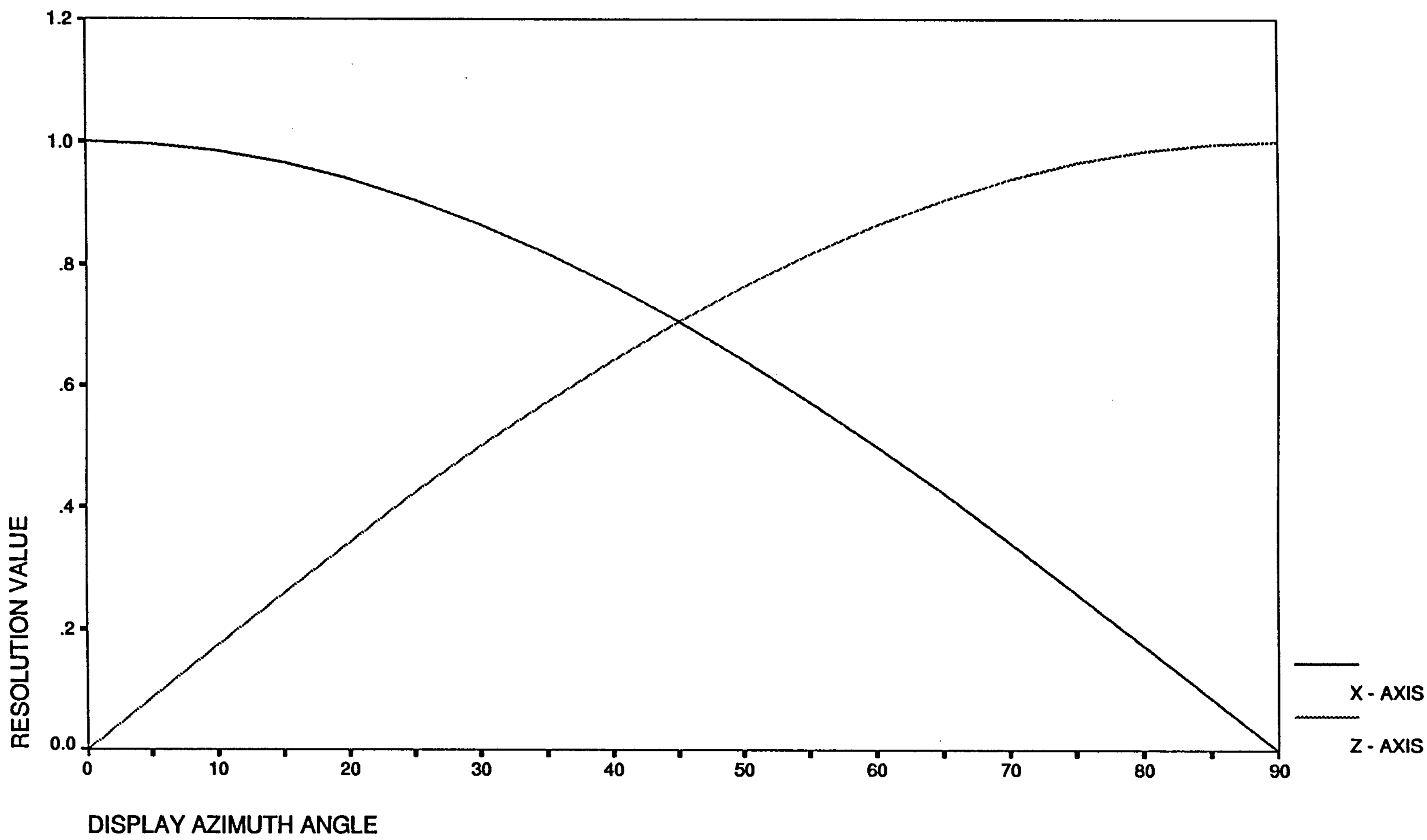


Figure 1.6b. Resolution effects for changes in the display azimuth angle.

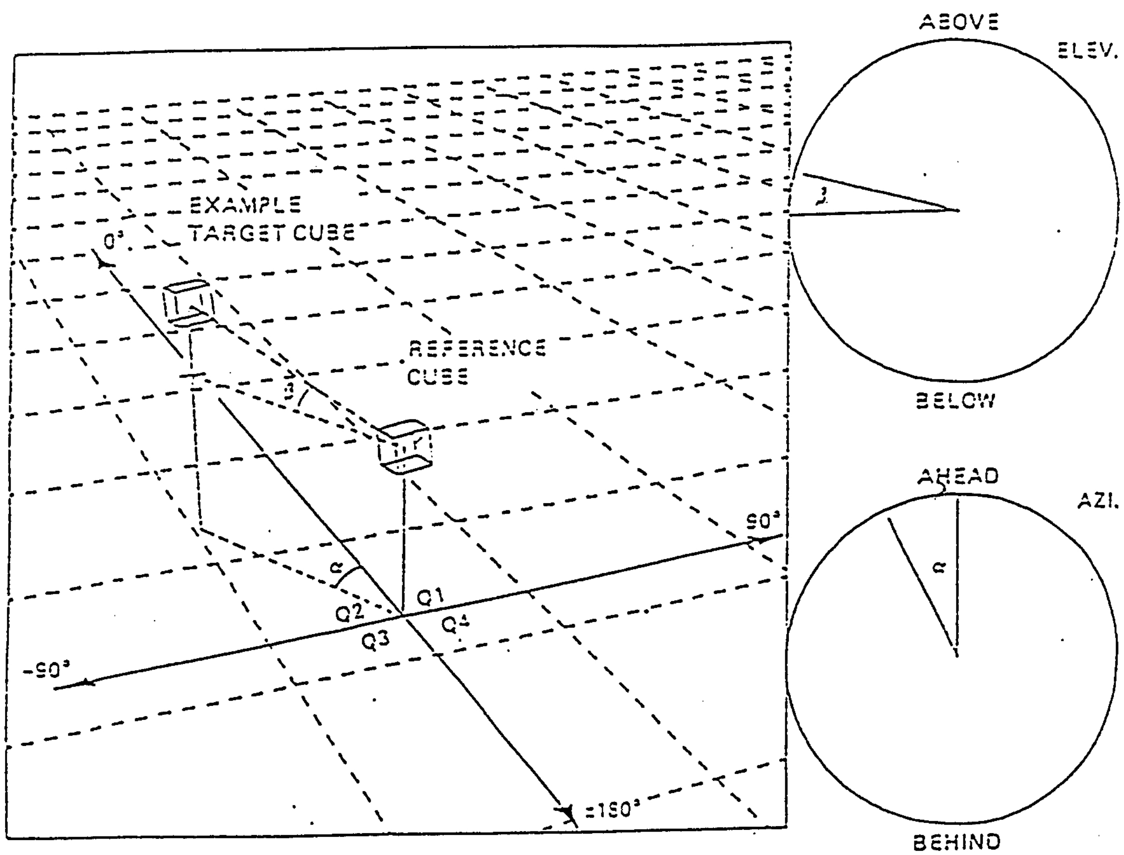


Figure 1.7. Perspective display and response dials used in the McGreevy and Ellis (1986) experiment (reproduced from McGreevy and Ellis, 1986).

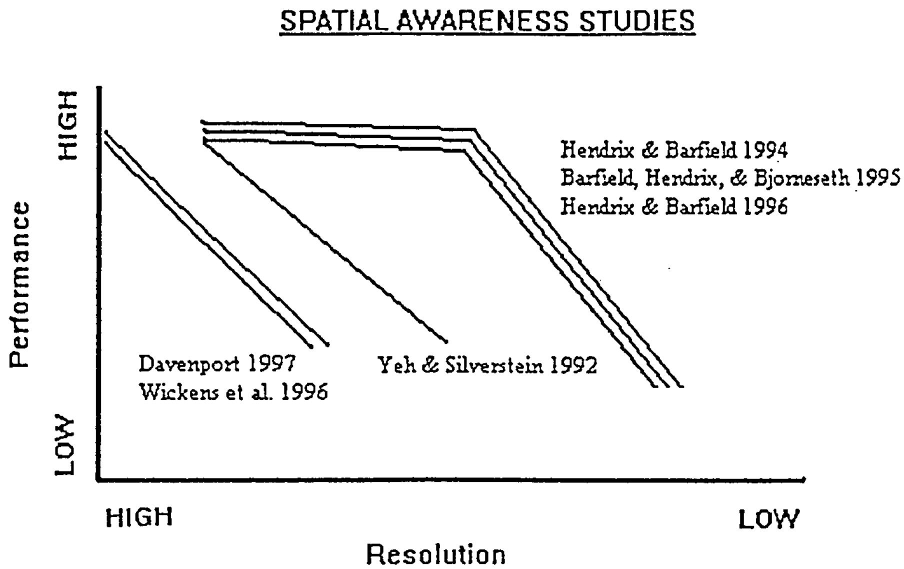


Figure 1.8. General findings of spatial awareness studies as performance for a given axis is related to its resolution.

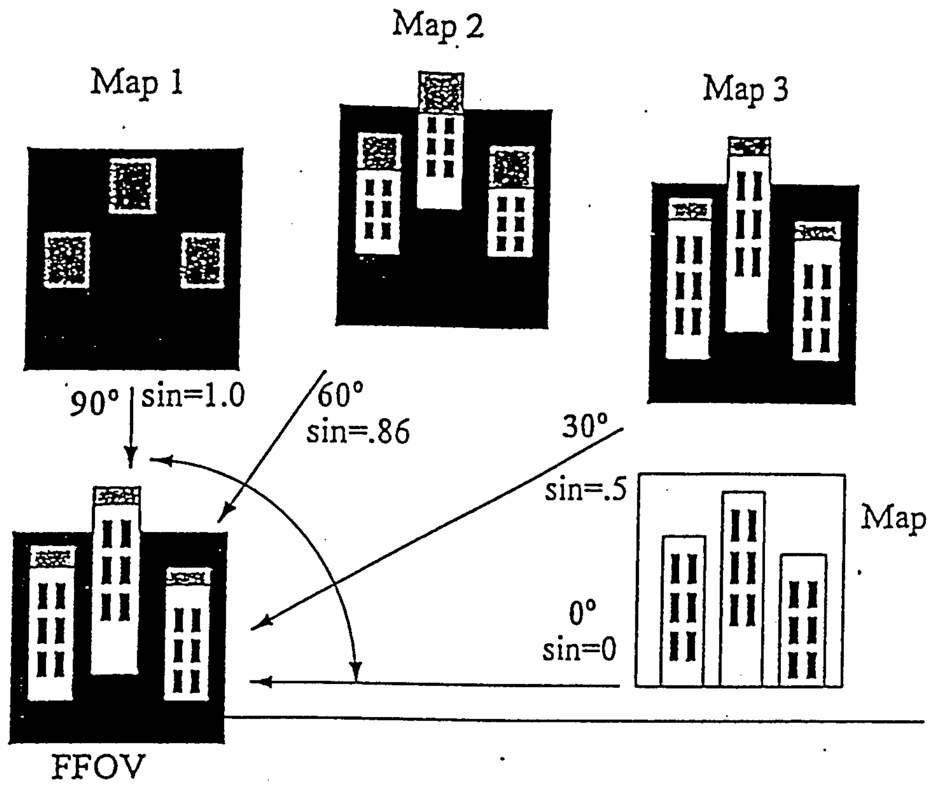


Figure 1.9. Resolution of a scene as influenced by the display elevation angle from which the scene is presented (reproduced from Hickox and Wickens, 1996).

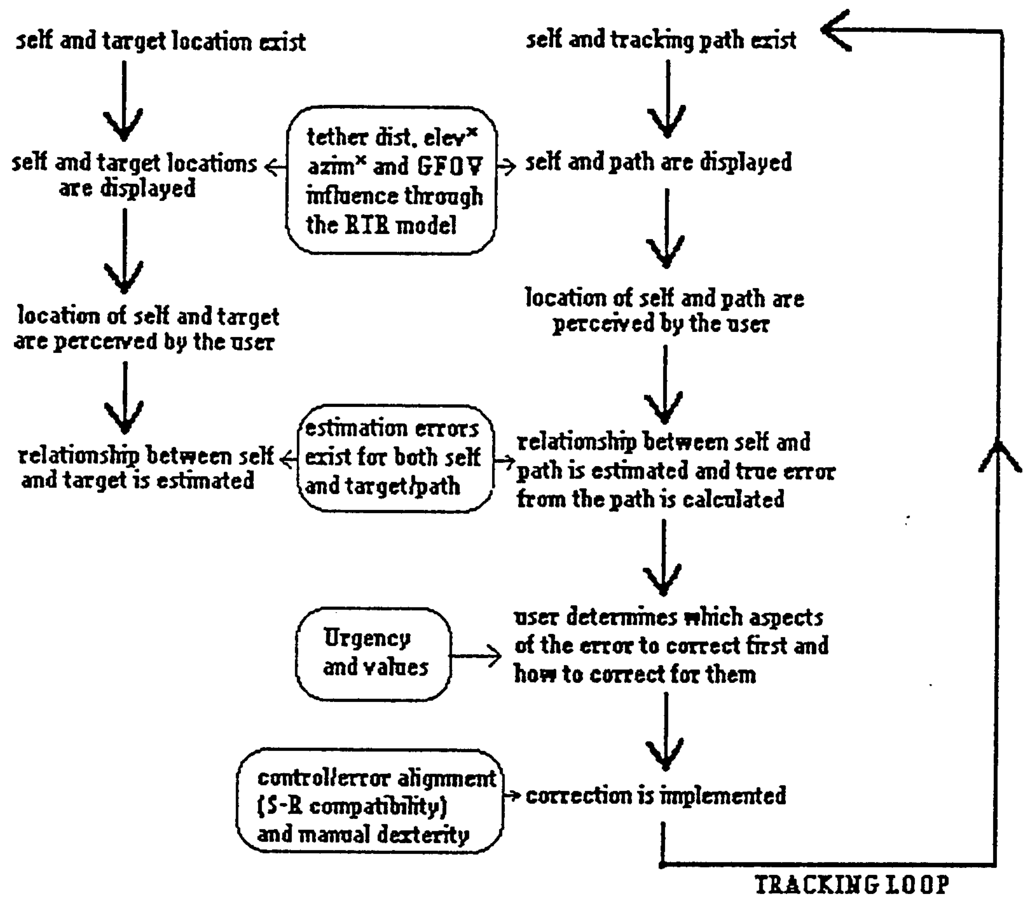


Figure 1.10. Mechanisms for spatial awareness (left) and local guidance (right).

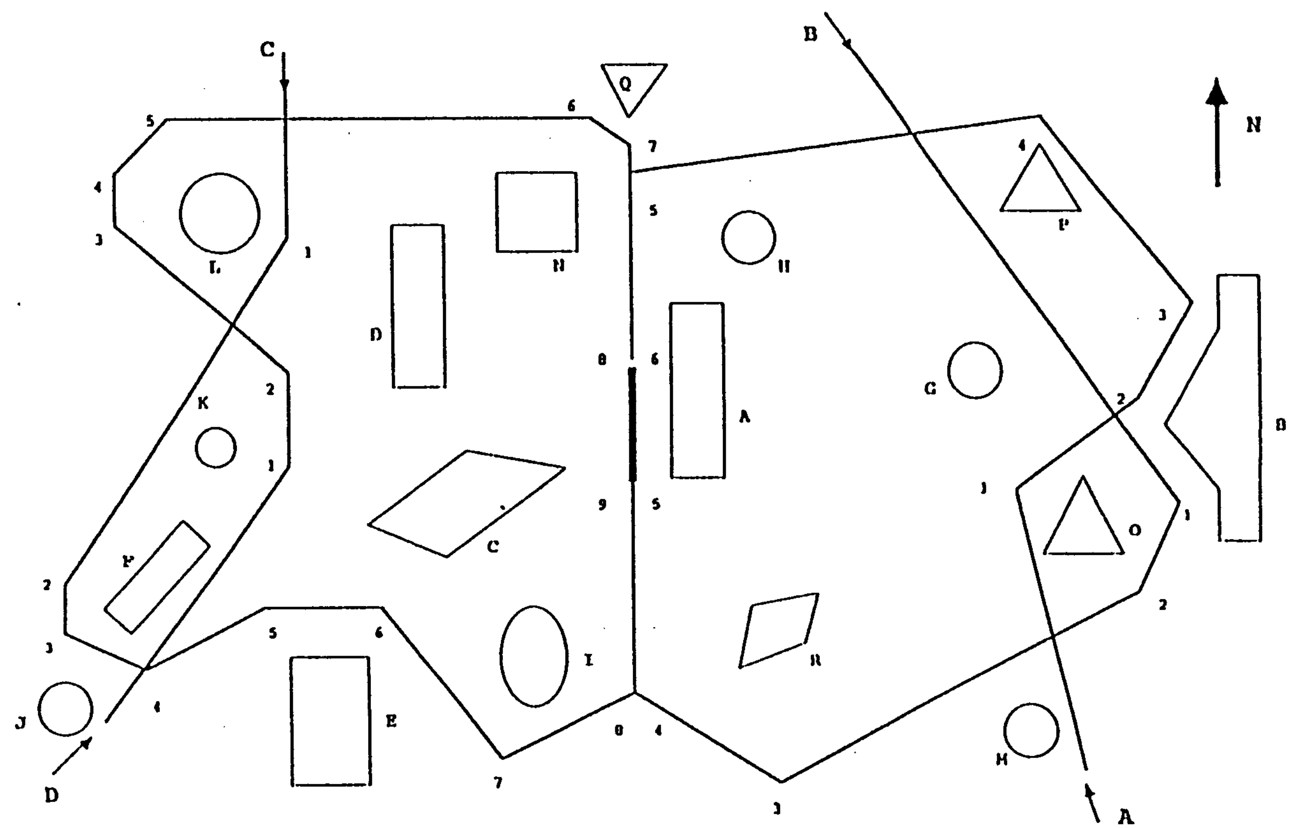


Figure 2.1. Simulated world used for the present experiment.

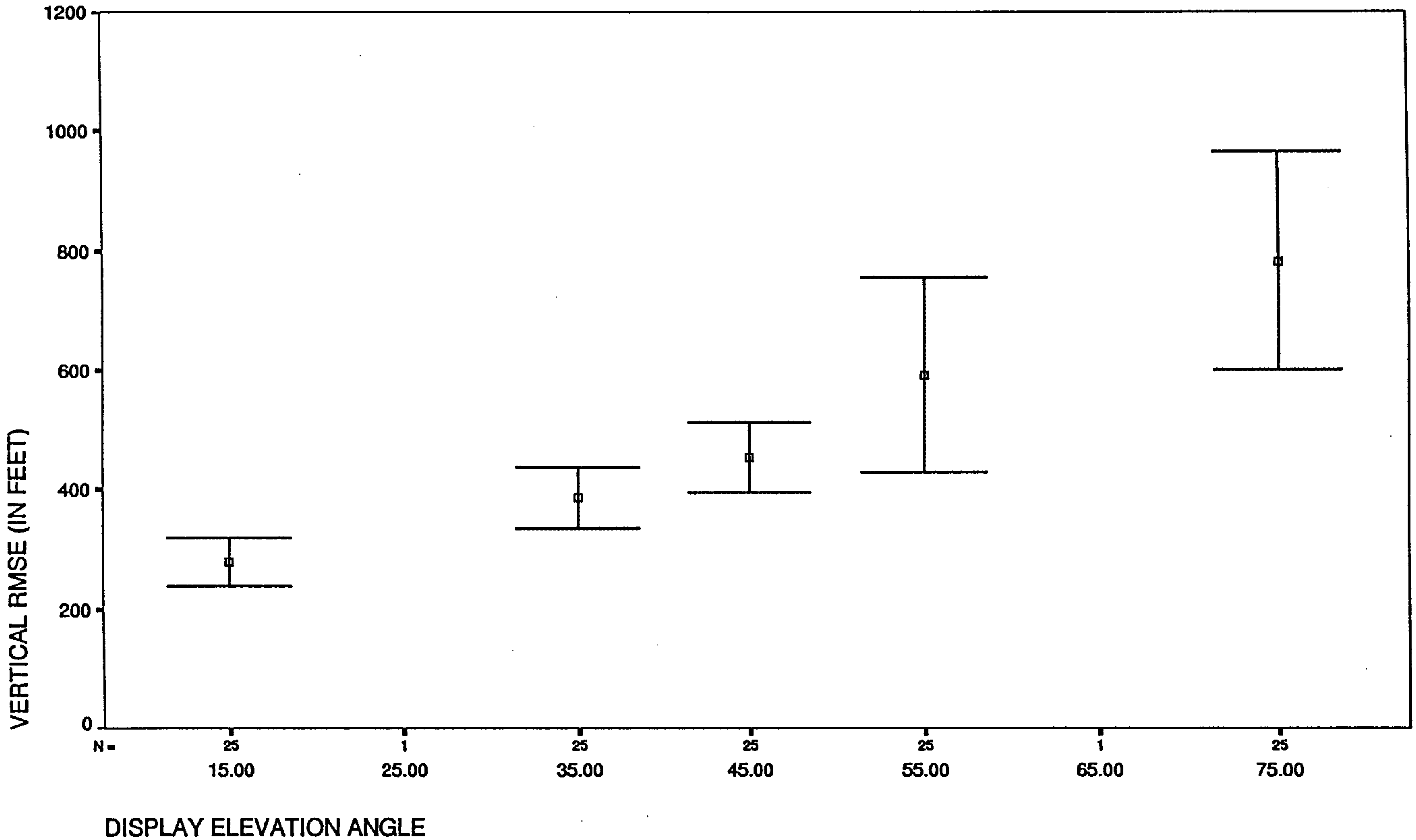


Figure 3.1. Vertical RMS error by display elevation angle.

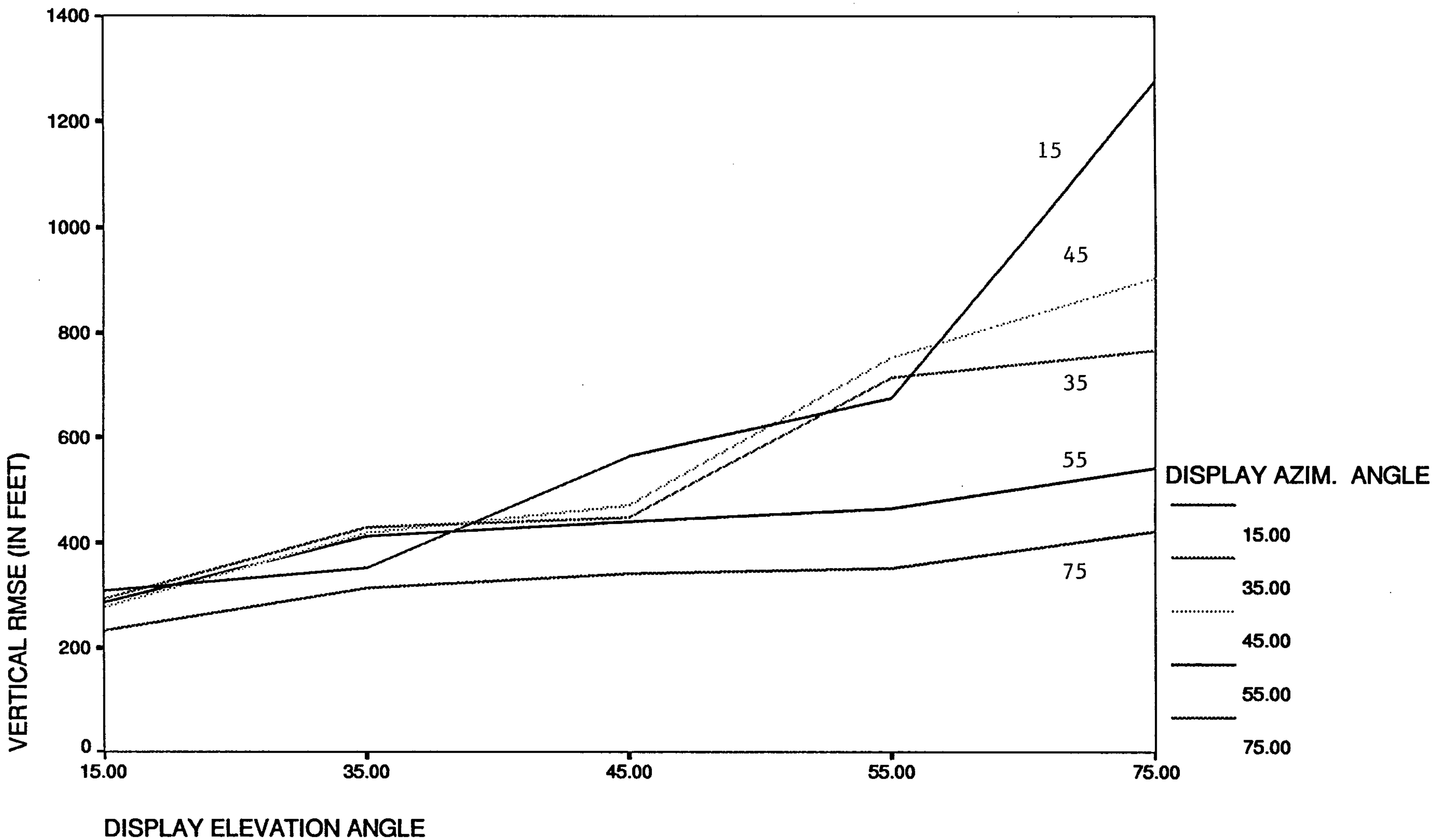


Figure 3.2. Vertical RMS error by display elevation angle and display azimuth angle.

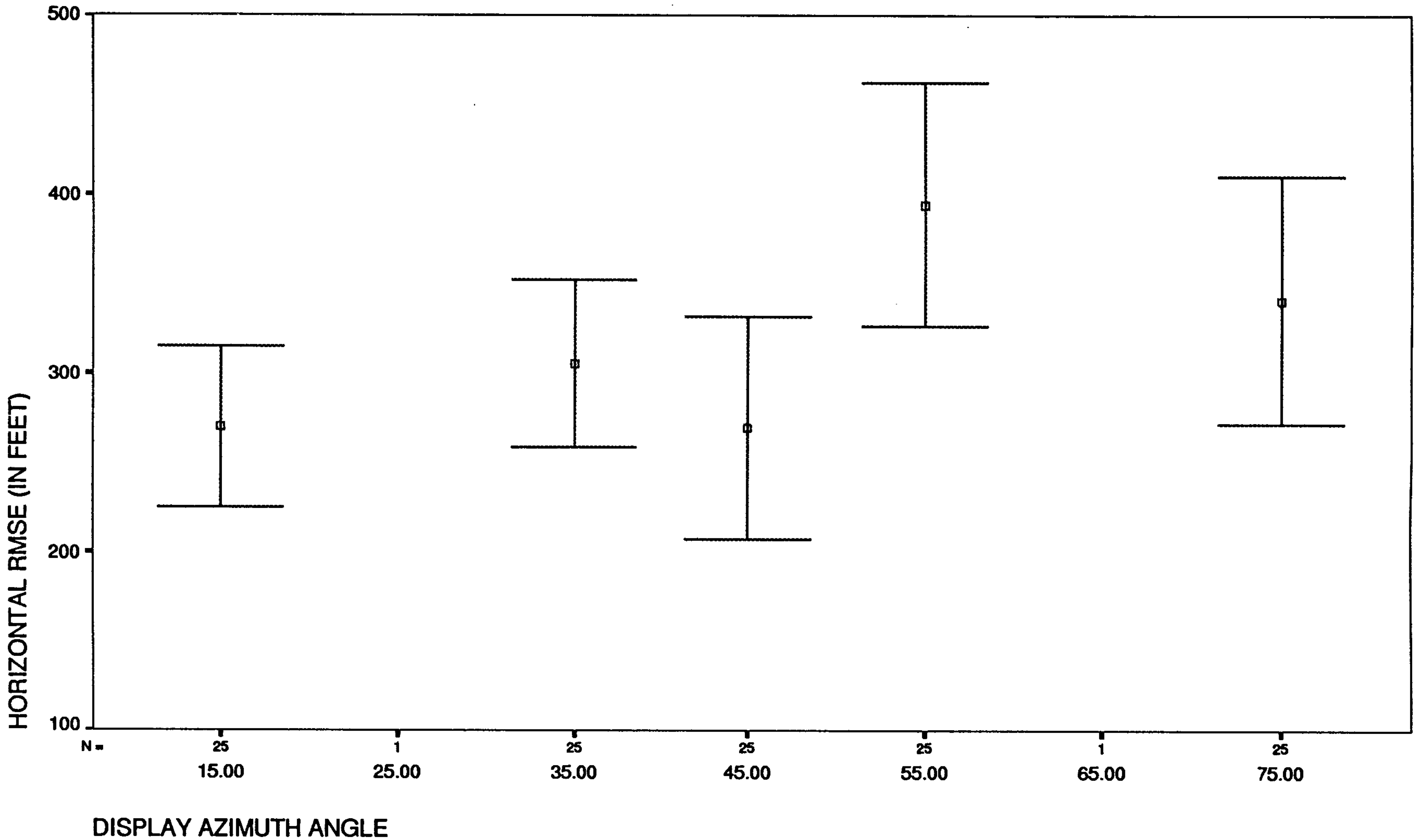


Figure 3.3. Horizontal RMS error by display azimuth angle.

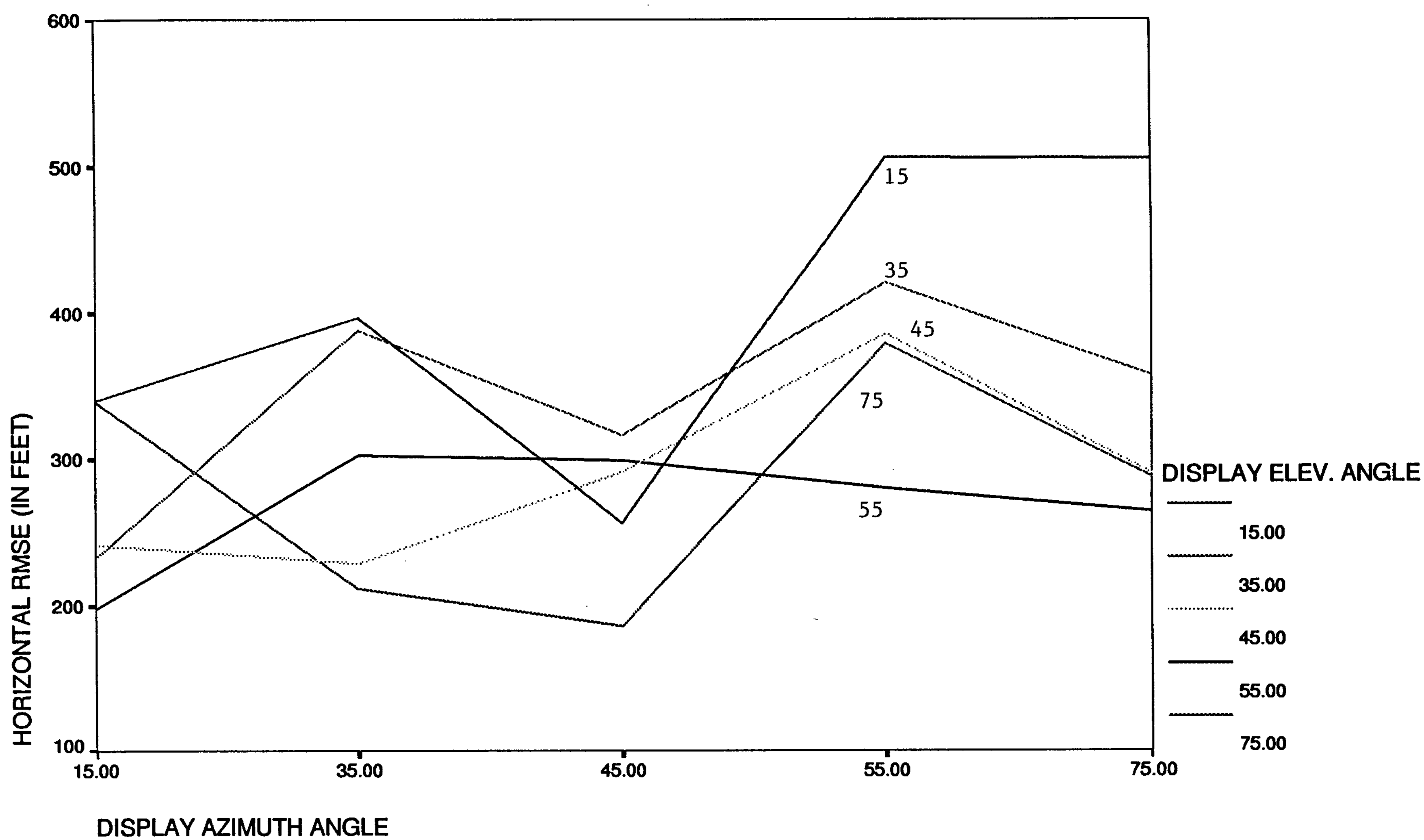


Figure 3.4. Horizontal RMS error by display azimuth angle and display elevation angle.

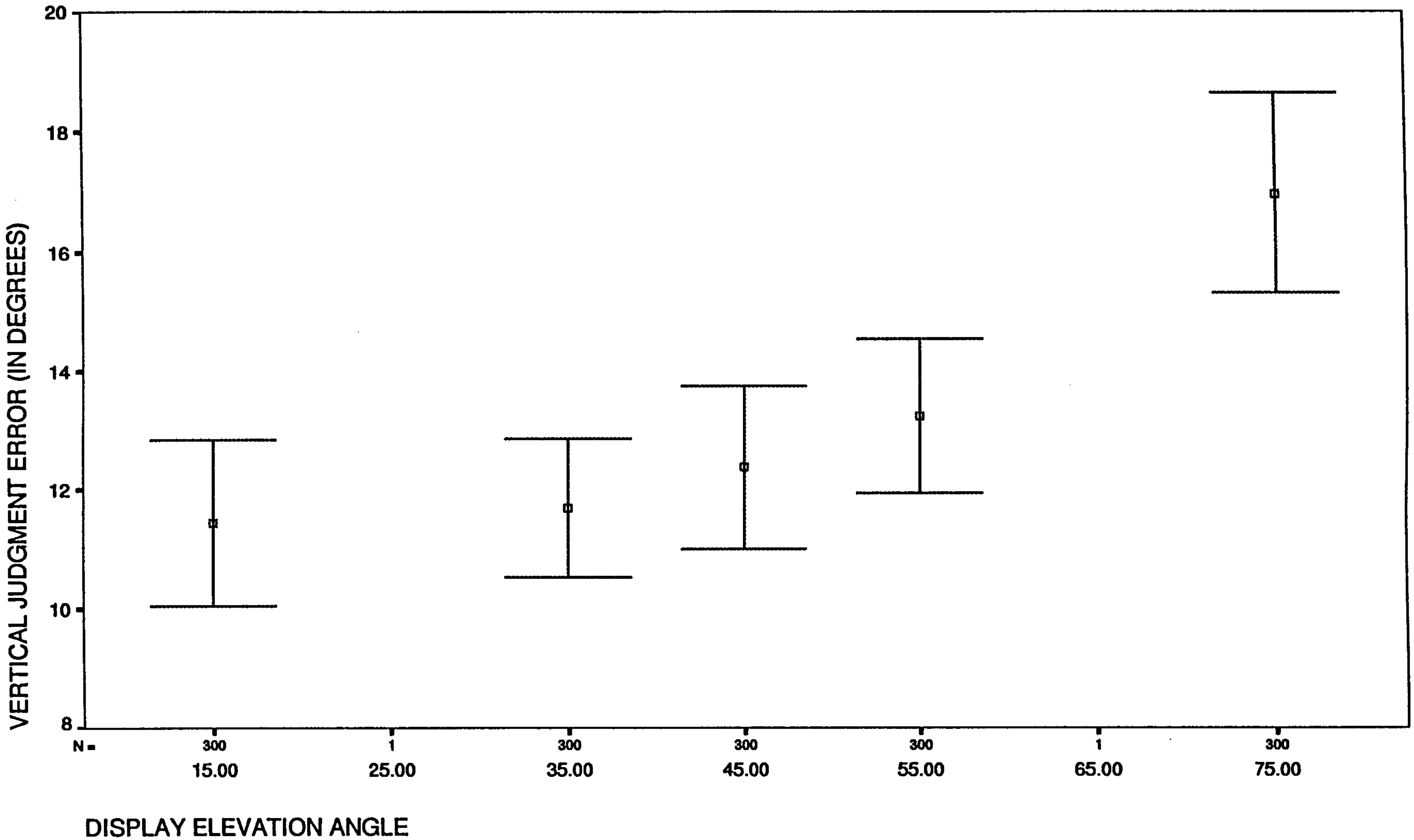


Figure 3.5. Vertical judgment error by display elevation angle.

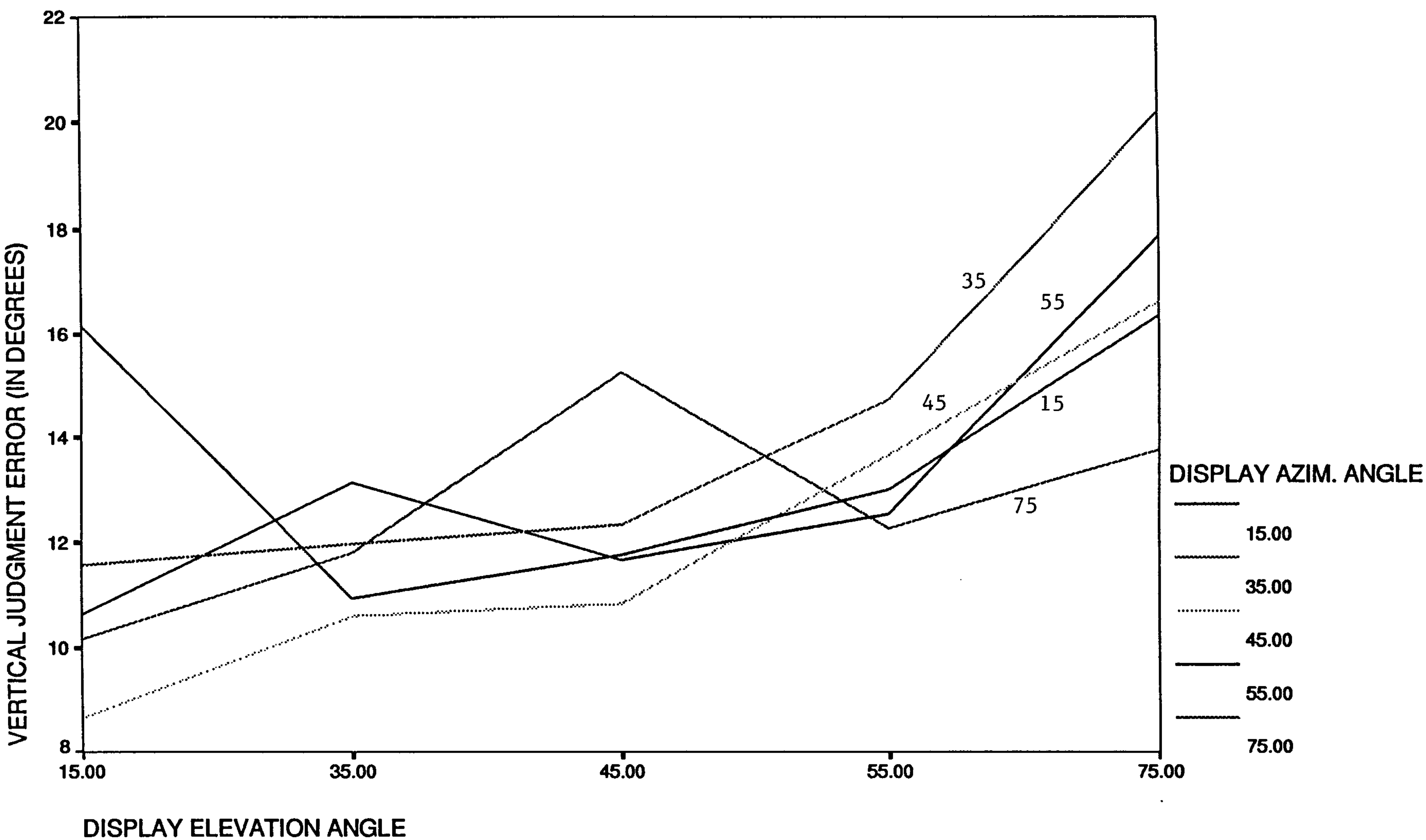


Figure 3.6. Vertical judgment error by display elevation angle and display azimuth angle.

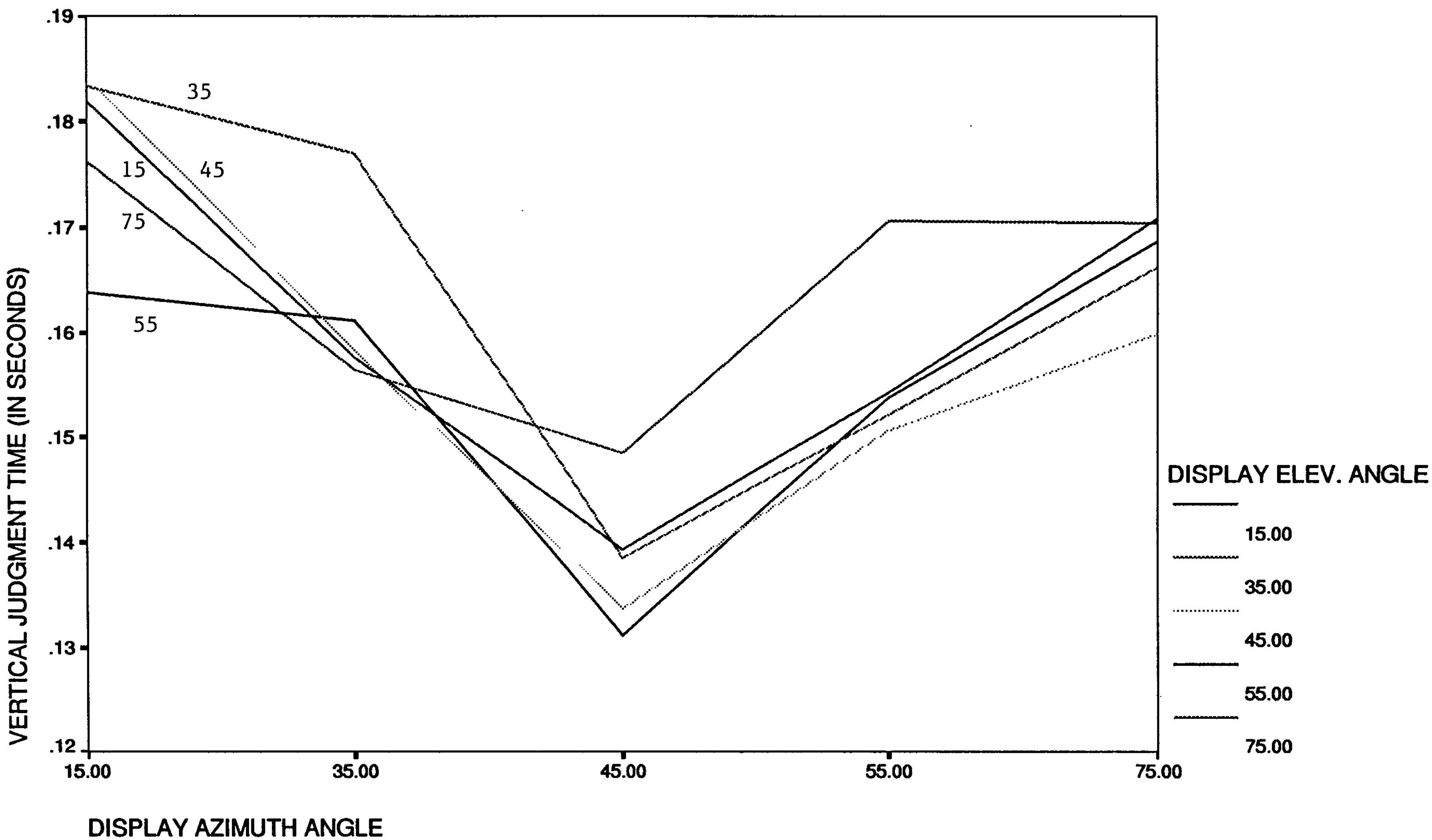


Figure 3.7. Vertical judgment time by display azimuth angle and display elevation angle.

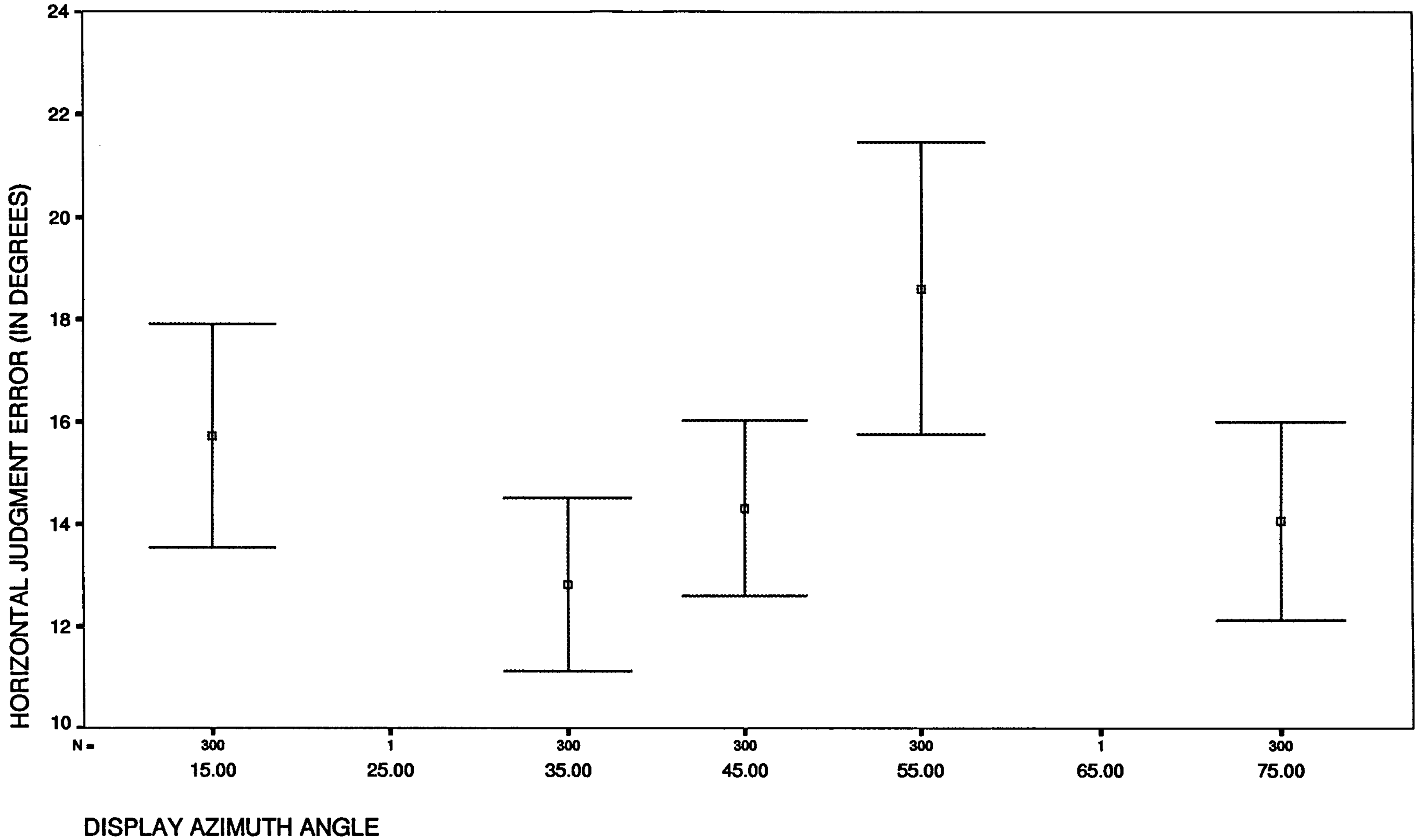


Figure 3.8. Horizontal judgment error by display azimuth angle.

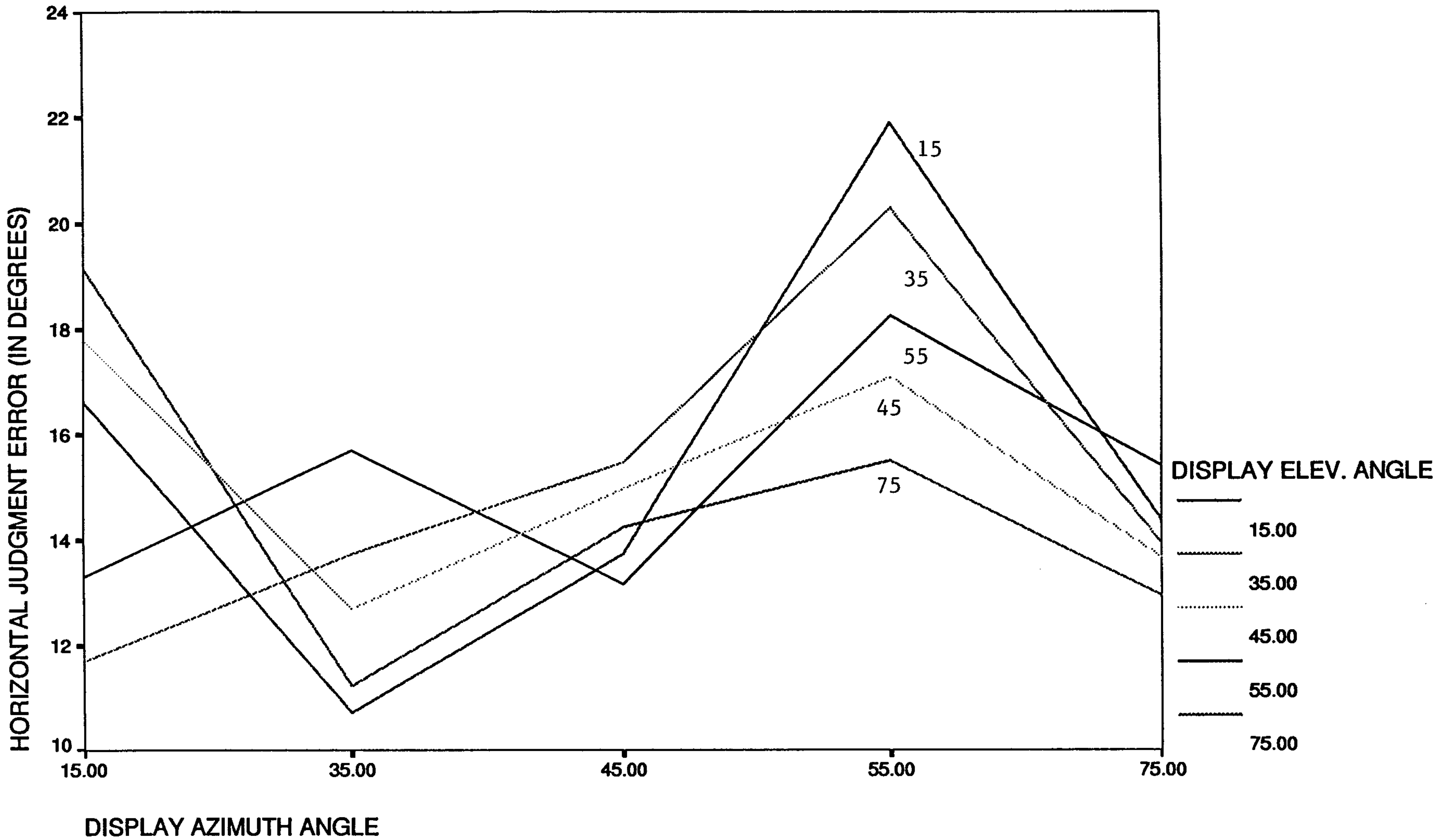


Figure 3.9. Horizontal judgment error by display azimuth angle and display elevation angle.

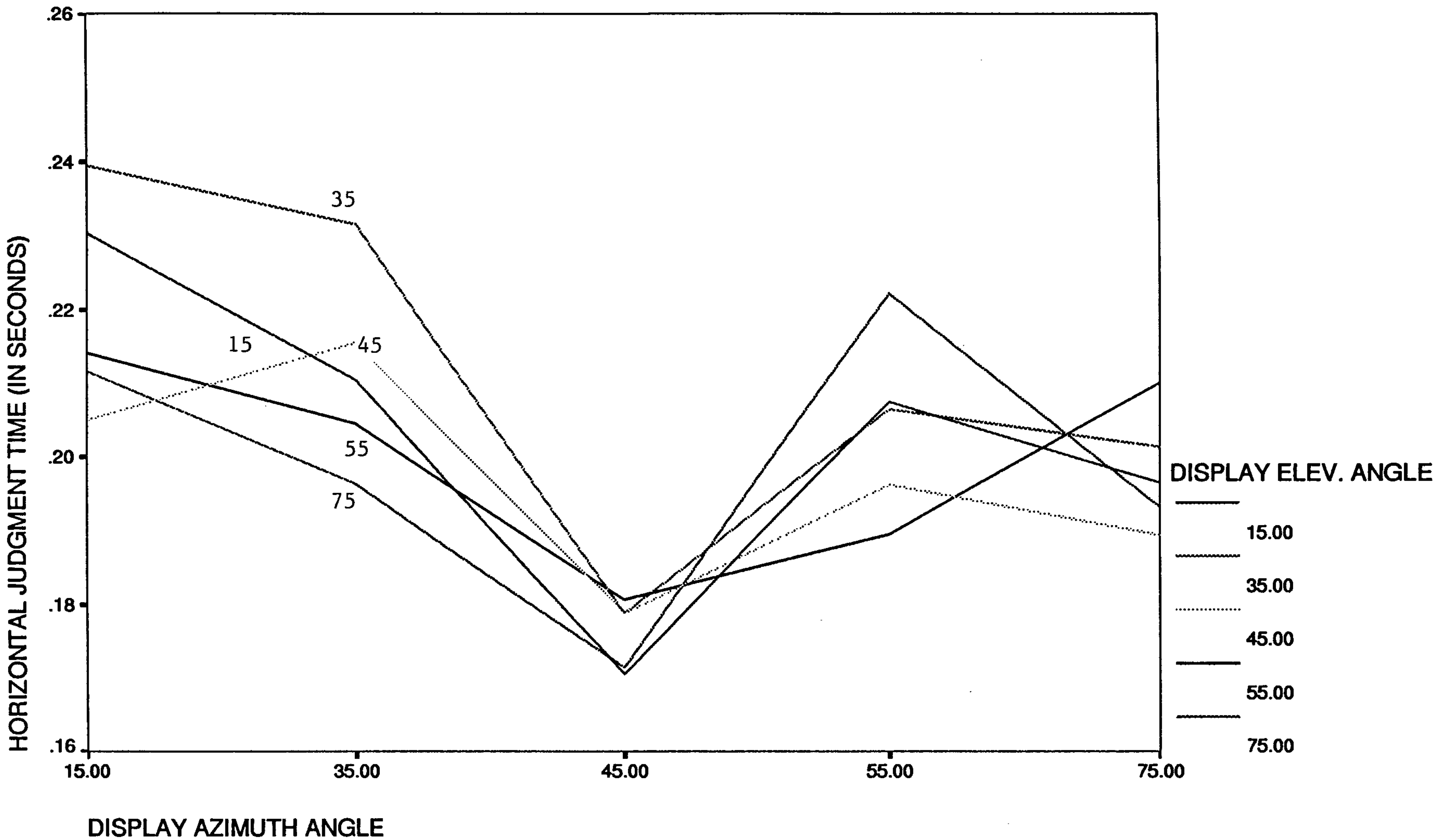


Figure 3.10. Horizontal judgment time by display azimuth angle.

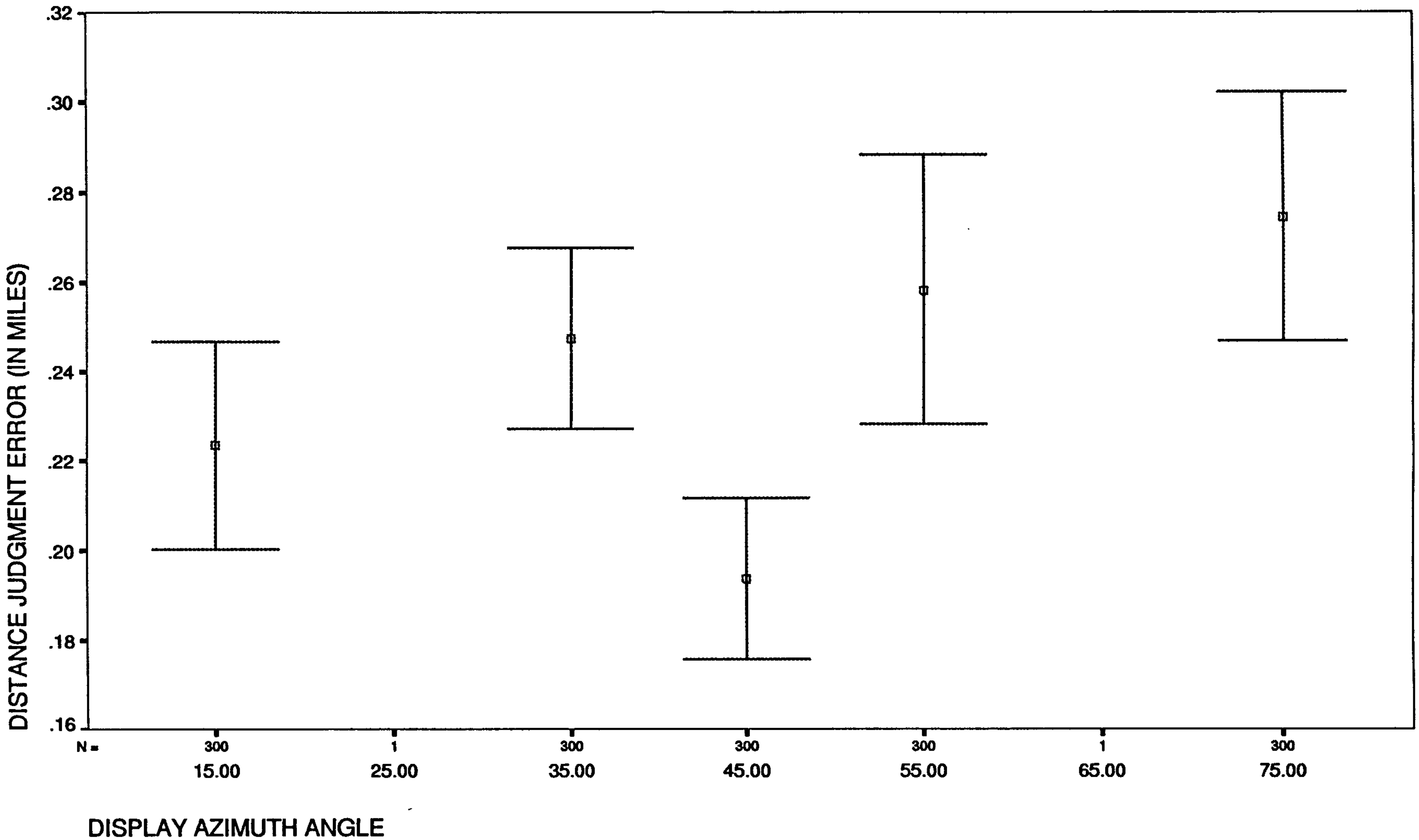


Figure 3.11. Distance judgment error by display azimuth angle.

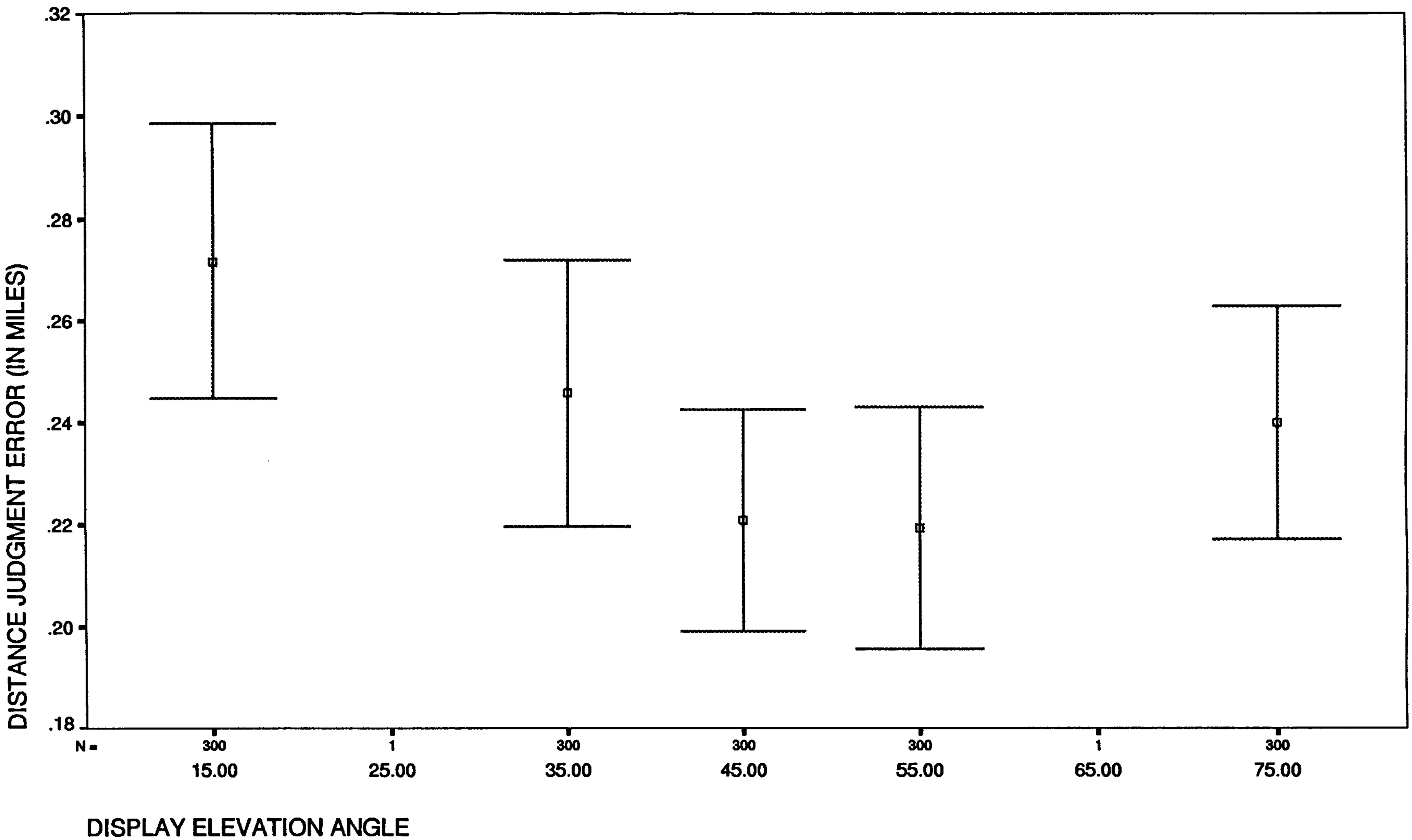


Figure 3.12. Distance judgment error by display elevation angle.

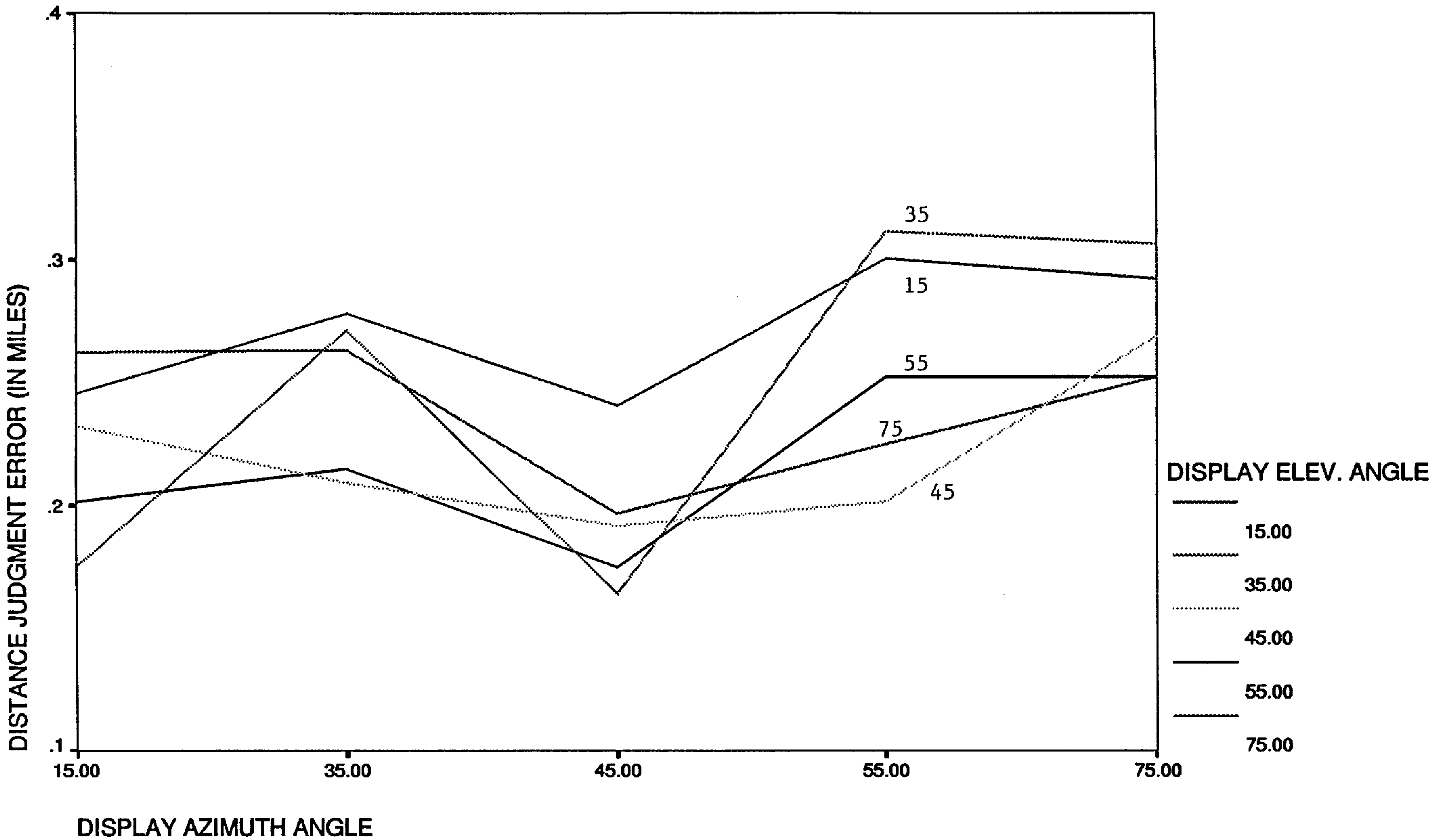


Figure 3.13. Distance judgment error by display azimuth angle and display elevation angle.

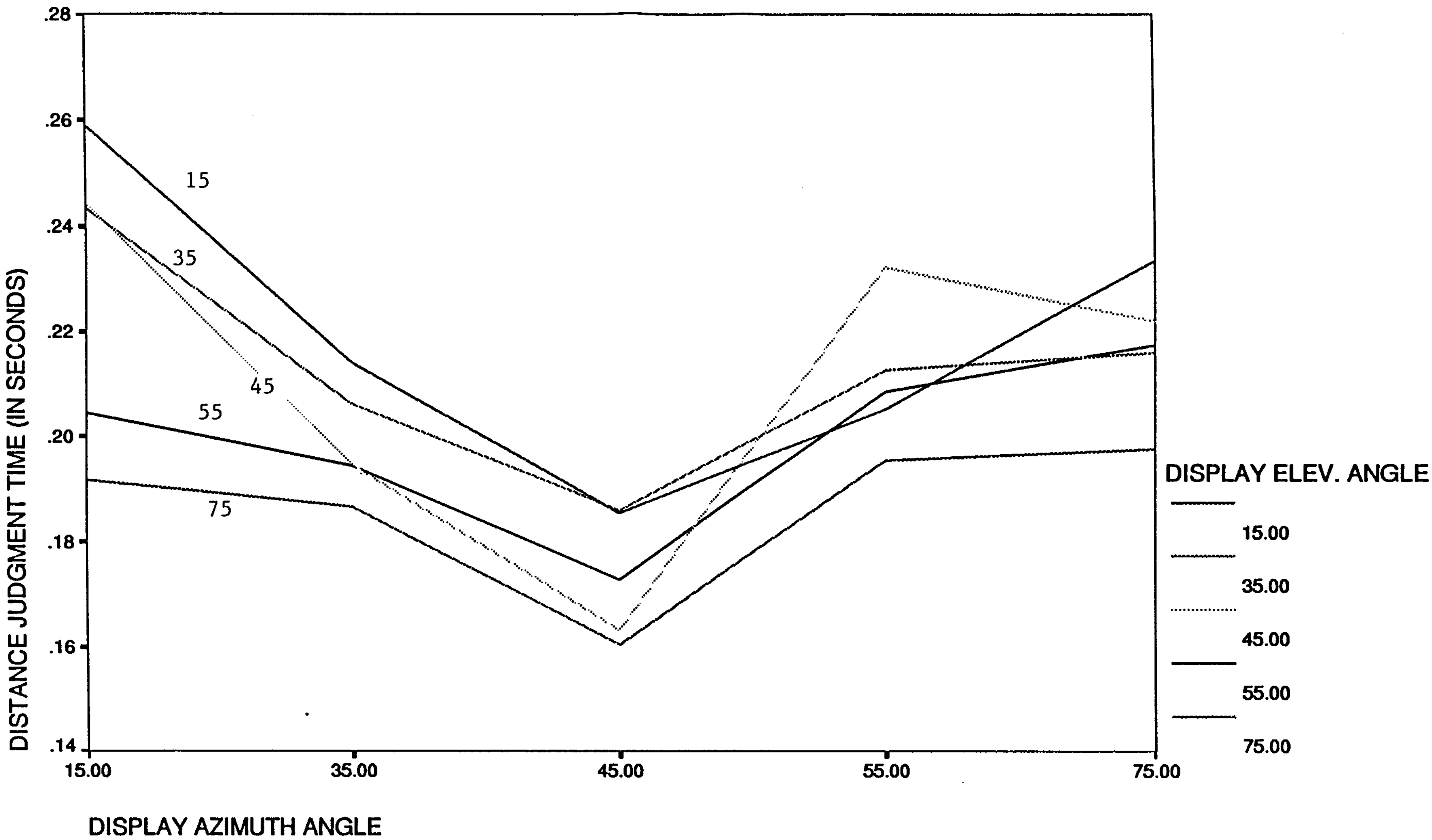


Figure 3.14. Distance judgment time by display azimuth angle and display elevation angle.

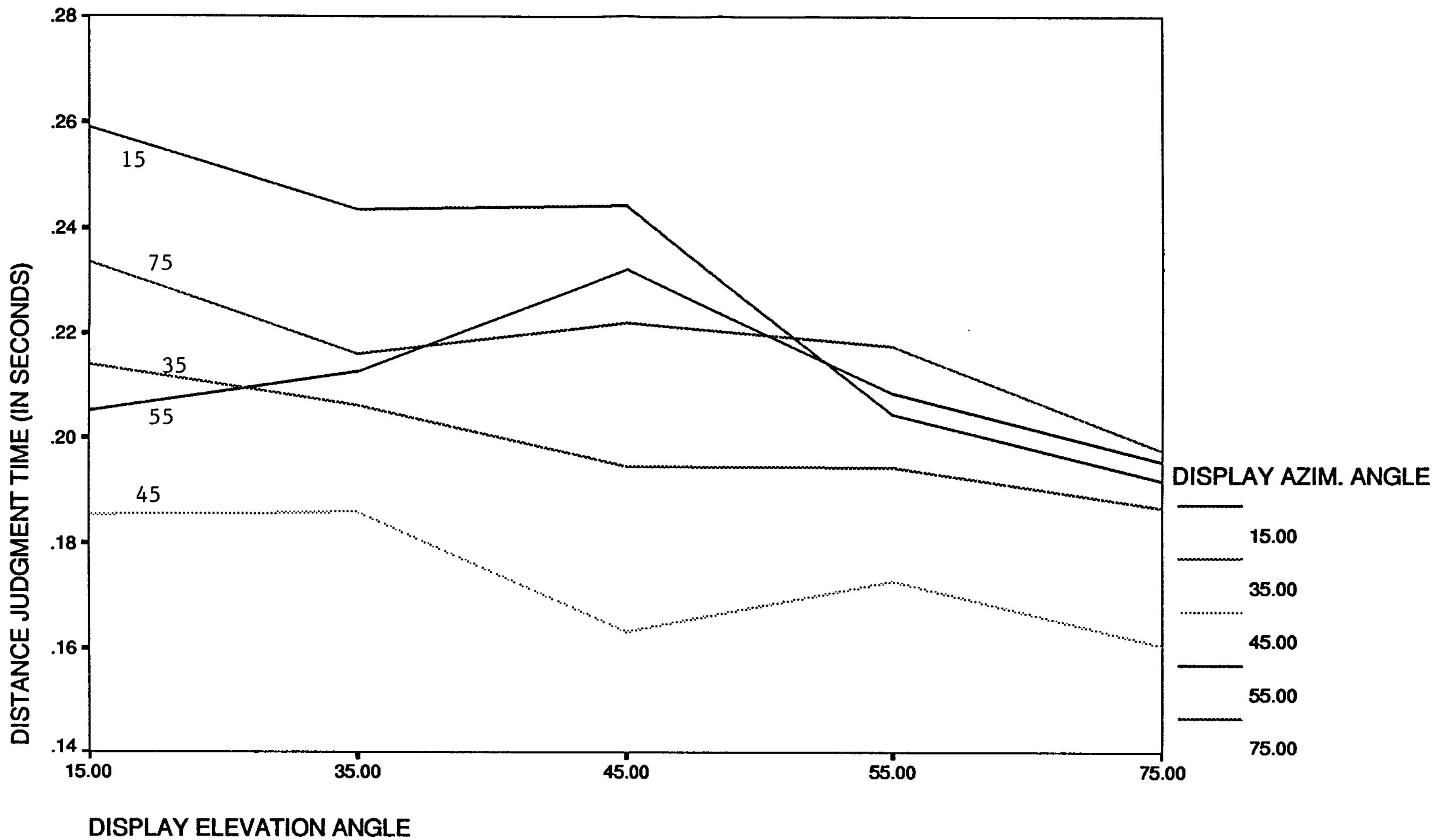


Figure 3.15. Distance judgment time by display elevation angle and display azimuth angle.

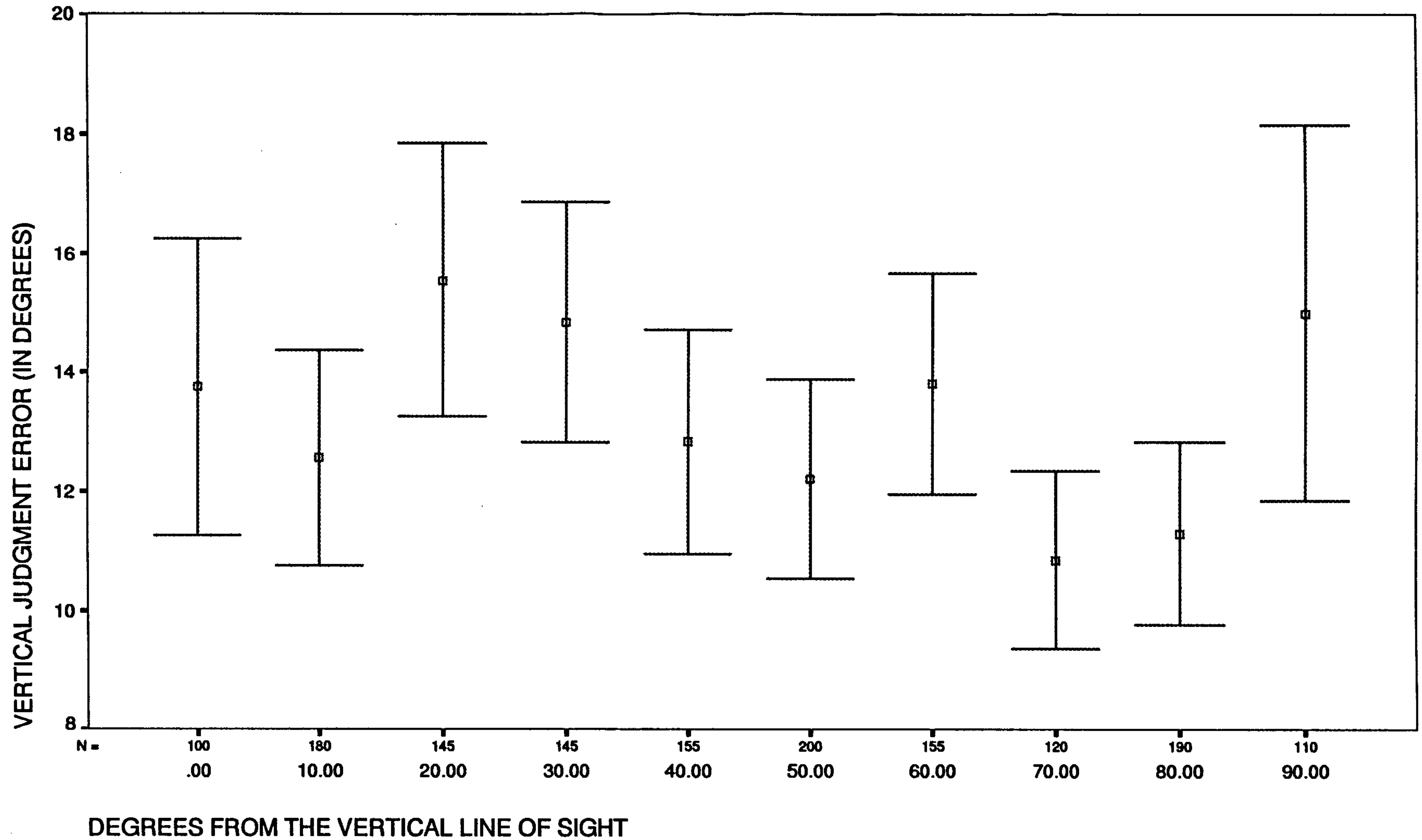


Figure 3.16. Vertical judgment error by degrees from the vertical line of sight.

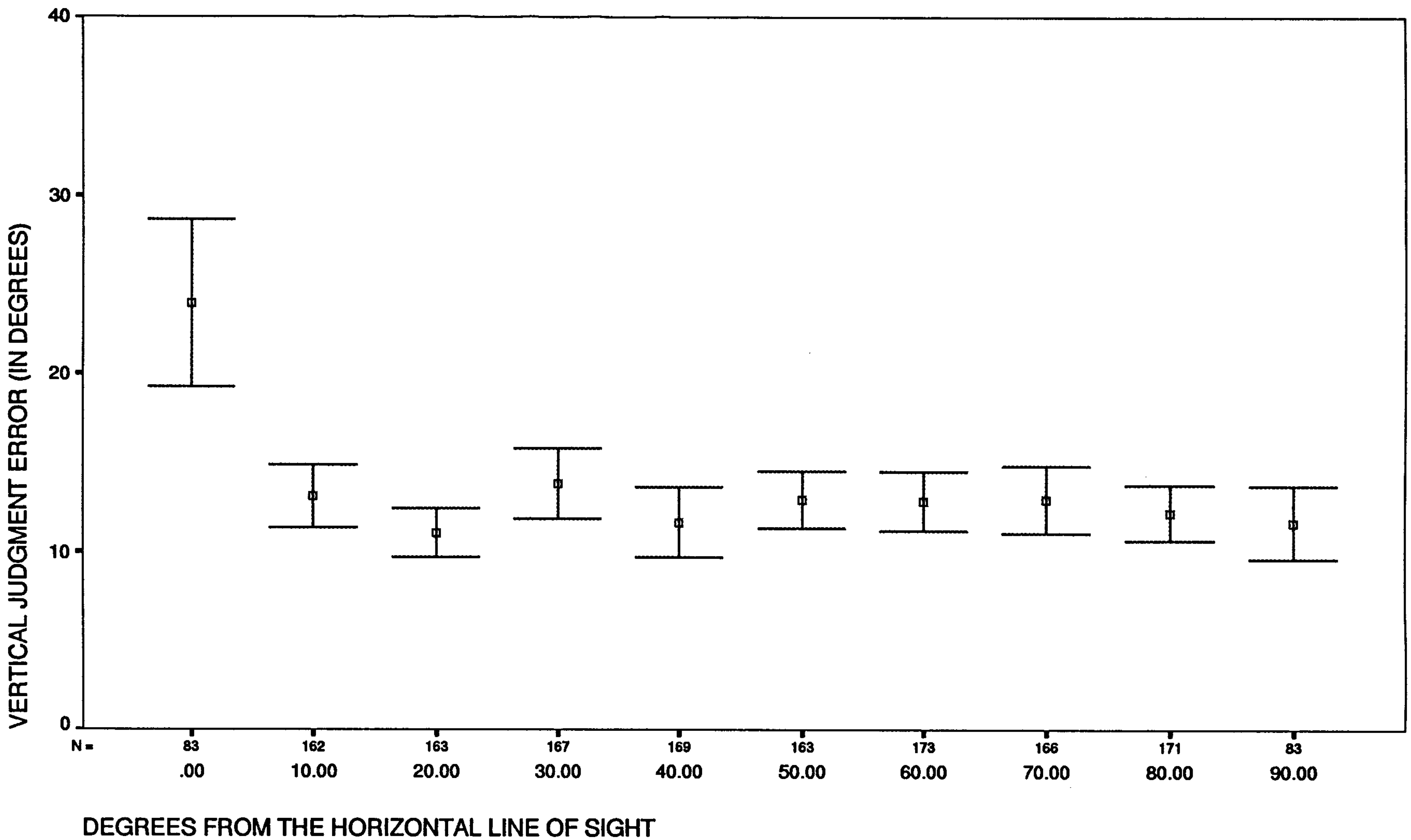


Figure 3.17. Vertical judgment error by degrees from the horizontal line of sight.

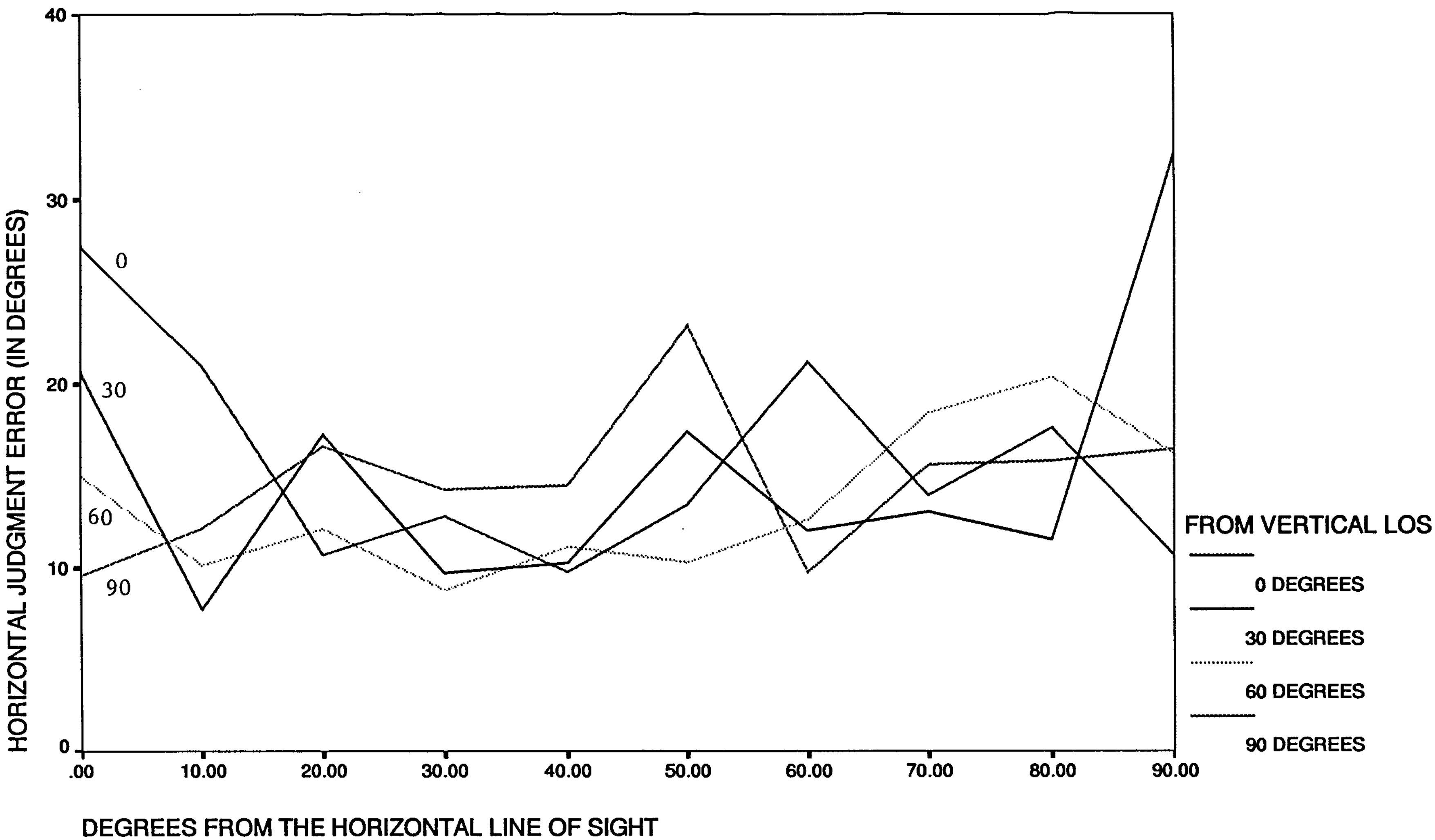


Figure 3.18. Horizontal judgment error by degrees from the horizontal line of sight.

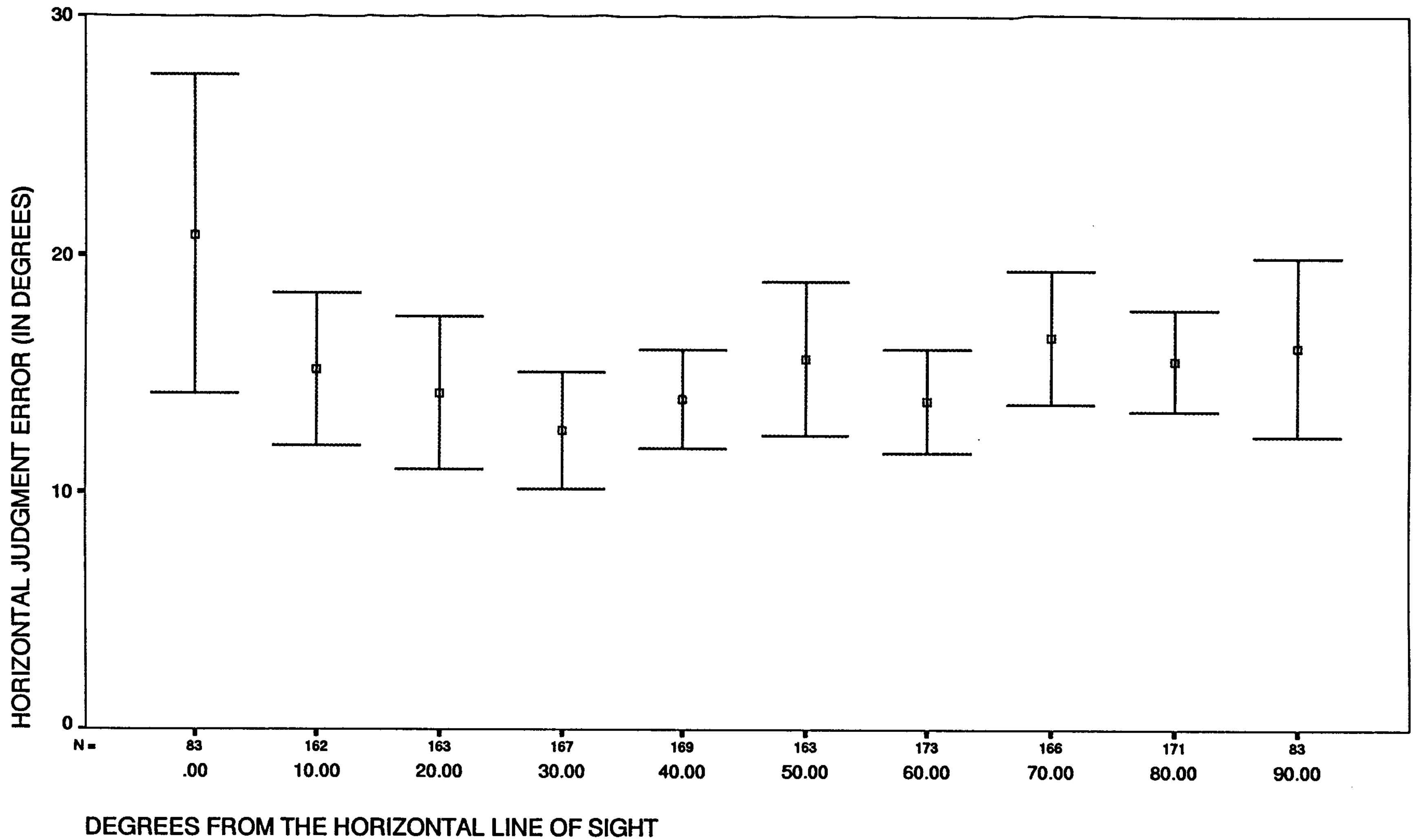


Figure 3.19. Horizontal judgment error by degrees from the horizontal line of sight.

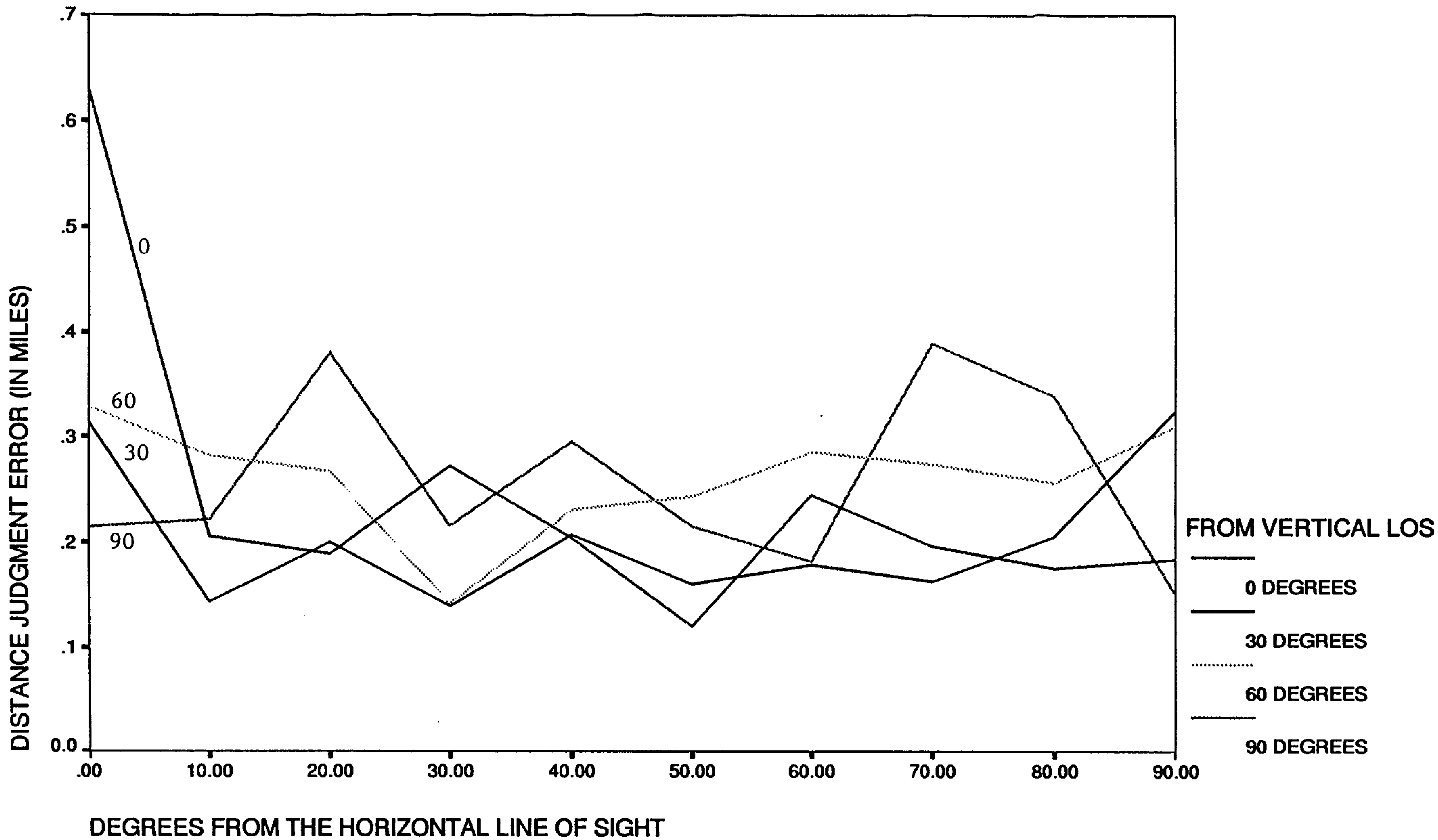


Figure 3.20. Distance judgment error by degrees from the horizontal line of sight.

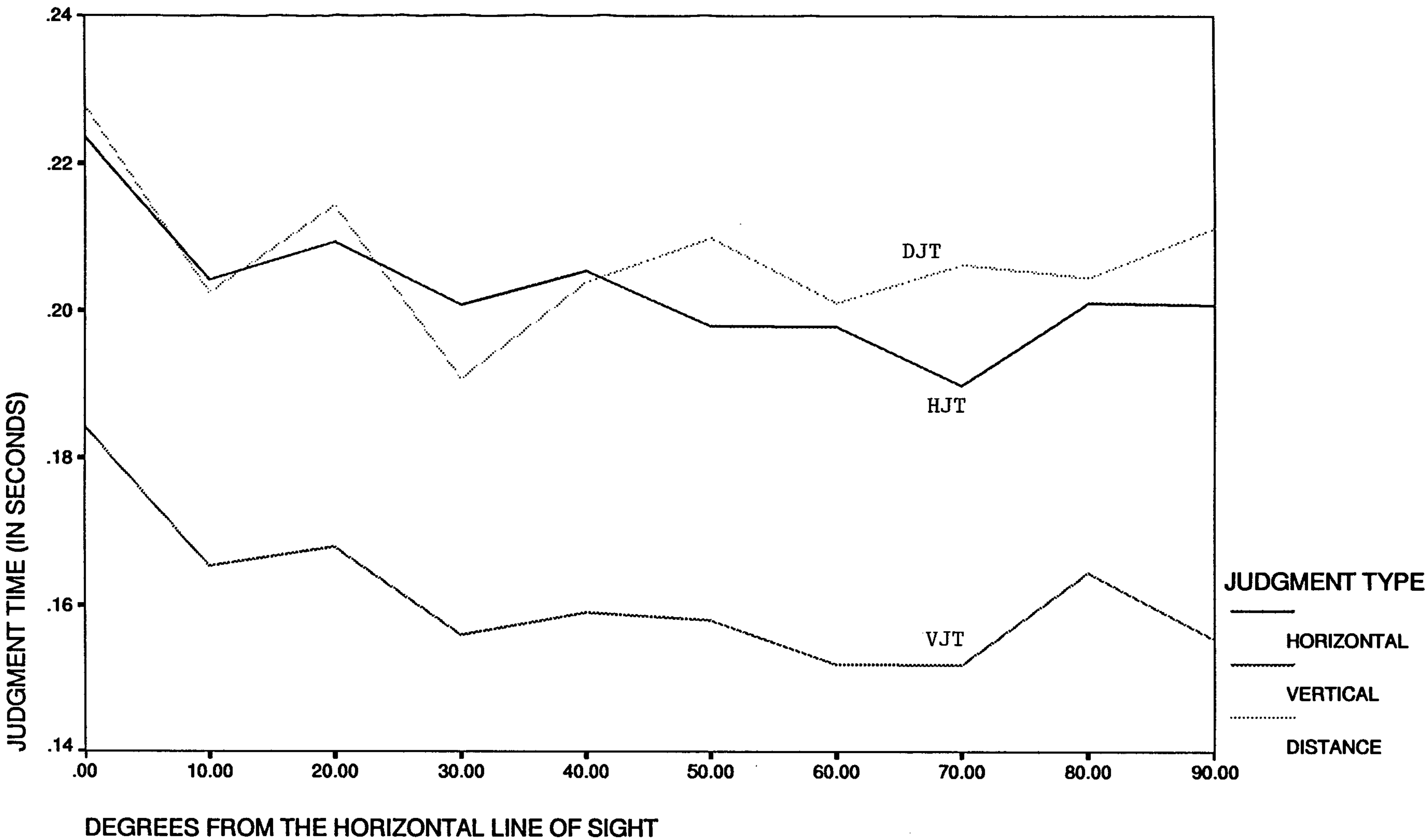
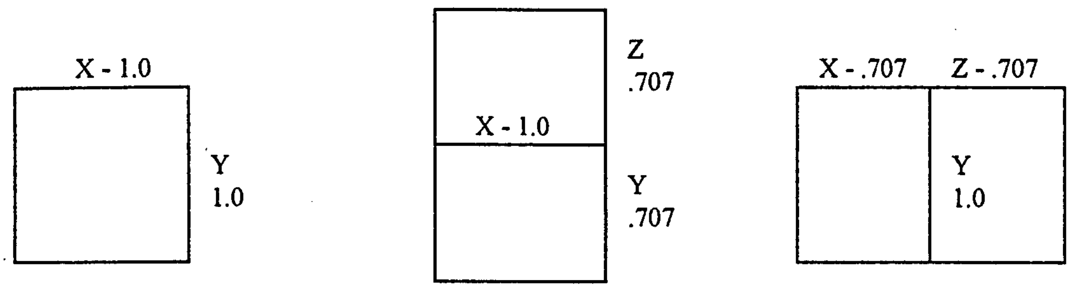


Figure 3.21. Judgment time by degrees from the horizontal line of sight.



0' azim., 0' elev. | **0' azim., 45' elev.** | **45' azim., 0' elev.**

A | B | C

Figure 4.1. Resulting resolution values for the three axes of a cube viewed from three display conditions.

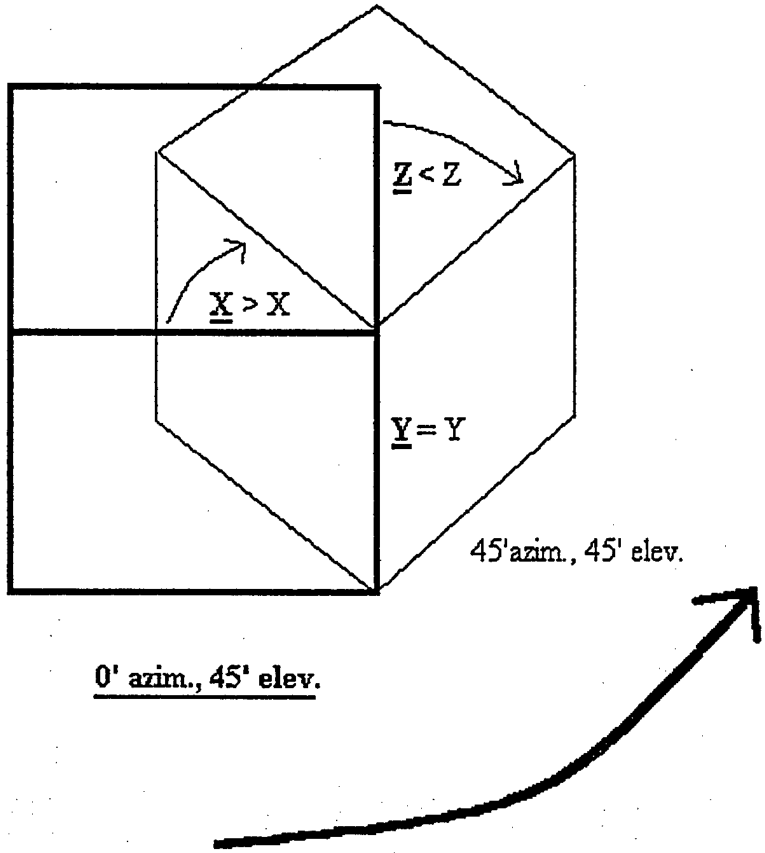


Figure 4.2. Effects on resolution values for the three axes of a cube when viewed with an angular displacement for the display elevation and display azimuth parameters.

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