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# The Effects of Training on Errors of Perceived Direction in Perspective Displays

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Space Administration



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# CONTENTS

	<u>Page</u>
SUMMARY.....	1
INTRODUCTION.....	1
Perspective Displays and Direction Errors.....	1
Previous Error Models.....	2
Effects of Training on Error Reduction.....	2
METHODS.....	3
Experimental Task.....	3
Experimental Hardware.....	4
Experimental Subjects.....	4
RESULTS.....	4
Errors.....	4
Learning.....	6
VIEWPOINT MISESTIMATION MODEL OF ERRORS.....	9
Forward Transformation (Presentation).....	9
Reverse Transformation (Perception).....	10
Source of Error Pattern.....	11
MODEL EXPLANATION OF DATA (FIT).....	12
Model Reproduction of Error Pattern.....	12
Model Reproduction of Error Bias.....	15
Model Failure to Reproduce Peaks in the Data Plot.....	16
Model Description of Learning.....	16
LEARNING MODEL.....	17
Model Description.....	17
Discussion of Data.....	17
Possible Tests of Model.....	20
FUTURE WORK.....	20
REFERENCES.....	21



## **SUMMARY**

An experiment was conducted to determine the effects of training on the characteristic direction errors that have been observed when subjects estimate exocentric directions on perspective displays. Changes in five subjects' perceptual errors were measured during a training procedure designed to eliminate the error. The training was provided by displaying to each subject both the sign and the direction of his judgment error. The feedback provided by the error display was found to decrease but not eliminate the error. A lookup table model of the source of the error was developed in which the judgment errors were attributed to overestimates of both the pitch and the yaw of the viewing direction used to produce the perspective projection. The model predicts the quantitative characteristics of the data somewhat better than previous models did. A mechanism is proposed for the observed learning, and further tests of the model are suggested.

## **INTRODUCTION**

### **Perspective Displays and Direction Errors**

Perspective displays can be useful instruments for representing spatial information (Ellis, McGreevy, and Hitchcock, 1987). When an operator is performing tasks in which three-dimensional (3-D) spatial relationships are important, a graphical image representing a real-world scene is a more intuitive means of obtaining information than tabular data or planview maps are. Such tasks include maintenance of situation awareness in flying, and control of robots when operator perception of the position of tools and the proximity of obstacles is required. The mathematical formulation for creating a perspective projection is well known, and high-speed-graphics computers make the computation and presentation of these images fast and easy (Foley and Van Dam, 1982).

However, producing an accurate two-dimensional (2-D) projection of a 3-D scene on a display screen does not guarantee that a human subject will correctly reconstruct the spatial information. Previous studies have shown, in particular, that there are errors in the judgment of relative direction of objects that vary both with actual direction and with the perspective parameters used to generate the display (McGreevy and Ellis, 1986; Grunwald and Ellis, 1986; Kim, Ellis, Tyler, Hannaford, and Stark, 1986; Ellis, Tyler, Kim, McGreevy, and Stark, 1985).

## Previous Error Models

McGreevy and Ellis (1986) showed that subjects misjudge both the azimuth (the angle left or right from straight ahead) and the elevation (the angle up or down from level) of a target object with respect to a reference object in perspective displays, and that the error varies systematically with both true target position and perspective parameters. They attributed the error to a combination of two effects, the 2-D effect and the virtual space effect. The 2-D effect model states that to some extent subjects are making judgments based upon the spatial relationships between the objects in the projected image rather than reconstructing the original 3-D relationships. The virtual space effect model states that subjects are reconstructing a distorted 3-D space because they are not viewing the display from the center of projection.

Grunwald and Ellis (1986) showed similar systematic errors in judgments of target azimuth. However, their experiments were done with the subject at the center of projection to eliminate any possible virtual space effect. Their model states that subjects use *a priori* knowledge and assumptions about the shapes of objects in the display in order to reproduce the 3-D spatial information. But the model only predicts an error pattern similar to the experimental data when it models the subjects as if they were looking through a telephoto lens. This telephoto bias is approximately equivalent to the virtual space effect described by McGreevy and Ellis (1986) but is based on a significantly different "virtualization technique" to reconstruct the space depicted in the flat display. The virtual space effect resulted from a point by point reprojection of the points on the picture surface back into a virtual space. The telephoto bias was based on constrained hypothetical warping of assumed shapes until a mismatch score of observed bundles of lines of sight corresponding to objects and potential lines of sight was minimized. Despite this major difference in how the errors in direction judgment were modeled, the data and models from both approaches show that the judgment errors were smallest when the subject was viewing the scene from behind the geometrically correct center of projection.

## Effects of Training on Error Reduction

The goal of this study was to determine the effects of displaying the judgment errors to the subjects. The previous studies have shown that, with the correct perspective parameters, the errors could be minimized by introducing a compensatory distortion; but can the subjects be trained to eliminate the systematic error entirely? Do the subjects change their judgments in response to delayed feedback? And does the training affect how the judgments are made? In addition to the exploration of displaying the errors, a new model of the source of the direction judgment errors based upon view vector misestimation in both pitch and yaw is presented. The model represents a generalization of classical theories of slant overestimation (Ellis, Smith, McGreevy, 1989; Sedgwick, 1986; Perrone, 1982)



## METHODS

### Experimental Task

The experimental task in this study was almost exactly the same as that used in the previous studies (McGreevy and Ellis, 1986; Grunwald and Ellis, 1986; Ellis and Grunwald, 1988). The subjects were shown a simulated 3-D scene in perspective projection. The scene contained a ground plane, a reference cube, and a target cube. The ground plane was represented by a half grid of irregularly spaced parallel lines. These lines indicated the "straight ahead direction" of the scene. In previous studies a full grid was used with a set of lines perpendicular to the straight ahead direction so that a reference was provided in the  $\pm 90^\circ$  azimuth directions. The reference cube sat above the ground grid, at the center of the display. Direction judgments were made with respect to the reference cube and the straight ahead direction. The target cube appeared at various locations around the reference cube on a fixed-radius circle so that the distance between the cubes was fixed. The height of both cubes above the ground grid was fixed and equal. Both cubes were independently and randomly tumbling in place slowly ( $<1$  rpm), and each had a reference line extending from its center to the ground plane with a cross mark to indicate the point of intersection with the ground plane. The viewpoint was behind, and a fixed distance from, the reference cube; it was always directed toward the reference cube (fig. 1).

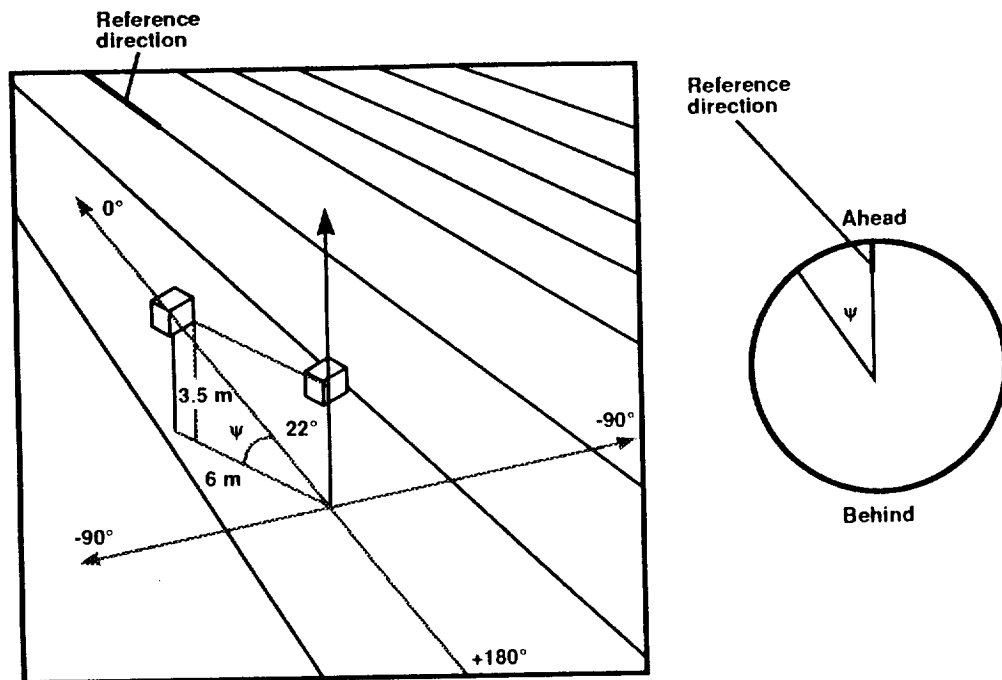


Figure 1. Overview of experimental task.

## Experimental Hardware

A Silicon Graphics IRIS 2400 TURBO graphics workstation was used to present the simulated scene. In addition to the scene that appeared in a 28- by 28-cm window, the workstation also drew a judgment dial. The subjects used a mouse to indicate the perceived target direction on the dial and to signal the completion of a judgment. The workstation presented the scene in a perspective projection, and the screen was placed so that the subjects were at or near the center of projection, 48 cm from the surface of the screen. The screen was placed below the subjects' eye level so that the subjects were looking down at an angle of approximately  $22^\circ$ .

## Experimental Subjects

Five subjects, two of whom were pilots, were asked to reproduce, on the dial, the target azimuth—the angle between the straight ahead direction and the direction from the reference to the target cube. In contrast to the experiments of McGreevy and Ellis(1986), we restricted the task to azimuth judgments only; the subjects were not asked to estimate target elevation, which was always 0. The subjects were truthfully told that the target cube would never appear in one of the cardinal directions. A set of 54 data points representing three replications of 18 target azimuth positions was used for each run. The azimuth positions ranged from  $-175^\circ$  to  $165^\circ$  in  $20^\circ$  increments. Each subject completed ten runs with target directions presented randomly from the complete set of 54. The viewpoint was fixed with both a view yaw and a view pitch of  $-22^\circ$  with respect to the straight ahead direction. All of the perspective parameters, including field of view ( $30^\circ$ ), were fixed.

For each subject, the first three runs were done with no error display. A scene with the target cube in one of the 18 positions was presented to the subject. The subject used the mouse to indicate on the dial the perceived target azimuth and to signal the judgment. The next target position was presented immediately after the judgment was signaled. The last seven runs were made with error display. First, the target was presented as in the runs without error display. As soon as the direction judgment was signaled, an error cube appeared on the target circle in the direction indicated by the subject on the dial. If there was an error in judgment, the cube would be at a different azimuth than the target cube and the subjects could see their error in the scene. The subjects then moved the error cube with the mouse to coincide exactly with the target cube in the scene and could see their error again with an error pointer on the dial. This technique provided delayed feedback of the errors after the open-loop direction judgments were made. Only after the error was corrected in the scene and on the dial was the computer signaled to present the next target position.

## RESULTS

### Errors

Figure 2 shows the error in target azimuth judgment (perceived azimuth – presented azimuth) averaged across subjects for the first three runs without error display. The sinusoidal pattern matches the pattern of error measured in previous studies (McGreevy and Ellis (1986);

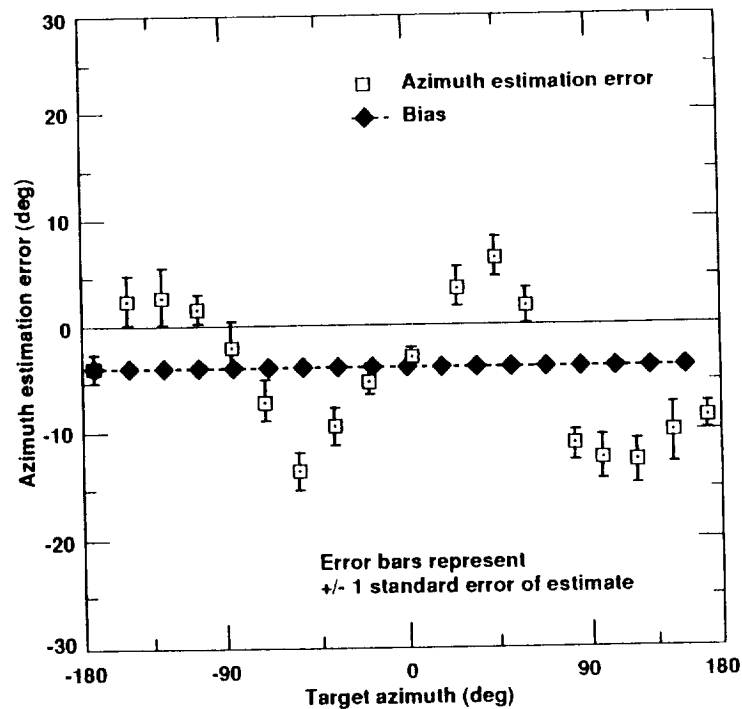


Figure 2. Mean target azimuth judgment errors.

Grunwald and Ellis (1986)). The peak-to-peak amplitude of error is about  $18^\circ$ , with a maximum positive error of about  $5^\circ$  for target azimuths of  $45^\circ$  and  $-135^\circ$  and a maximum negative error of about  $-13^\circ$  for target azimuths of  $-55^\circ$  and  $125^\circ$ .

The data clearly show a bias which is calculated to be  $-3.6^\circ$ . This bias was a characteristic of the data in all the previous experiments, but it has not been satisfactorily explained.

Another interesting feature of the data is the zero error angles, the target directions for which the subjects make correct judgments. The data indicate that these angles occur at the positions  $-165^\circ$ ,  $-105^\circ$ ,  $15^\circ$ , and  $75^\circ$ . These data are surprising because we expected that subjects would make correct judgments along the  $0^\circ$ - $180^\circ$  axis where there is a reference line in the ground grid. This result might indicate that the subjects did not believe the instruction that the targets would not appear in the cardinal directions. If the subjects failed to judge an angle when the targets appeared near the reference direction, at  $5^\circ$  and  $-175^\circ$ , and instead assumed that the targets were straight ahead, we would expect and did see an error at those positions of approximately  $-5^\circ$ . This behavior tends to pull the error signal down and shift the zero error angle to  $15^\circ$  and  $-165^\circ$ .

The statistically significant effect of target azimuth ( $F = 4.092$ ;  $df = 1, 17$ ;  $p < 0.001$ ) is not surprising and agrees with previous studies. This represents the statistical significance of the sinusoidal pattern of error.

Figure 3 shows the judgment error standard deviation versus target azimuth. There are clear minima near the straight ahead direction, but not the same minima exhibited in the earlier study by

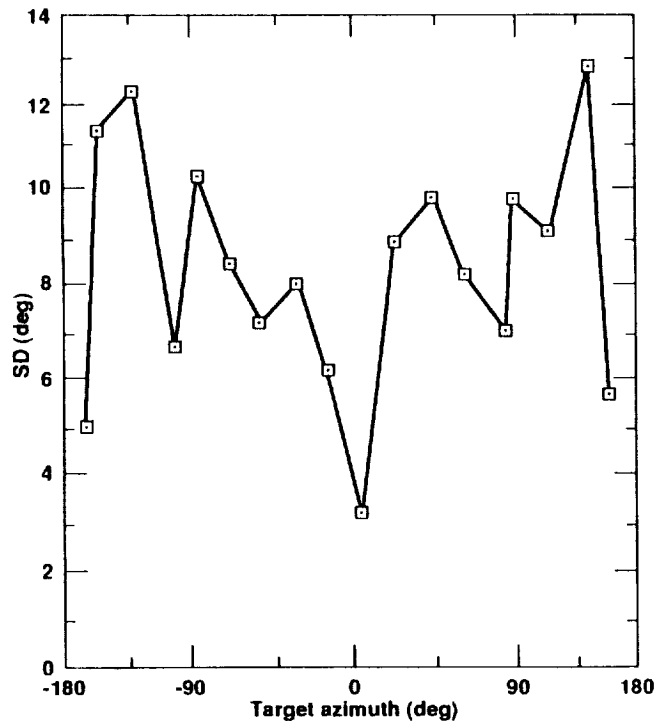


Figure 3. Standard deviations of the judgments.

Grunwald and Ellis (1986). Even though there are some points that could be characterized as secondary minima, they are not in the perpendicular direction. This finding matches those of earlier experiments which also used only a half grid and is not surprising since there is no reference line in the perpendicular direction. (Ellis, Tyler, Kim, McGreevy, and Stark, 1985; Ellis, Smith, McGreevy, and Grunwald, 1989.)

### Learning

The judgment error amplitude as the experiment proceeds with error display is shown in figure 4. The learning number represents the ordinal number of the runs with error display, and is a measure of the amount of feedback received to that point in the experiment. The amplitude of the data is approximated by the difference between the averages of the positive peaks and the negative peaks of the data. The amplitude increases when the error display is introduced and then drops to a relatively constant level of about 33% of baseline amplitude for most of the experiment before dropping again during the last run. With the exception of the first run, the error display data clearly show a decreased error amplitude that might be approaching some asymptotic value. However, it is also clear that this trend indicates the amplitude will not go to 0 with any reasonable amount of training, if at all.

Figure 5 shows the error bias during the experiment. The baseline data exhibit a strong negative bias. This result differs from results of earlier work in which data collected using a full grid as a ground reference showed almost no bias for a  $-22^\circ$  view yaw, but agrees with previous results using

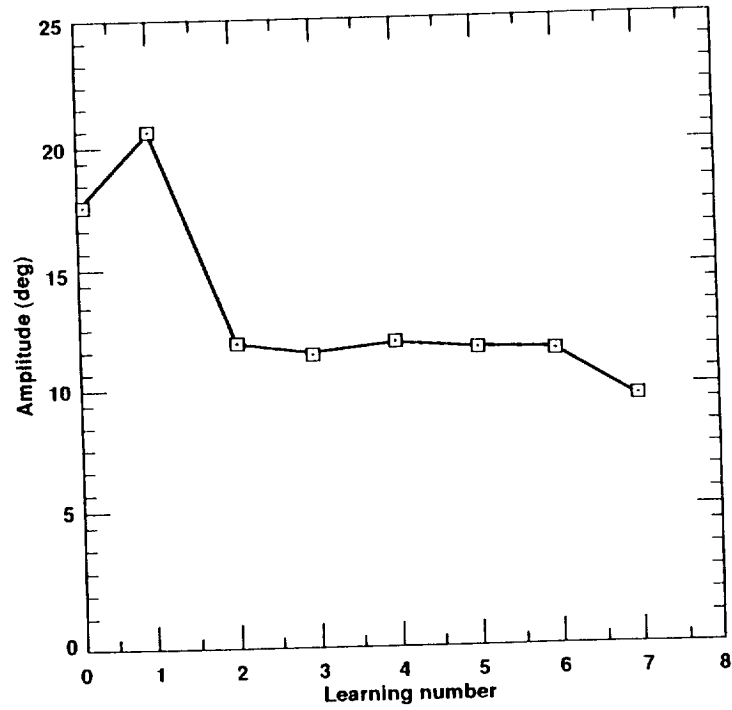


Figure 4. Mean amplitude of the error.

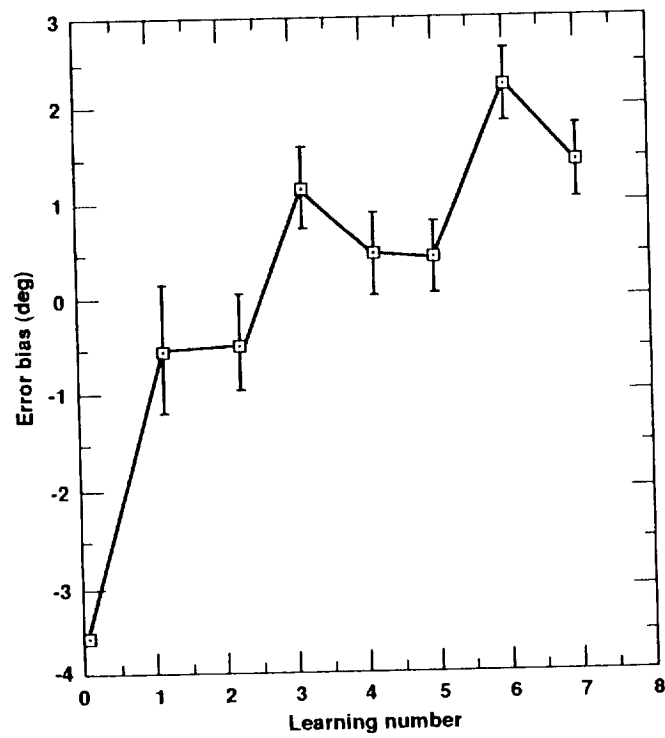


Figure 5. Mean bias level of the error.

only a parallel-line ground reference. Whatever the cause, the introduction of error display seems to eliminate the negative bias quickly and tends to pull the bias up throughout the experiment. The data show that at the end of the experiment the bias has moved to a positive nonzero value; it is important to note that the bias has been shifted, not eliminated.

There is a possibly significant effect of learning number ( $F = 2.749$ ;  $df = 17$ ;  $p < 0.026$ ) which is shown by the shift in the bias discussed above. A reason the effect shows up weakly could be that the learning takes place quickly and is followed by a period of little change. This would wash out the effect in the analysis of variance over the entire training period. As expected, target azimuth shows a strong effect even by itself ( $F = 7.631$ ;  $df = 1,17$ ;  $p < 0.001$ ). The interaction of target azimuth with learning number is not significant for the same reason the bias is not ( $F = 1.237$ ;  $df = 4,119$ ;  $p < 0.063$ ). Running more subjects and doing the analysis only over the learning period would settle the question of significance.

Figure 6 shows the baseline judgment errors and the errors after seven runs with error displayed. Whereas it is clear that the quantitative characteristics of the data—the amplitude, the bias, and the zero error crossing values—have changed, the qualitative characteristic of the data remains intact. Even though the variability is higher because the absolute values of the error are smaller, the after-error-display data still show a cyclical variance with target azimuth. This suggests that the addition of the error display is not introducing a new effect into the subjects' direction judgments, but rather that the learning is working through the mechanism that is the source of the errors.

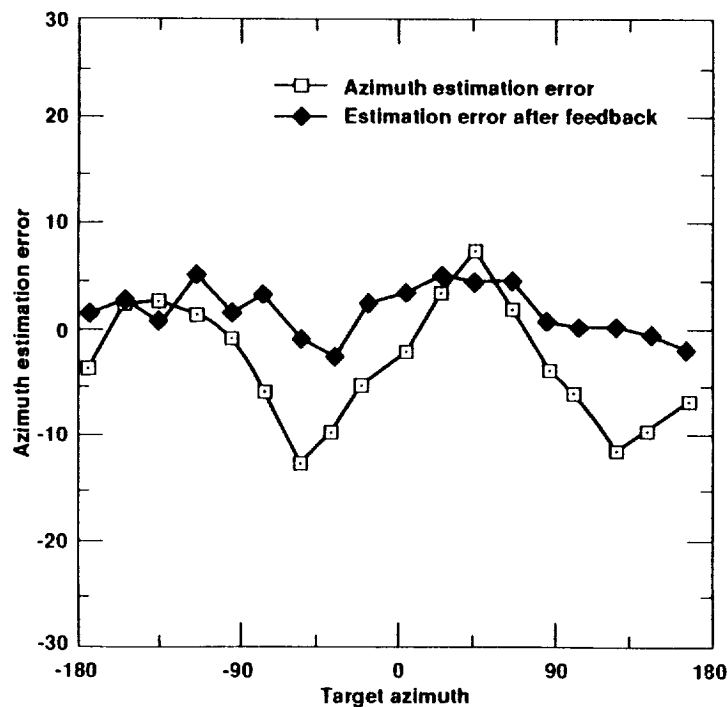


Figure 6. Mean error before and after error display.

## VIEWPOINT MISESTIMATION MODEL OF ERRORS

Two factors motivated the development of an alternate model for the mechanism of the target azimuth judgment errors: the need for an intuitive description of the judgment process, and the need for a system through which the learning could be said to be acting. The 2-D and virtual-space effects are both straightforward geometric descriptions for the errors. The 2-D effect is descriptive only, and indicates a failure to transform the stimulus to the 3-D world. The data demonstrate that the judgment errors persist even when the scene is viewed from the center of projection, indicating that something other than the virtual-space effect is operating. Additionally, these effects have static characteristics that are determined by the geometry of the situation; there are no parameters which could change to explain the effects of the learning. On the other hand, neither the existence of a telephoto bias nor the means by which it produces the judgment errors is easily understandable. And, though the amount of telephoto bias is a subjective parameter that could change with training, the subjects would probably notice this effect because they would perceive the scene as growing larger. These factors and others prompted a reevaluation of the geometry of the display in a search for another cause for the errors.

The target azimuth is an angle in the ground plane that is presented in some 3-D orientation. The angle is distorted because it has been rotated out of the plane of the projection. The amount of rotation, and therefore the distortion, is determined by the view yaw, the view pitch, and the view distance. If we view the scene straight down, at a view pitch of  $-90^\circ$ , the target azimuth angle will appear undistorted. Therefore, it seems logical that the subjects would use their perceived view direction and location when trying to reproduce the target azimuth. In other words, the subjects know they are viewing the scene from a certain view yaw and view pitch, and the angle they see projected is to  $Y$  degrees, therefore the target azimuth that would create the angle that they see distorted must be  $X$  degrees. If the subjects could perfectly estimate the viewing direction, the judgment would be correct. But if the subject uses the wrong viewing location to interpret the image, there will be an error in judgment. This is the basis for the viewpoint misestimation model of the judgment errors.

### Forward Transformation (Presentation)

There are two factors operating to distort the angle the subjects see: the viewpoint rotations and the perspective projection. The model assumes that the subjects have acquired, through experience of observing the world, a method of determining the effects of each factor on the objects they see around them. The computer determines the distortions by projecting the relevant positions in the simulated scene to the screen. The relevant points for a target azimuth judgment are the position of the target cube, the position of the reference cube and the position of a point in the straight ahead direction. The only position that changes during the experiment is the target cube position, and this is computed from the target azimuth. With the simulated 3-D positions known, the computer projects them to the screen in perspective and with viewpoint rotations.

In a perspective projection, points are projected from the 3-D space through a center of projection onto a projection plane represented by the display screen. The view vector is the vector from the center of projection to the center of the display screen. The projection has the effect that, as an object moves away from the viewpoint along the view direction, it appears to shrink toward the view vector;

equal-sized objects appear different sizes at different distances from the viewpoint, the more distant object appearing smaller. A perspective projection will not distort angles at the center of the projection, but it will distort them in other areas of the scene. The amount of distortion is proportional to the field of view of the perspective, which is the angle subtended by the screen from the center of projection. The formulation of a perspective projection is well known and is not presented here (Foley and Van Dam, 1982).

The viewpoint location is essentially two rotations of the 3-D coordinate system with respect to the screen coordinates. As stated above, a viewpoint pitch of  $-90^\circ$ , looking straight down on the scene, produces no distortion. The angles around the projected horizontal axis are compressed, and those around the vertical axis are expanded, as the pitch increases. The viewpoint yaw rotates all of the angles through this distortion. Again, the formulation for the viewpoint rotations is well known and is not presented here (Foley and Van Dam, 1982).

All of the positions are projected to the screen with these transformations. From the screen coordinates it is a simple trigonometric operation to determine the projected angle. This is the angle between the straight ahead direction and the target direction that the subject observes on the display screen.

The computer must run through numerous operations to arrive at the angle projected on the screen from the target azimuth, but the subject probably does not use a similar process for determining the relationship between target azimuth and projected angle. The subject may have an intuitive means of determining the relationship arrived at through experience. Based on his or her observations in the real world, the subject may be thought to have created lookup tables with the correspondence of real angles to observed angles based upon views of known objects and the *efference copie* of proprioceptive and vestibular measurements of yaw and pitch. Table 1 includes two lookup tables for different viewing locations. Using these lookup tables the subject can predict what the projected angle will be for a given target azimuth and vice versa for a given view location.

### **Reverse Transformation (Perception)**

On the computer the process of determining the target azimuth from the projected angle is numerical, not analytical. First, the computer determines the projected angle from the screen coordinates of the projected objects. The computer then uses the projection process and sweeps through possible target positions until it finds the one that corresponds to the projected angle. The computer can do this for any viewing location, but for a particular viewing location there is a one-to-one correspondence between target azimuth and projected angle.

For the subjects this process can be likened to using the lookup table in reverse. First they determine which lookup table to use, judging from their estimation of the viewing location, and then they find the target azimuth that corresponds to the projected angle they see.



Table 1. Lookup tables

View azimuth $-22.0^\circ$ View elevation $-22.0^\circ$		View azimuth $-33.0^\circ$ View elevation $-31^\circ$	
Target azimuth, deg	Projected angle, deg	Target azimuth, deg	Projected angle, deg
-175.0	-173.5	-175.0	-175.0
-155.0	-156.4	-155.0	-159.4
-135.0	-146.2	-135.0	-147.8
-115.0	-138.3	-115.0	-137.4
-95.0	-130.6	-95.0	-126.3
-75.0	-121.4	-75.0	-111.8
-55.0	-107.2	-55.0	-89.7
-35.0	-78.8	-35.0	-55.5
-15.0	-29.0	-15.0	-19.3
5.0	6.5	5.0	5.0
25.0	23.6	25.0	20.6
45.0	33.8	45.0	32.2
65.0	41.7	65.0	42.6
85.0	49.4	85.0	53.7
105.0	58.6	105.0	68.2
125.0	72.8	125.0	90.3
145.0	101.2	145.0	124.5
165.0	151.0	165.0	160.7

### Source of Error Pattern

If the subject misestimates the viewing location, and uses the lookup table for the wrong view, an error will be produced in the target azimuth estimation across all of the target locations. This is the source of the azimuth judgment errors in the viewpoint misestimation error model.

Using the lookup table concept (fig. 7), we can see the source of the error pattern. The viewpoint for the experiment is fixed. For each target azimuth chosen, the computer displays the scene with the projected angle shown in the correct lookup table. In this example, the subject has misestimated the viewpoint. Using the wrong lookup table, the one for the view estimation, the subject estimates the target azimuth. Because the wrong lookup table is used, the subject finds a target azimuth different from the true target azimuth in the table, and makes an error in judgment. For the entire series of target positions the use of the wrong lookup table produces an error pattern like the one shown in figure 8.

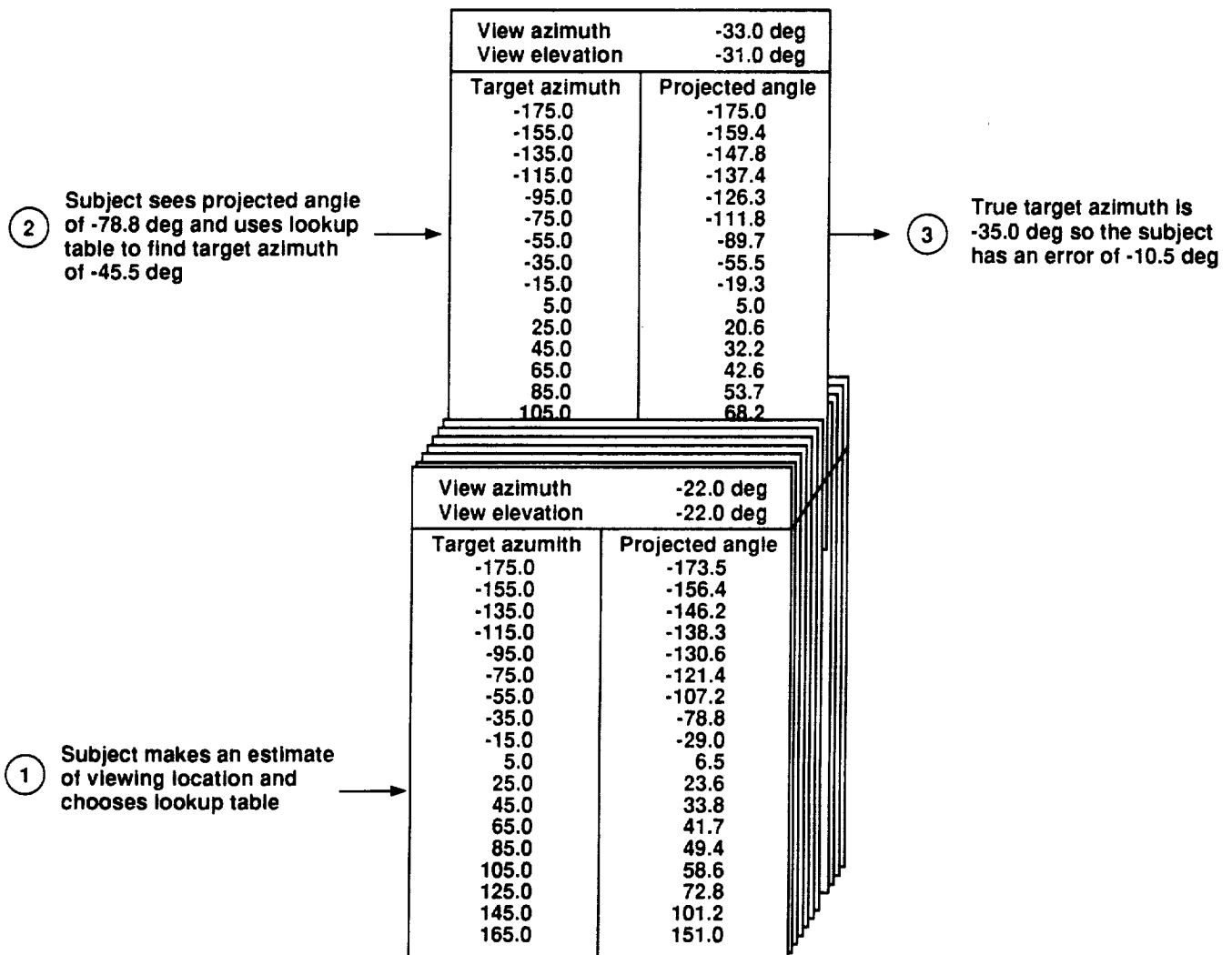


Figure 7. Use of the lookup table.

## MODEL EXPLANATION OF DATA (FIT)

### Model Reproduction of Error Pattern

Figure 9 shows the least squares fit of the model data to the baseline data. The model data is for a view yaw estimation of  $-33.0^\circ$  and a view pitch estimation of  $-31.0^\circ$ . The model parameters are found by means of a grid search technique on both view yaw and view pitch with a resolution of  $1^\circ$ . In general the fit to the data is very good; the model reproduces the cyclical pattern closely. It does not quite reproduce the peaks in the data at  $\pm 45^\circ$ , and it predicts, as this model always does, that there should be zero crossings at  $0^\circ$  and  $180^\circ$ . It does predict the bias level of the data, and the

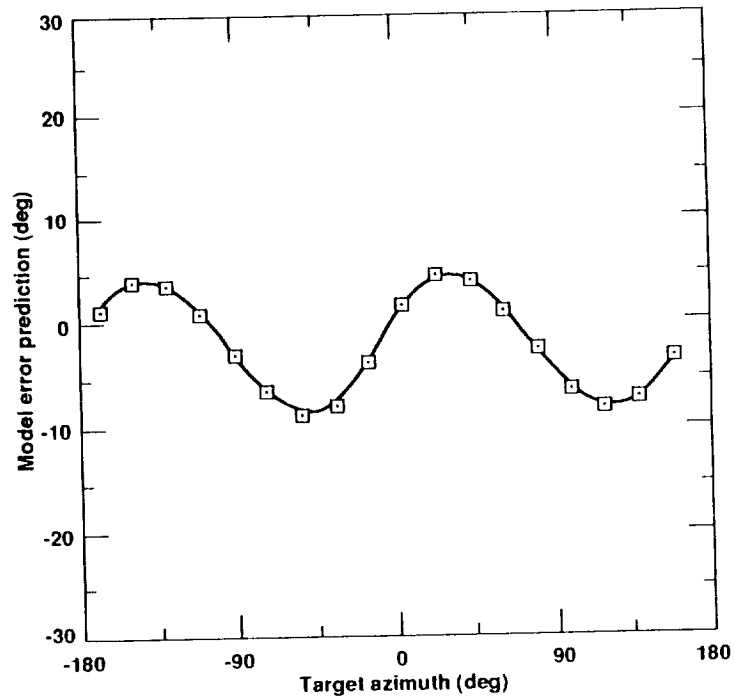


Figure 8. Model error pattern.

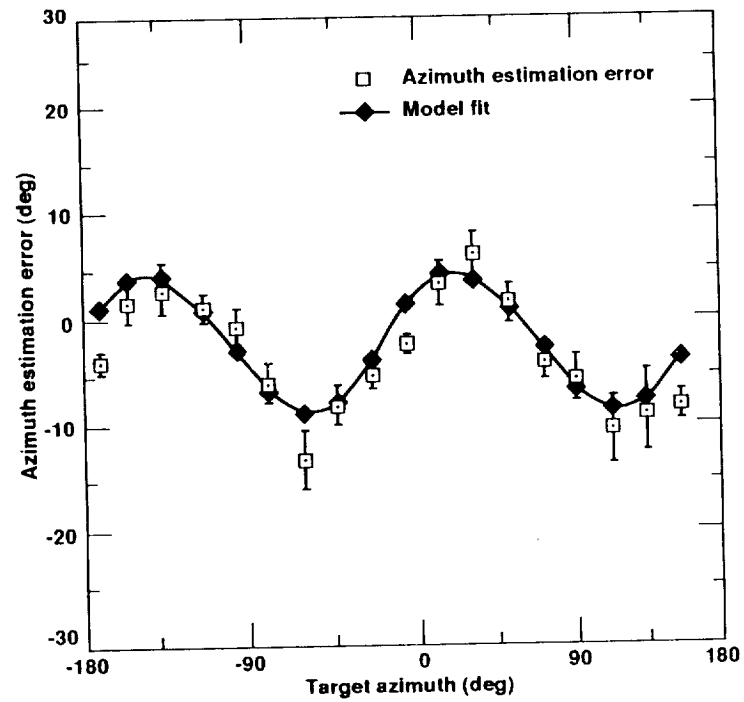


Figure 9. Model fit to mean experimental data.

misestimation of the viewpoint it finds is consistent with some earlier experiments in which subjects are asked to directly estimate their viewpoint on a similar scene (Ellis and Grunwald, 1988).

Figure 10 is a plot of the amplitude of the errors predicted by the model for both view yaw and view pitch misestimations on a scene where the true view yaw is  $-22.0^\circ$  and the true view pitch is  $-22.0^\circ$ . In general, it shows that the error amplitude increases with increasing misestimation in either parameter.

A careful examination of this figure also shows that a view yaw overestimation combined with a view pitch overestimation produces a smaller amplitude than that which would be produced with no misestimation of the view pitch. At least for small errors around the true viewing direction, if both the view yaw and the view pitch are overestimated or underestimated, then the error amplitude

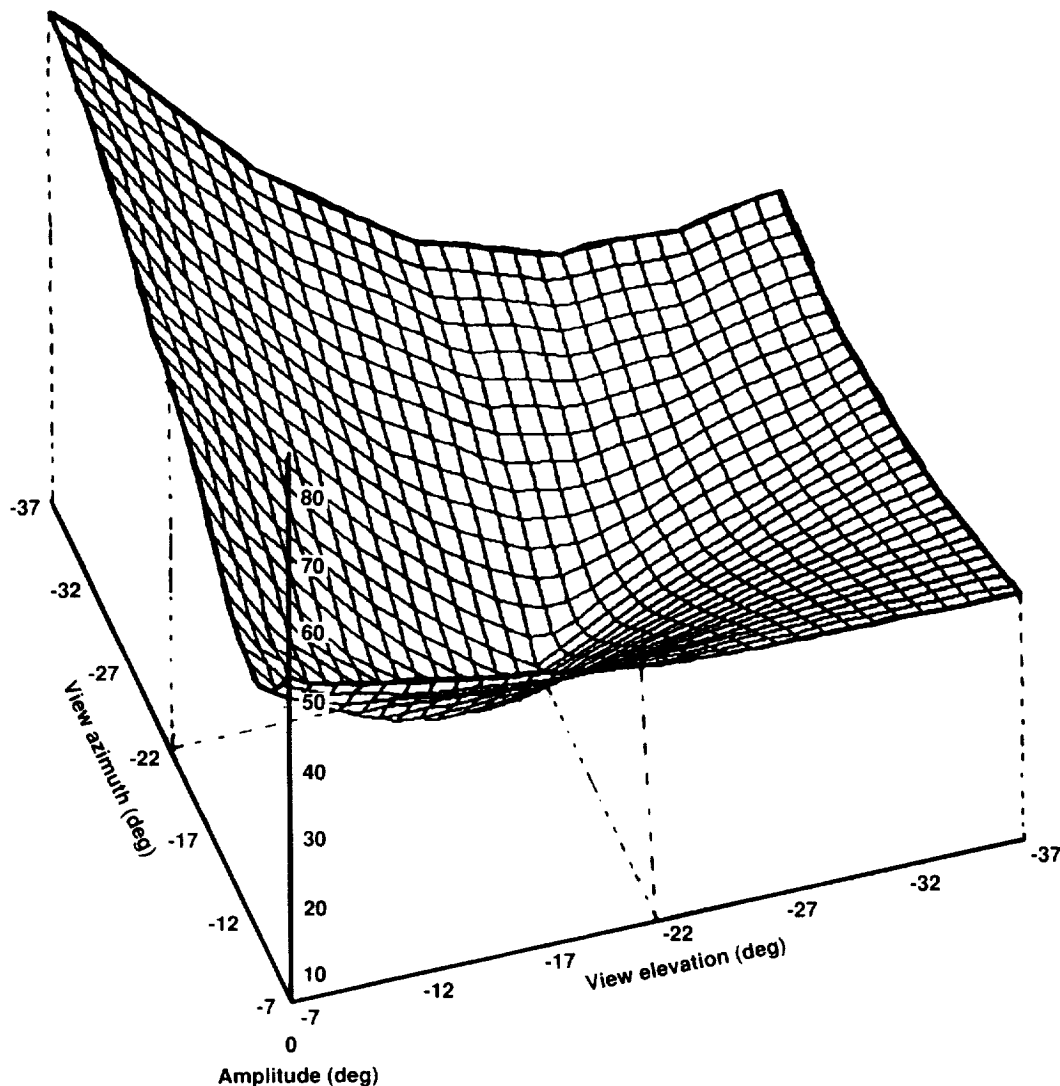


Figure 10. Model error amplitude for view yaw and pitch.

is smaller than if one is overestimated and the other is underestimated. This opposing error tendency was unexpected.

Another important characteristic of the data is the zero error crossings, those target positions for which the subjects make correct judgments. The model always predicts one crossing in the straight ahead direction, but the secondary crossing moves around in the parameter space. These shifts could be described as phase changes in the error signal, but because one crossing is pinned at  $0^\circ$  the crossing's movement is actually a combination of a phase shift and a change in the bias level. The key here is that the model predicts different zero error crossings if the subjects are using different estimations of the view location. Figure 11 shows the zero error crossings for the data and the model fits. A shift in the off-axis zero error crossings can be seen during learning, and the model predicts the crossings very well.

### Model Reproduction of Error Bias

A plot of the model error bias for view yaw and pitch is shown in figure 12. It shows that the model predicts a nonzero bias for most areas in the parameter space. As with the amplitude values, we see here an opposing contribution to the bias from view yaw and view pitch. For regions in the parameter space where both are overestimated or underestimated, the change in the bias level is small, whereas when one is overestimated and the other is underestimated, the effect on bias is large. These findings not only show that the model can reproduce the characteristics of the experimental data, but also that changes in the model parameters should produce predictable changes in the data.

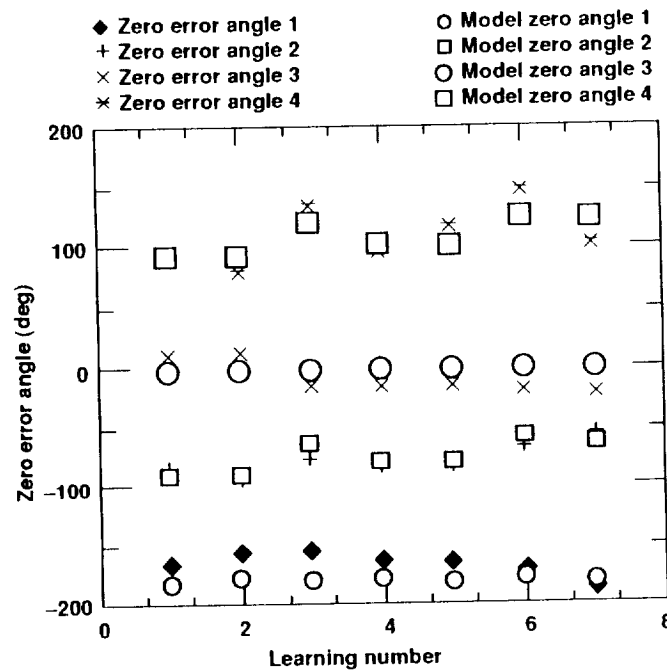


Figure 11. Zero error crossings for data and model.

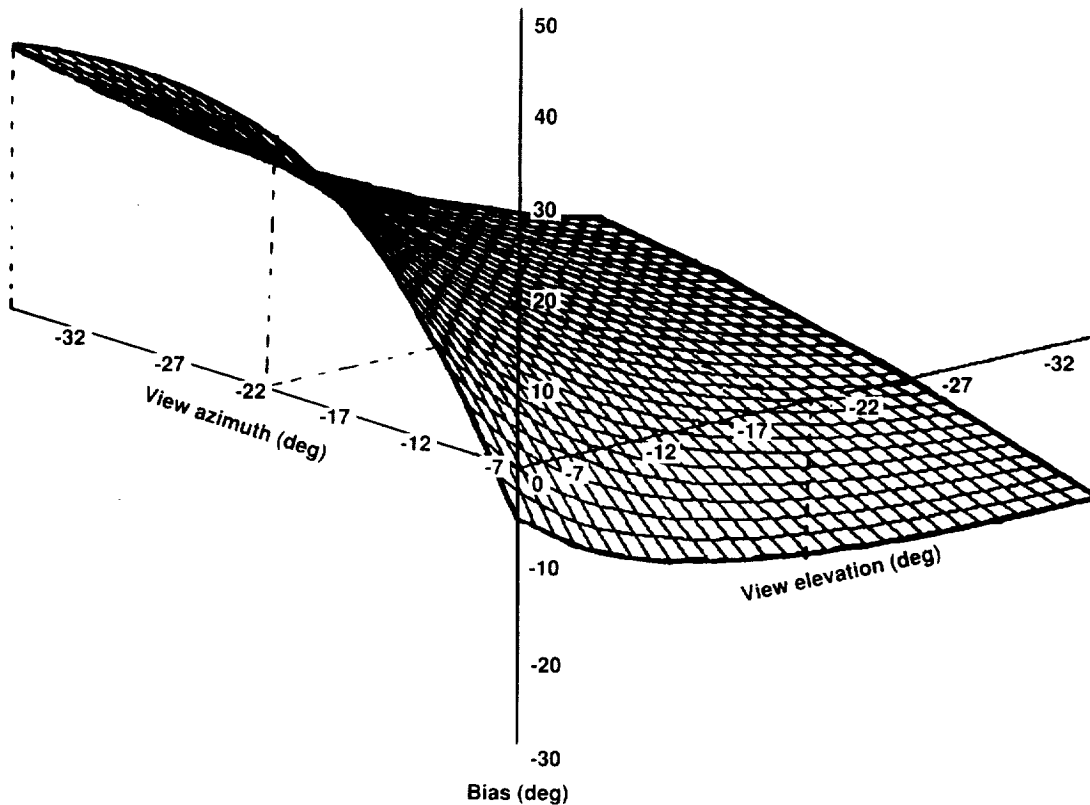


Figure 12. Model error bias for view yaw and pitch.

### Model Failure to Reproduce Peaks in the Data Plot

The model predicts a smoothly changing error pattern, with rounded peaks (fig. 9). This characteristic of the model consistently underestimates the peaks in the data around the oblique axes. The experimental data exhibit sharper peaks that suggest the presence of an effect not explained by the model.

A possible explanation for the data peaks is a transformation of the noise in the lines of site to the screen coordinates of the display. The model assumes that the subject can determine the exact screen coordinates for all of the points in the display, but a small, uniformly distributed error around the true screen coordinates in the x and y directions would produce a skewed target azimuth estimation that might explain the characteristics of the experimental data. Symmetrical errors in the picture plane produce asymmetrical errors in the 3-D space (Ellis, Smith, Grunwald, and Tyler, 1988).

### Model Description of Learning

The match of the errors predicted by the model to the errors observed in the experiment has been discussed. Here, the model's description of how the subject's errors change with the error display will be examined. The model characterizes the baseline errors as an overestimate in both view

yaw of  $-11^\circ$  and view pitch of  $-9^\circ$ . With the introduction of error display the model describes changes in these estimates.

Figure 13 shows the model fit to the data for the baseline data and for each of the runs with error display. The model provides a good fit to the data throughout the experiment with respect to the curve shape, the bias level and the zero error crossings. The model still underestimates the data peaks. Most notably, the model fits describe a behavior of changing the viewpoint estimation in the direction of a closer estimate of the true view location.

The model description of yaw overestimation during error display is illustrated in figure 14. There is a general trend of decreasing view yaw error. This corresponds to the decreasing error amplitude observed in the experiments. Notice that some of the subjects make good viewing estimates throughout the experiment but all subjects' estimates converge with the addition of error display.

The changes in view pitch error during learning are illustrated in figure 15. The trend of decreasing error with error display can again be seen. Again some of the subjects give good viewpoint estimates from the beginning whereas others need the error display. Also, notice the narrower convergence on pitch as opposed to yaw. This might be because subjects had their head position as a cue for pitch—they were looking down at the screen; they had no cue for yaw.

The model describes the reduction in error with error display as the subject's making a more accurate estimation of the viewing location of the display. Obviously, we can find a best fit to the model for any set of data; but the fact that the model not only fits the real data well, but consistently reproduces the subcomponents of the data such as amplitude, bias, and zero error crossing, justifies this interpretation of the analysis. As the subjects see their errors they modify their estimates of the viewing locations to better match the true target azimuths.

## **LEARNING MODEL**

### **Model Description**

Figure 16 is a block diagram of a possible model of the learning mechanism. It shows that subjects update the lookup table that they use as a result of seeing the errors they make using their current view location estimate.

### **Discussion of Data**

The justification for using this type of model for the learning mechanism can be seen by examining the data. First, the consistency of the model fit throughout the learning period indicates that the

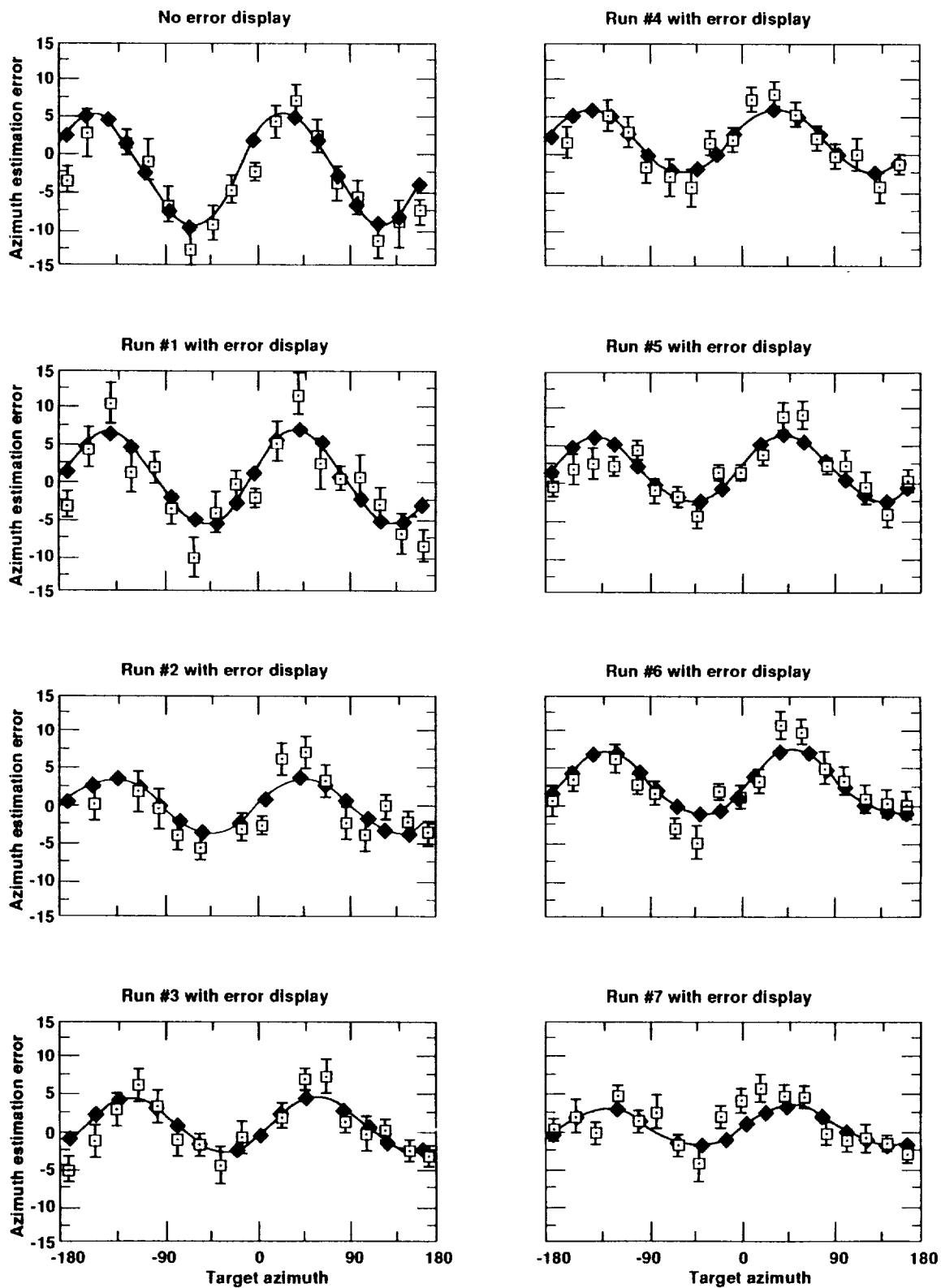


Figure 13. Model fits to the mean data during error display trials.



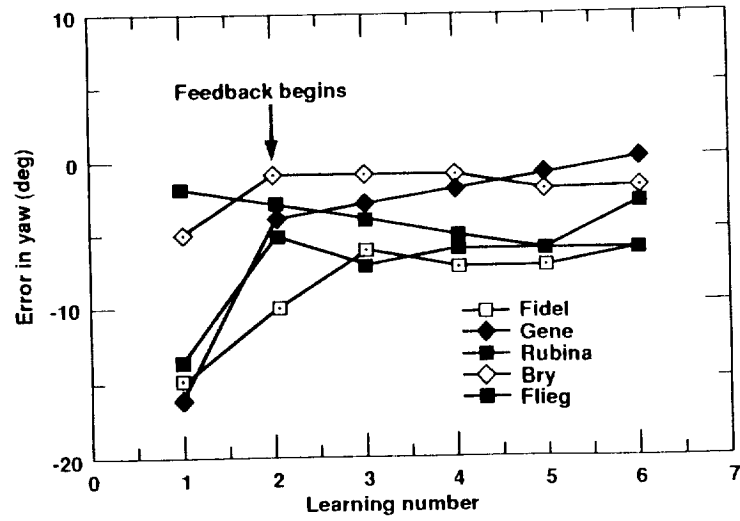


Figure 14. Model description of yaw overestimation during error display.

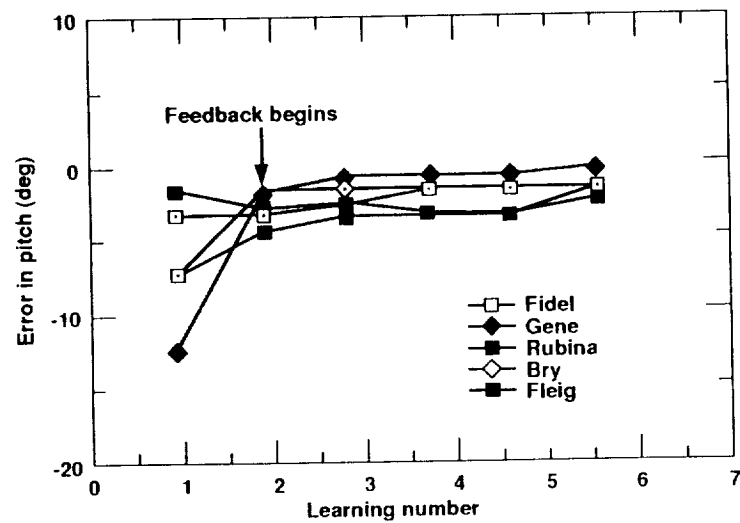


Figure 15. View pitch and error during learning.

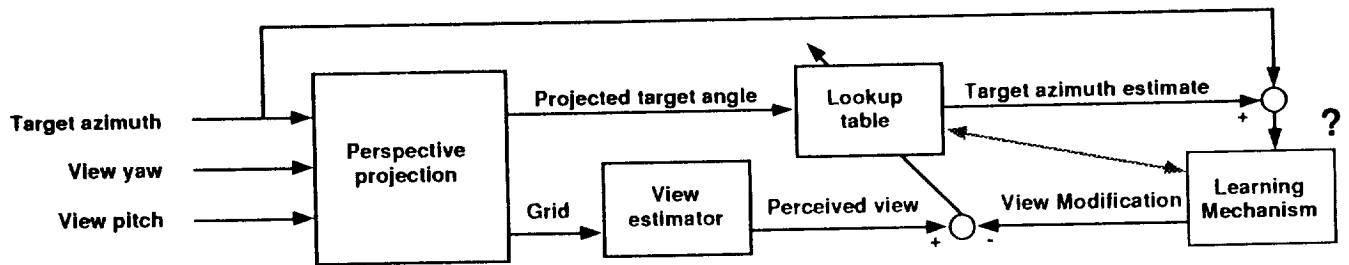


Figure 16. Learning mechanism.

viewpoint misestimation model of the error is justified and that the subjects are not abandoning the method it describes as a means of reducing their errors. The zero error crossing and the bias are two examples of agreement of the data with the model that would be absent if the subjects were using a method of correcting their errors without changing their perception of the situation.

### **Possible Tests of Model**

One clear way to test this learning model would be to ask the subjects to estimate the view yaw and pitch before, during, and after the learning period. Some experiments have been done that indicate that subjects do overestimate the view yaw and pitch, and that the magnitude of the errors is about the same as that predicted by the model. However, a changed estimate after the experiment would be strong support for the model. Another possible test is to run experiments with a changing viewpoint to see how that affects the data, and to examine how the model behaves. A final test would be to examine the pattern of generalization as defined by learning theories. If the viewing pitch and yaw are true model parameters, training on one set of target azimuths should be essentially completely transferable to another distinct set. Alternatively, if the learning were based on a case by case method and the subject were simply learning local corrections to apply to targets at various azimuths, performance on a set of target positions that had not appeared in a training set should be very poor (Atkeson, 1989).

### **FUTURE WORK**

There are two areas which need to be explored that are beyond the scope of this report.

First, the three models for the error need to be examined and compared in more detail. None of them satisfactorily explains all of the observed characteristics of the experimental data. They represent differing aspects of the same problem with different levels of complexity. It is possible that they each represent a partial explanation of the data and only need to be unified.

Second, the learning model needs to be implemented on a computer to test its reliability. A computer model would greatly aid in the development of experiments that would test the learning model's validity.

The computer model for learning and the learning experimental data itself could be used to compare the three error models.

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