

**UNITED STATES AIR FORCE  
ARMSTRONG LABORATORY**

---

**DISTANCE ESTIMATION  
WITH NIGHT VISION GOGGLES:  
A DIRECT FEEDBACK TRAINING METHOD**

Keith K. Niall

US/Canada Scientist and Engineer  
Exchange Program Participant

Jack D. Reising

HUGHES TRAINING, INC, Training Operations  
6001 South Power Road, Bldg 561  
Mesa AZ 85206-0904

Elizabeth L. Martin

Marcus H. Gregory, 1Lt, USAF

HUMAN RESOURCES DIRECTORATE  
AIRCREW TRAINING RESEARCH DIVISION  
6001 South Power Road, Bldg 558  
Mesa AZ 85206-0904

June 1997

DTIC QUALITY INSPECTED 2

19970903 124

*Approved for public release; distribution is unlimited.*

AIR FORCE MATERIEL COMMAND  
Armstrong Laboratory  
Human Resources Directorate  
7909 Lindbergh Drive  
Brooks Air Force Base TX 78235-5352

## NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This paper has been reviewed and is approved for publication.

**ELIZABETH L. MARTIN**  
Project Scientist

**DEE H. ANDREWS**  
Technical Director

**LYNN A. CARROLL, Colonel, USAF**  
Chief, Aircrew Training Research Division

Please notify AL/HRPP, 7909 Lindbergh Drive, Brooks AFB, TX 78235-5352, if your address changes, or if you no longer want to receive our technical reports. You may write or call the STINFO Office at DSN 240-3877 or commercial (210) 536-3877.

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1997	3. REPORT TYPE AND DATES COVERED Final - March 1996 to September 1996	
4. TITLE AND SUBTITLE  Distance Estimation with Night Vision Goggles: A Direct Feedback Training Method			5. FUNDING NUMBERS C - F41625-95-C-5011 PE - 62202F PR - 1123 TA - B4, B2 WU - 06, 06	
6. AUTHOR(S)  Keith K. Niall Jack D. Reising			Elizabeth L. Martin Marcus H. Gregory	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  Armstrong Laboratory Human Resources Directorate Aircrew Training Research Division 6001 South Power Road, Building 558 Mesa AZ 85206-0904			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  AL/HR-TR-1996-0148	
11. SUPPLEMENTARY NOTES  Armstrong Laboratory Principal Investigator: Dr Elizabeth L. Martin (602) 988-6561				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT ( <i>Maximum 200 words</i> ) An experimental demonstration was made of the efficacy of immediate feedback in improving observers' estimates of distance where those estimates were made outdoors at night while wearing night vision goggles (NVGs). Initially, observers made unguided estimates of distances between marked positions in an open field. Those distances ranged from 25 ft to 210 ft. Later, the same observers made more estimates. After each, they were told the measured distance between the positions. During this training, the observers' eye height from the ground plane was either at a standing position or at an elevated position (12 ft from the ground). After the training--either immediately after, or after a week, or at both times--observers made unguided estimates of distance again. These estimates of ground distance made with the NVGs were significantly improved from the first unguided estimates; average improvement for the group of observers persisted for at least one week after training. Direct feedback training appears to be more effective at improving performance at distance estimation (in terms of both precision and error variability) than the training assessed in previous experiments where no verbal feedback was given.				
14. SUBJECT TERMS Distance perception; Feedback; Knowledge of results; Linear perspective; Night vision goggles; NVGs; Training; Optical aids			15. NUMBER OF PAGES 35	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION ABSTRACT UL	

## CONTENTS

	<u>Page</u>
INTRODUCTION.....	1
METHOD.....	5
Observers.....	5
Apparatus and Stimuli.....	5
Procedure.....	7
Pretest.....	7
Training.....	7
Posttest.....	7
RESULTS.....	8
DISCUSSION.....	27
CONCLUSION.....	28
Future Research.....	28
REFERENCES.....	29

## FIGURES

<b>Figure No.</b>		<b>Page</b>
1	Mean Error in Distance Estimates: Reising & Martin (1995).....	3
2	Variability of Error in Distance Estimation: Reising & Martin (1995).....	4
3	Targets in an Open Field.....	6
4	Triangles among Targets in a Field .....	8
5	Effect of Feedback on Distance Estimates .....	11
6	Effect of Feedback on Consistency of Judgments.....	16
7	Moving Averages of Difference Scores for Individual Observers.....	17, 18
8	Moving Averages of Ratios for Individual Observers .....	19, 20
9	Distance versus Angular Subtense.....	24

## TABLES

<b>Table No.</b>		
1	Accuracy over Trials, as Assessed by Three Dependent Measures .....	10
2	Summary Table for Analysis of Variance .....	12
3	Differences of Mean Error Scores from Zero.....	14
4	Individual Differences of Mean Error Scores.....	15
5	Consistency of Distance Judgments, in Terms of Triangle Inequalities.....	15
6	Summary of Regression Analyses.....	22
7	Partial Correlation of Distance and Visual Angle with Responses.....	23

## PREFACE

This report documents the effectiveness of direct and immediate feedback at reducing errors in estimation of distance under night vision goggle (NVG) conditions. NVG-aided distance estimation was assessed at a standing position and at an elevated position (to an eye height of about 12 ft). Training was administered on the ground for some subjects and at an elevated position for other subjects. Retention of this feedback training was assessed by NVG-aided distance estimation after one week. Direct feedback is effective in reducing errors in distance estimation. Improvements in performance persisted for at least one week after training.

The work was conducted by the Armstrong Laboratory, Aircrew Training Research Division (AL/HRA), under Work Units 1123-B4-06, Night Vision Device Training Research, and 1123-B2-06, Aircrew Training Research Support. Support was provided by Hughes Training, Inc. (HTI), Training Operations, under contract F41624-95-C-5011. HTI supports AL/HRA by supplying night vision device subject matter expertise and human factors expertise in the areas of research, development, test, training, and evaluation. We would like to acknowledge Peter Froeb's patient assistance in conducting the experiment reported here.

# DISTANCE ESTIMATION WITH NIGHT VISION GOGGLES: A DIRECT FEEDBACK TRAINING METHOD

## INTRODUCTION

Night vision goggles (NVGs) are used in both rotary-wing and fixed-wing aircraft to enhance the ability to conduct operations under cover of darkness. NVGs provide an intensified image of landscapes illuminated by ambient energy in the night environment; specifically, the photosensitive components of the goggles are most sensitive to the red and near-infrared portion of the electromagnetic spectrum (approx. 600-900 nanometers). The NVG device amplifies the energy in this portion of the spectrum: Luminance of the post-objective image can be between 2,000 to 7,000 times that of an image that enters the goggles. As a consequence of their design, most NVGs affect field of view (FOV) and resolution as well. Depending on their make and type, they provide a limited FOV of approximately 40 deg of visual angle; visual acuity can be expected to be approximately 20/30 Snellen acuity at best, under optimal lighting conditions.

Since NVGs have a restricted field of view and a diminished resolving power when compared to the capability of the unaided human eye in daylight, we can anticipate that NVG users unaccustomed to these altered viewing conditions may experience misperceptions or illusions. Numerous field reports suggest that NVG viewing does induce misperceptions that compromise flight safety, including difficulty in judging ground distances or the separation of objects. Foyle and Kaiser (1991) reported that NVG-aided distance estimation is significantly poorer than unaided distance estimation on the ground in daylight. Crowley (1990) tasked helicopter pilots to maintain a set altitude under NVG or unaided daylight conditions. Pilots made significantly more errors in the former than in the latter condition. The misperception of distance with NVGs was attributed to limits on resolution rather than to limits on the field of view. By contrast, DeLucia and Task (1995, p. 383) find "effects of NVGs (compared to unaided vision) did not occur in the field when participants judged when to initiate a turn to maneuver a car in front of a wall without collision." In addition, there may be important differences between judgments with NVGs made on the ground and those made in the air.

The present experiment is one of a series conducted under NVG conditions, to determine how distance estimation can be improved with structured training. The earlier studies are reported by Reising and Martin (1994, 1995); they employed a training procedure known as "perceptual calibration." Observers saw targets at distances known to them (i.e., "this is what a hundred feet looks like on the ground"), and the observers were instructed to "calibrate their eyes" to those distances. The procedure has some affinity to the way pilots report they learn to gauge altitude by sight. Pilots will view the out-the-window scene, then check a distance-rendering instrument--such as a radar altimeter--to put a number to the aircraft's altitude. They will then view the target from another distance and check the instrument again. It is this cycle of observation and instrument reading that has become known as perceptual calibration.

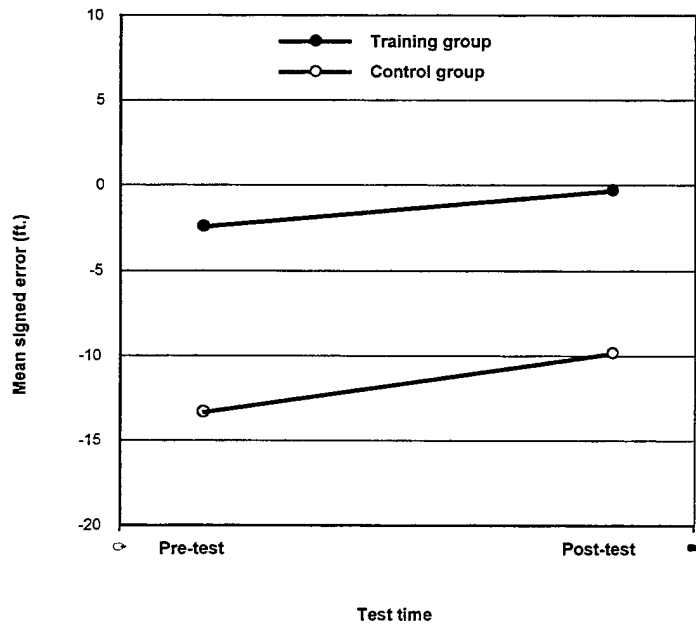
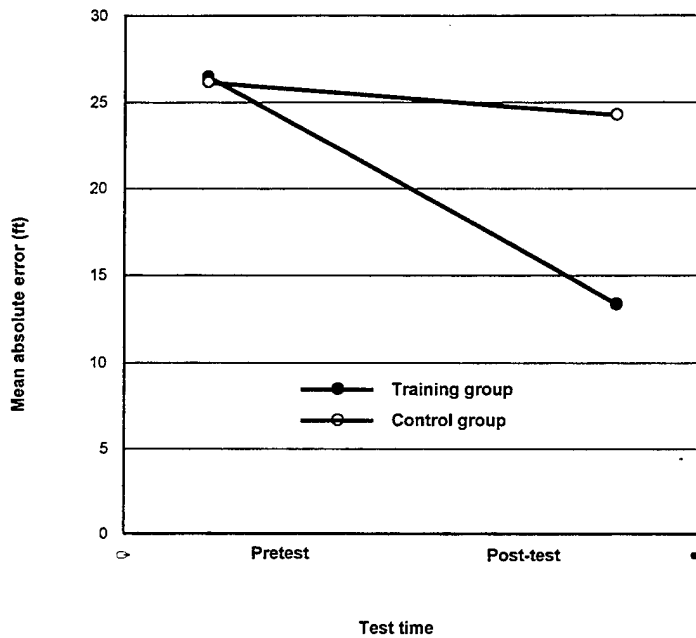
In Reising and Martin's experiments, observers were able to read distance markers placed next to targets. These markers indicated the distance between the target and the observer's position (the egocentric distance of the target). The observers were also informed of the unmarked distances

between a pair of targets (called exocentric distance). Reising and Martin (1995) concluded that absolute error in distance estimation was significantly lower on average for a group that had undergone "perceptual calibration" than for a control group. A review of the data revealed no significant improvement in NVG-aided distance estimation when signed error was the dependent variable of the analysis, rather than absolute error in distance (See Fig. 1).

Using signed error in distance as the dependent measure, there was a significant and substantive difference between groups in the pretest condition. The treatment group had an initial advantage. The mean magnitude of this difference between groups was unchanged at posttest, though both groups' estimates improved slightly. Then the two groups appeared as different in amount of improvement, because the variability of errors in the treatment group was reduced between pretest and posttest (Fig. 2). The change in variability is just as well represented by inspection of the variability of the signed errors. When absolute errors are computed, there is an interaction between test means and group means. That interaction was interpreted as an improvement in mean performance for the treatment group over the control group. The interaction is the result of a difference in the variability of error scores, which can be noticed in the variability of the signed scores. The use of absolute values confounds mean tendency and changes in variability. The appearance of an interaction in mean tendency for the absolute scores is an artifact due to the copresence of two factors: (a) a pre-existing difference between treatment and control groups, and (b) the posttest scores of the treatment group centered about zero. The use of signed error may be termed a wider interpretation in the choice of a dependent measure and the use of absolute error may be termed a narrower interpretation, in the sense that signed error includes information that is omitted in absolute error. The narrower interpretation forestalls one possible conclusion from a set of results: It prevents the conclusion that there is accurate performance in the presence of variation about the mean. Questions persist of the best dependent measure, and of the efficacy of perceptual calibration techniques in improving distance estimates. These questions are not specific to the study at hand. For example, root mean square (RMS) measures are commonly applied to gauge deviation from flight paths. (As for the dependent measure, it may be that some other measure--such as the ratio of estimated distance to ground distance--is better than the difference of estimated distance and ground distance.)

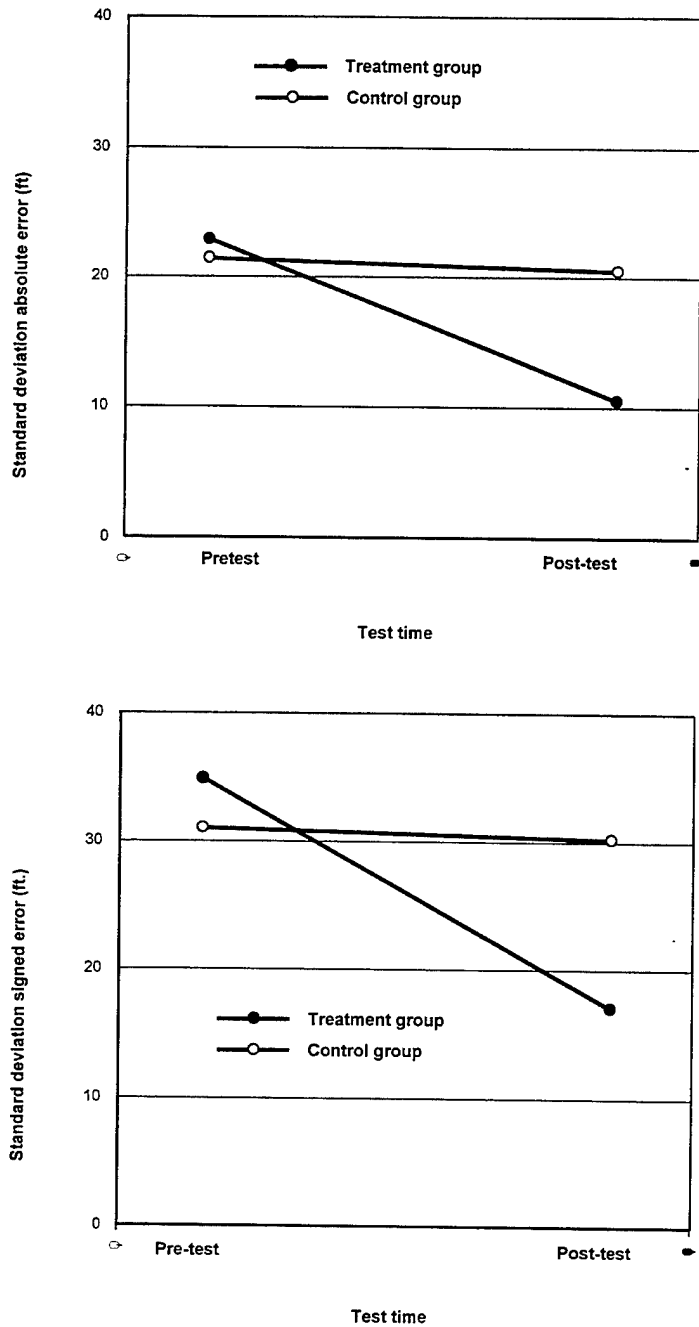
The present experiment was conducted to determine the efficacy of a slightly different kind of training for NVG-aided distance estimation, one of the most effective feedback techniques in general: immediate and direct feedback. This has been shown to be an effective technique in outdoor viewing without the use of NVGs, as in Gibson and Bergman (1954), and Gibson, Bergman, and Purdy (1955). Direct feedback training occurs when observers are required to make an explicit estimate of distance, and they are informed of the true ground distance immediately after making their judgment.

Many issues relevant to training have not been addressed, including effects specific to illumination levels and transfer of training, say from ground training to distance estimates made from the air. It may be that pilots need to be trained before every mission to account for differences in the perceived NVG scene that vary with operational conditions. Or, NVG-aided distance estimation training may need to occur only under low illumination conditions and may transfer to high illumination conditions. Furthermore, training may persist for an extended duration, requiring



**Figure 1. Mean Error in Distance Estimates: Reising & Martin (1995)**

Mean error in distance estimates is plotted for Reising and Martin's (1995) experiment. The upper graph plots mean absolute values of the difference between estimated distance and ground distance. The lower graph plots mean values of the difference between estimated distance and ground distance, but preserves the sign of the difference. These values are graphed by condition of test (pretest, posttest) and group (treatment or control). When the sign of the error in estimate is taken into account, the interpretation of mean differences in the experiment is altered. The mean absolute values are: (treatment pretest: 26.5 ft), (treatment posttest: 13.4 ft), (control pretest: 26.2 ft), (control, posttest: 24.3 ft). The mean signed values are: (treatment pretest: -2.4 ft), (treatment posttest: -0.3 ft), (control pretest: -13.3 ft), (control, posttest: -9.8 ft).



**Figure 2. Variability of Error in Distance Estimation: Reising & Martin (1995)**

Variability of error in distance estimates is plotted for conditions of Reising and Martin's (1995) experiment. The upper graph plots the standard deviation in absolute values of the difference between estimated distance and ground distance. The lower graph plots the standard deviation in values of the difference between estimated distance and ground distance, but preserves the sign of the difference. These values are graphed by condition of test (pretest, posttest) and group (treatment or control).

only intermittent recurrent training. This experiment assesses whether distance estimation performance can be improved, and whether improvement persists for at least one week after training. Observers in the experiment view a number of distances both from standing and from elevated vantage points. This is done in order for the experimental analysis to distinguish between the effects of visual angle and distance on judgments of distance.

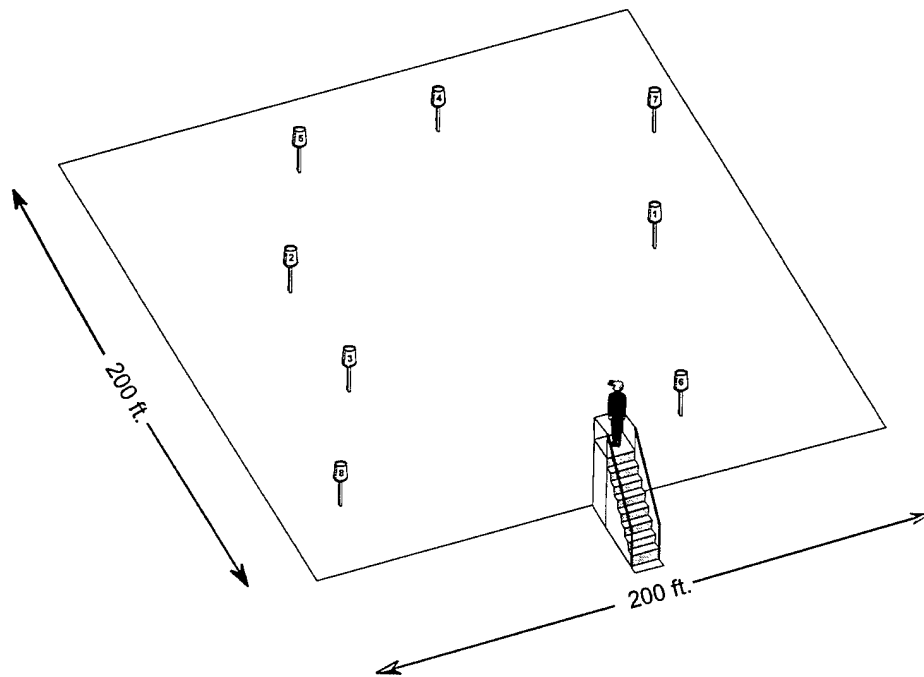
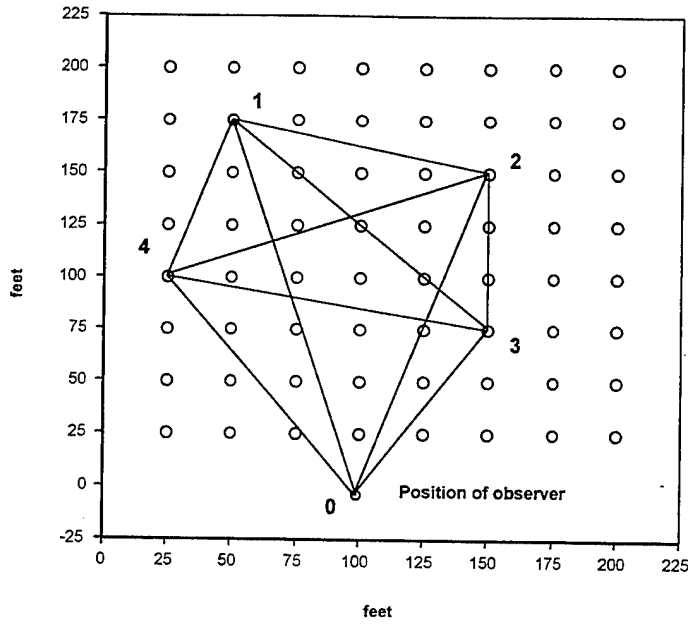
## METHOD

### Observers

Twelve observers (9 male and 3 female) volunteered for the experiment. All observers had at least 20/20 photopic visual acuity and received specific training on F4949 NVG adjustment procedures (as described by Antonio & Berkley, 1993). Ages ranged from 21 to 40 years, with a mean of 33.6 years. None of the observers had previous experience with NVGs. All demonstrated at least 20/30 NVG-aided visual acuity after NVG adjustment as measured with a Hoffman Engineering ANV-20/20 NVD Infinity Focus System.

### Apparatus and Stimuli

The experiment was conducted in a large open field. A few trees were visible about 300 yd beyond the test area. Some cultural lights were visible in the far distance; none were located within 3 mi of the direction of gaze of the test area, and most were more than 15 mi away. The area was divided into a 175 x 175 ft square grid, marked off in 25 ft increments. The markings that defined these increments were not visible through NVGs, but they were retained for the purpose of arranging the stimuli. At any one time, eight targets were randomly positioned in 8 of 64 distinct locations defined by the 25 ft increments of the grid (Fig. 3a). The targets consisted of white cylinders that were approximately 2 ft high and 1 ft in diameter. Each cylinder was raised on a pole approximately 2 ft high. Observers viewed the targets 25 ft away from the midpoint of one edge of the square. Observers viewed the targets both from the ground and elevated on a platform that could be reached by stairs. (See Fig. 3b. The platform was a standard B-1 stand used for aircraft maintenance.) The stand raised the observers 7 ft 7 in. 1 off the ground, from the base of the wheels to the floor of the platform. All testing was conducted under clear starlight conditions, though the presence of cultural lights increased ambient illumination. NVIS radiance (as defined in Military Specification, MIL-L-85762A, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible), measured from the targets was  $3.62 \times 10^{-9}$  NR<sub>A</sub>, which is approximately equivalent to a quarter moon. The radiance was measured with a Hoffman Engineering NVG-103 Inspection Scope. The NVG used was a Class A ITT F4949D (S/N 2590).



**Figure 3. Targets in an Open Field**

The experiment was conducted in an open field. Targets could be positioned in one of 64 locations; though eight targets were present in the field at once, only four of these were used at one time. The positions of the four targets (1, 2, 3, and 4) plus the position of the observer (marked 0) define ten distances among locations. Observers were asked to estimate each of these distances. The arrangement of the targets was determined in advance by random assortment. A less schematic overview is included as well, to clarify the relation of the observer to the ground plane.

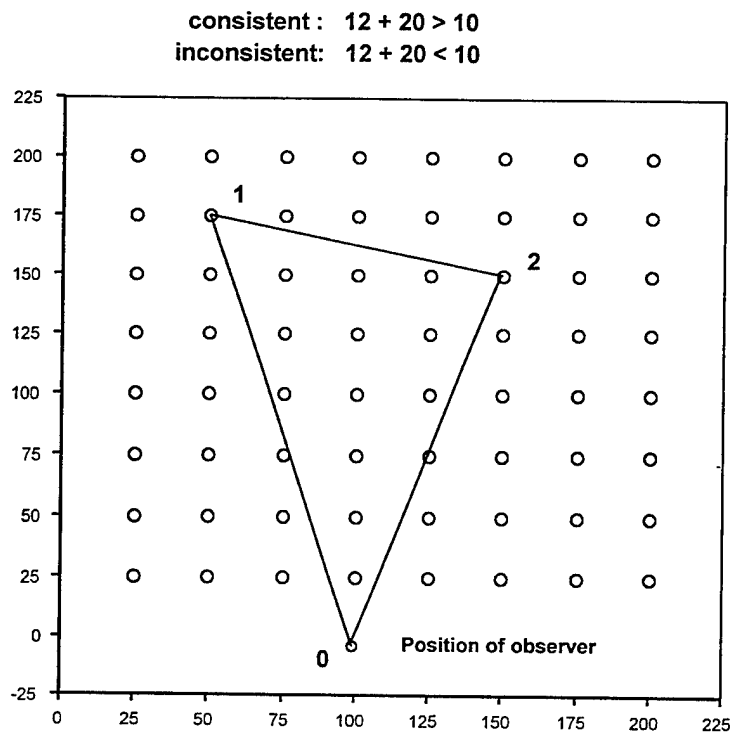
## Procedure

**Pretest.** This part of the procedure assessed the accuracy of observers' distance estimates in the absence of formal training; the data from this portion of the experiment serve as a baseline for assessing the impact of the training procedure. The observers first adjusted the NVGs using the infinity focus system. They were then either positioned on the ground (immediately under the stand) or elevated on top of the stand. Four of the eight targets were used for distance judgments at one time. All targets were readily distinguished (under NVG viewing conditions) by labels on which large black numbers were printed. Observation position (ground or elevated) was manipulated.

The observers were required to judge all distances between four targets (six distances) as well as the ground distances of each of the four targets to their own position (four distances). The targets were configured in the field in a pre-defined random arrangement, among 64 possible positions. The observer made ten judgments of the distances of these targets from one another, that is, of a group of four targets (of the eight present in the field). The observer also made judgments of the distances of each of these targets from her or his own position (cf. Figs. 3 and 4). For example, if the targets are  $\{1,2,3,4\}$  and the observer's position is  $\{0\}$ , then the pairs that define the distances to be judged are:  $\{1,2; 1,3; 1,4; 1,0; 2,3; 2,4; 2,0; 3,4; 3,0; 4,0\}$ . The observer made these judgments from one of two positions, either STANDING at the edge of the field, or ELEVATED on a stand, so that the eye height of the observer was raised 7 ft 7 in. The starting position of the observers was counterbalanced. The order in which these distances were judged was randomized, and dictated by the experimenter. After judging ten distances, subjects were repositioned (to the ground or else elevated on the platform, depending upon their starting location), and asked to judge another ten distances on the second four targets. The observers' verbal estimates of distance were recorded by the experimenter. Observers were not given a specific time limit in which to make their estimates.

**Training.** After pretesting, observers were given training. Half the observers were trained on the ground only and the other half were trained on the stand only. Two target sets were used for training. The first target set was the same eight targets used during the pretest. Observers were asked to estimate twenty distances, and the experimenter provided verbal feedback. The actual distance was provided verbally by way of feedback immediately after each estimate was made. After the first target set (20 distances) was estimated and corrected, the target positions were reconfigured, and 20 more distances were estimated and corrected. This training lasted for approximately 15 to 20 minutes.

**Posttest.** After training, a posttest was administered. A new target set was used, and the posttest procedure was the same as the pretest--no feedback was administered. Each observer was assigned to one of three groups, and each group included four observers. The groups differed in the posttest conditions. Posttests occurred either immediately after the second training period, or one week after training. One group received the immediate posttest only, another group received only the posttest after one week, and a third group received both the immediate and one-week posttest.



**Figure 4. Triangles Among Targets in a Field**

The positions of three targets (or two targets and the position of the observer) define a triangle on the ground. Judgments on the sides of this triangle can be compared for their consistency, in terms of the triangle inequality. The three judgments (that represent the three sides of the triangle) are inconsistent if the two shorter estimates of the three estimates do not sum to more than the third estimate. Four targets and the observer's position define ten triangles on the ground. We can count the number of times that triads of judgments violate the assumption that the sum of two shorter distances are greater than the longer distance, among judgments of distance on those triangles. This count (between zero and ten) is taken to indicate the geometric consistency of an observer's judgments on a trial.

## RESULTS

The results of the experiment can be stated simply: Training improves performance under NVG viewing conditions, and that improvement persists for at least one week. Observers learn to estimate distances quickly with NVG devices under the illumination conditions of the experiment. Though their verbal estimates of distance have an initial bias of underestimation, and though their estimates have small but persistent differences, observers soon learn to estimate distance accurately when given direct feedback. As a reflection of that accuracy, the geometric consistency of observers' estimates also increases with feedback. These improvements in consistency and accuracy transfer to unguided performance, both immediately after training, and

after a delay of one week. Observers' estimates of distance parallel actual distance, not visual angle or its tangent function. There is a small (in terms of feet estimated) but robust effect that may be attributed to the difference between "egocentric" and "exocentric" distance. Such effects may best be explained by the influence of foreshortening rather than the product of some psychological mechanism for the estimation of distance. The results of this experiment are consonant with the view that foreshortening is not a cue for the estimation of distance; it is the aggregate effect of perspective which impedes the estimation of distance.

Observers underestimated distances by 20 ft on average before training, while performance did not differ significantly from perfect performance (in mean value, with some variability) either during training or during posttests. Observers estimated distances accurately in the first feedback trial. ("Estimate" will be used to designate a single response, while "trial" will be used to designate a group of responses by an observer in one portion of the experiment. The trials are counted as follows: 1. unguided pretest; 2. first feedback trial; 3. second feedback trial; 4. immediate posttest; and 5. delayed posttest.) There are several ways to measure this performance (Table 1). One is to take the signed difference of the verbal estimate from the actual distance; another is to take the ratio of the verbal estimate to the actual distance. Both measures follow the same pattern across trials (Fig. 5). The absolute value of the difference between estimated distance and actual distance does not show the trend as clearly, because variations about zero have the same effect on this measure as a consistent bias (a consistent overestimate or underestimate).

An analysis of variance (ANOVA) can be applied to the results, ignoring one condition. One may question if performance changed from the pretest condition to the first posttest condition. (One group of subjects received two posttest conditions; we set aside their second posttest for the purposes of this single analysis.) There are various ways to ask this question, corresponding to different dependent measures. Let us consider the log ratio of the estimated and actual distances. This measure is not susceptible to the effects of skew in observations, as are the signed difference of the estimated and actual distances, or the absolute value of that difference. One observer failed to make one judgment: A mean value for the condition was substituted for this missing datum. Then we can perform a three-way repeated measures ANOVA on the data for all twelve observers, to ask three main questions: (1) Is there a difference between pretest and first posttest conditions on the dependent measure?, (2) Is there a difference between estimates taken at a standing position and estimates taken at an elevated position?, and (3) Is there a difference between distances from the observer to a target and distances between two targets, that is, between egocentric and exocentric distances? Call the factors that correspond to these questions **Test**, **Position**, and **Distance Type**, respectively. Of course, the possibilities of interaction between these factors are also evaluated in the ANOVA. (The summary of this ANOVA is listed as Table 2.) The statistics associated with two of the main effects are significant in this analysis: the effect of **Test**  $F(1,11) = 10.21$ ,  $p \leq .01$  and the effect of **Distance Type**  $F(1,11) = 55.35$ ,  $p \leq .01$ . None of the other effects is significant. This indicates that scores changed between pretest and posttest, and scores were different for egocentric distances than for exocentric distances. What this leaves unsaid is whether these changes are improvements. An improvement occurs when the observer's estimate and the actual distance become similar, that is,

**Table 1. Accuracy Over Trials, as Assessed by Three Dependent Measures**

Accuracy of performance in the experiment can be assessed in several ways. Here, mean accuracy across trials is tabled in terms of the signed difference of estimated distance minus actual distance, the ratio of estimated distance to actual distance, and the absolute value of the difference between estimated distance versus actual distance. Generally, performance improves between the first trial and the second, and observers make precise estimates of distance in Trials 2 through 5 on average. The third dependent variable--the absolute value of the difference between estimated distance and actual distance--shows the trend less clearly, because variations of the measure about zero have the same effect on the measure as a constant bias, i.e., as a consistent overestimate or underestimate.

---

Dependent measure (ft)			
Trial	<u>Estimated - Actual</u>	s.e.	n
1	-19	3	240
2	-2	2	239
3	-1	2	240
4	-1	2	160
5	-1	2	160

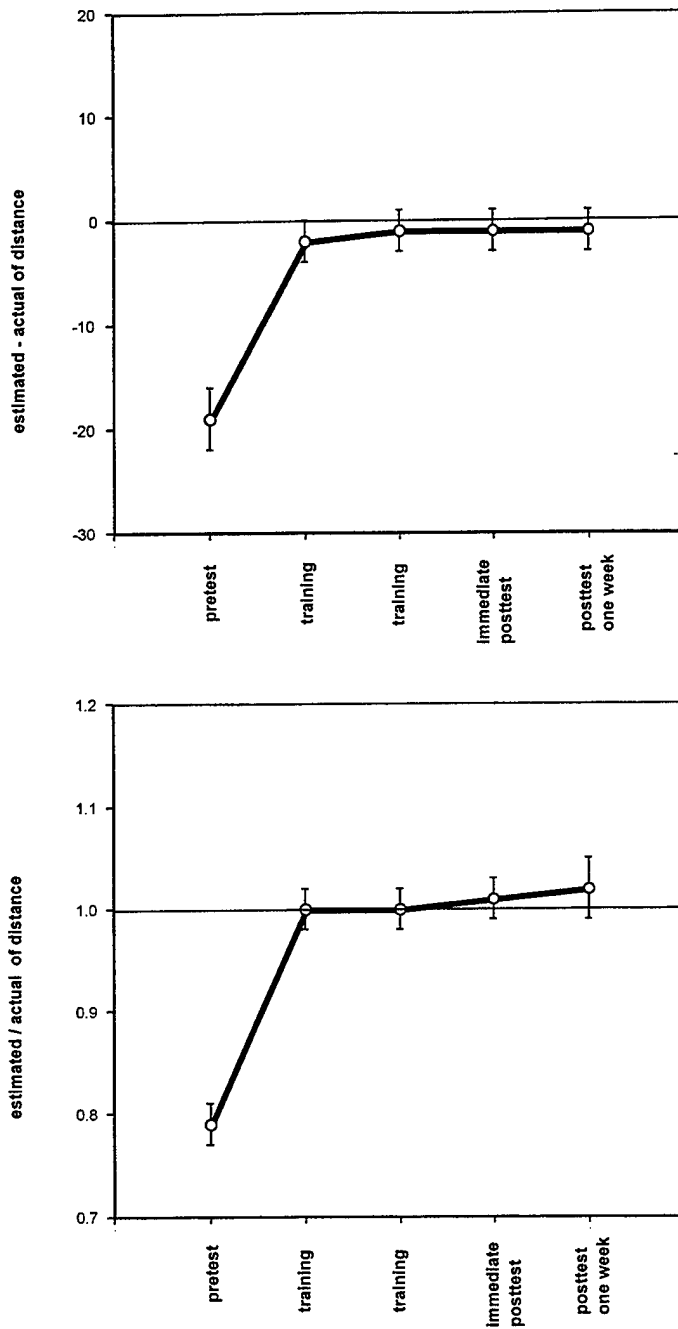
  

Trial	<u>Estimated / Actual</u>	s.e.	n
1	0.79	0.02	240
2	1.00	0.02	239
3	1.00	0.02	240
4	1.01	0.02	160
5	1.02	0.03	160

Trial	<u>Abs (Estimated - Actual)</u>	s.e.	n
1	39	2	240
2	21	1	239
3	18	1	240
4	23	1	160
5	26	2	160

---



**Figure 5. Effect of Feedback on Distance Estimates**

Training with feedback improves distance estimates. Mean errors are plotted by successive trials in the experiment (i.e., pretest, first training trial, second training trial, immediate posttest, and posttest at one week). The signed difference of distance estimates from ground distance is plotted, and the ratio of distance estimates to ground distance is plotted separately. Standard error bars are shown. Means for the first three trials (pretest, first training trial, second training trial) are based on 240 observations, while means for the latter two trials (posttests) are based on 160 observations. The dashed line in each graph indicates ideal performance on the measure.

**Table 2. Summary Table for Analysis of Variance**Dependent measure:  $\ln(\text{estimated distance}) - \ln(\text{actual distance})$ 

Source	df	SS	F statistic	
<i>Test (pretest/posttest)</i>	1	11.90	10.21	$p \leq .01$
<i>Test X Subjects</i>	11	12.82		
<i>Position (ground/elevated)</i>	1	0.09	0.92	nonsignificant
<i>Position X Subjects</i>	11	1.13		
<i>Test X Position</i>	1	0.08	1.15	nonsignificant
<i>Test X Position X Subjects</i>	11	0.80		
<i>Distance Type (egocentric/exocentric)</i>	1	5.96	55.35	$p \leq .01$
<i>Distance Type X Subjects</i>	11	1.18		
<i>Test X Distance Type</i>	1	0.03	0.67	nonsignificant
<i>Test X Distance Type X Subjects</i>	11	0.63		
<i>Position X Distance Type</i>	1	0.01	0.12	nonsignificant
<i>Position X Distance Type X Subjects</i>	11	0.98		
<i>Test X Position X Distance Type</i>	1	0.03	0.56	nonsignificant
<i>Test X Position X Distance Type X Subjects</i>	11	0.65		

when the difference between the estimated and actual distances approaches zero (when their log ratio approaches one). Do the difference scores in these conditions depart from zero (rather than simply being different one from another)? Table 3 makes these comparisons explicit. While pretest scores are different from zero in terms of the signed difference of distances, posttest scores are not significantly different from zero. Error scores for egocentric distances are also farther from zero than are error scores for exocentric distances overall.

Individual differences do persist: In terms of the difference between estimated distance and actual distance, there was either consistent overestimation or underestimation of distances by several observers. That is, observers differ in their ability to judge distance, despite training. Reising and Martin (1995) found that "subjects still vary as much as 6 ft on the critical distances (40 - 60 ft) after training." With regard to the present experiment, individual differences between mean pretest scores and mean posttest scores are listed in Table 4. The source of these individual differences has not been explored; such differences have been attributed to differences of lens accommodation and convergence of the eyes (e.g., Bourdy, Cottin, and Monot, 1991), but that kind of speculation goes well beyond the evidence of the experiment.

Observers became more consistent in their judgments of distance as they became more accurate. Each trial consisted of many judgments of distance. Some of these distances were connected in triangles (compare Fig. 4). Two groups of ten triangles could be formed from the distances presented in each of the five trials. For each of these triangles, it can be asked if the observers' judgments were consistent. The three judgments (that represent the three sides of the triangle) are inconsistent if the two shorter estimates do not sum to more than the third estimate. The number of times that the two shorter estimates do sum to more than the third can be taken as a measure of consistency of the observers' judgments. (The measure is tallied in Table 5.) In the experiment, distances among four targets and the distances of those targets to the observer define ten distances. Because all the targets are joined by distances, the four targets also define ten triangles. If the targets are  $\{1,2,3,4\}$  and the observer's position is  $\{0\}$ , then the triads of distances define ten triangles:  $\{1,2,3; 1,2,4; 1,2,0; 1,3,4; 1,3,0; 1,4,0; 2,3,4; 2,3,0; 2,4,0; 3,4,0\}$ . During the pretest the observers' estimates were not consistent (only 55% of triads qualified), but their consistency improved with feedback (to 79% of triads, Fig. 6). Computation of this measure is a way of tallying the geometric consistency of responses; the existence of changes in the measure does not imply that observers used any particular method to improve the consistency of their judgments, such as learning to triangulate distances.

Time-series plots can be made of the data to illustrate the training effect of immediate feedback for each observer. Each observer makes 20 judgments of distance on each trial. A 21-point moving average was taken across all estimates for each observer, and these are displayed in Figures 7 and 8. Performance becomes accurate with feedback and drifts from accuracy with time, though the performance of most observers is better on average at the end of the experiment than in the beginning.

**Table 3. Differences of Mean Error Scores from Zero**

Dependent measure: (estimated distance - actual distance)

<b>Pretest</b>	mean: -19.30	s.d.: 46.43	n: 240	t statistic: -6.44	$p \leq 0.001$
<b>Posttest</b>	mean: 0.01	s.d.: 29.94	n: 240	t statistic: 0.00	nonsignificant

Dependent measure: (estimated distance - actual distance)

<b>Egocentric</b>	mean: -22.91	s.d.: 39.75	n: 192	t statistic: -7.98	$p \leq 0.001$
<b>Exocentric</b>	mean: -0.80	s.d.: 38.09	n: 288	t statistic: -0.35	nonsignificant

Dependent measure: Ln ( estimated distance / actual distance )

<b>Pretest</b>	mean: 0.33	s.d.: 0.45	n: 240	t statistic: -11.48	$p \leq 0.001$
<b>Posttest</b>	mean: -0.01	s.d.: 0.29	n: 240	t statistic: -0.84	nonsignificant

Dependent measure: Ln ( estimated distance / actual distance )

<b>Egocentric</b>	mean: -0.31	s.d.: 0.39	n: 192	t statistic: -11.10	$p \leq 0.001$
<b>Exocentric</b>	mean: -0.08	s.d.: 0.40	n: 288	t statistic: -3.50	$p \leq 0.001$

**Table 4. Individual Differences of Mean Error Scores**

The effect of feedback on distance estimates varies from observer to observer. Here mean differences in estimate are tabled for the pretest condition (before feedback), for immediate testing after feedback, and for testing a week after feedback. One tabled score is the mean of twenty scores, each the difference between an estimated distance and an actual distance. Most observers improve markedly in performance.

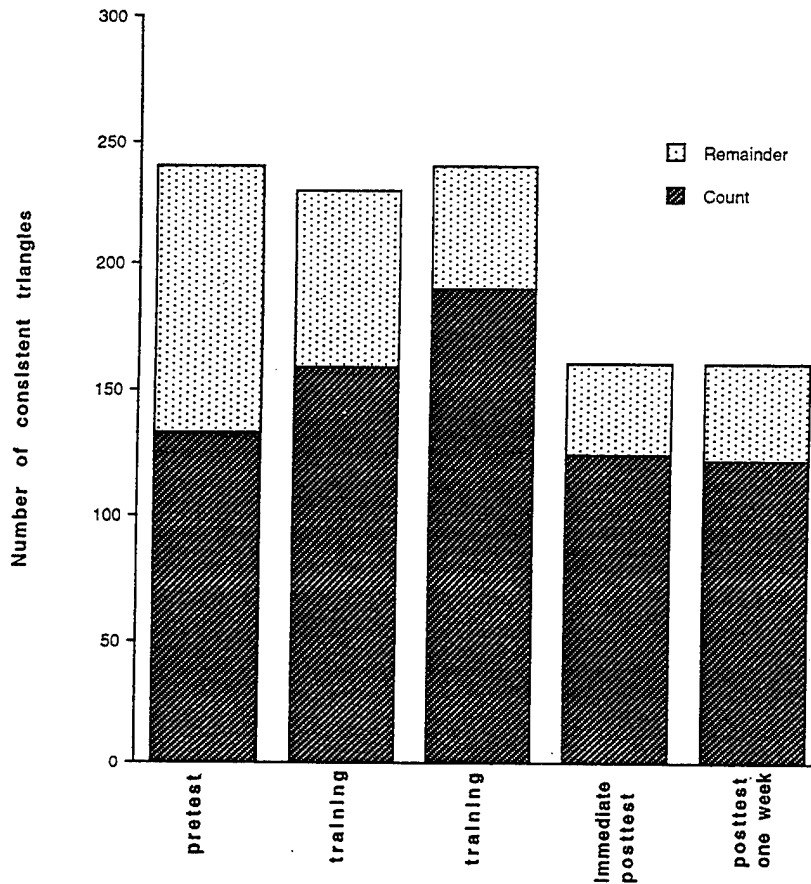
Observer	Pretest	Immediate	One week
1	-50.6	*	-4.2
2	-58.1	-13.2	*
3	-19.4	30.9	33.6
4	42.3	*	27.0
5	-23.4	2.3	*
6	11.7	-0.4	-3.7
7	-6.7	*	-5.5
8	-45.3	19.8	*
9	-18.3	-24.3	-28.1
10	-48.4	*	-7.9
11	32.7	-0.3	*
12	-48.0	-23.9	-26.2

**Table 5. Consistency of Distance Judgments in Terms of Triangle Inequalities**

A measure of consistency of distance judgments is tabled for trials of the experiments. Observers made 20 judgments of distance on each trial (i.e., two sets of ten judgments). The distances formed connected figures, so an observer might judge the distance between points 1 and 2, later the distance between points 2 and 3, and that between points 3 and 1. Triads of judgments on the sides of a triangle like this will obey the triangle inequality, if those judgments are consistent. If the first distance between points 1 and 2 is the longer side of this triangle, then the observer's three judgments of sides 12, 23, and 31 are consistent if the estimated length of 12 is less than the sum of the estimated lengths of 23 and 31. (The labels may be permuted, should the subject judge side 23 to be the longer side of the triangle.) If the three distances are consistent, then a tally is added to the count of the consistency measure.

**Consistency Measure** (based on number of violations of the triangle inequality)

Trial	Count	Proportion	Total	n
1	24	.55	133	240
2	23	.69	159	230
3	24	.79	190	240
4	16	.77	124	160
5	16	.76	122	160



**Figure 6**  
**Effect of feedback on consistency of judgments**

The number of consistent triangles implicit in observers' judgments is tallied by trial in the experiment. Consistency in judgment increases with training (direct feedback). The proportion of consistent judgments remains high in both posttest conditions after training. (There are fewer total judgments made in the posttest conditions, so the absolute count is lower.) The proportions of consistent trials for different trials are: pretest 133/240, first training 159/230, second training 190/240, immediate posttest 124/160, one week posttest 122/160. The number of total judgments is less by ten in the first training trial, since one observer failed to make one judgment.

Those are the major results of the study. There are a number of other questions that arise from theoretical concerns about judgments of distances. One account, perhaps the prevailing one, is that observers cannot judge distance itself (for instance, as in Higashiyama & Shimono, 1994) since distance is not "present to the eyes." Instead, it is supposed that observers gauge the optical angle subtended by a distance, and from the measure of that angle plus other information, observers will unconsciously calculate distances, which then are reflected in the observers' estimates (this explanation is recounted in Levin & Haber, 1993). A simpler account is that when observers are asked to judge distance under NVG viewing conditions with or after feedback, they do judge distance.

Reasons to question the former account emerge from the results of the present experiment. One is that while estimated distances are well predicted by actual distances in every

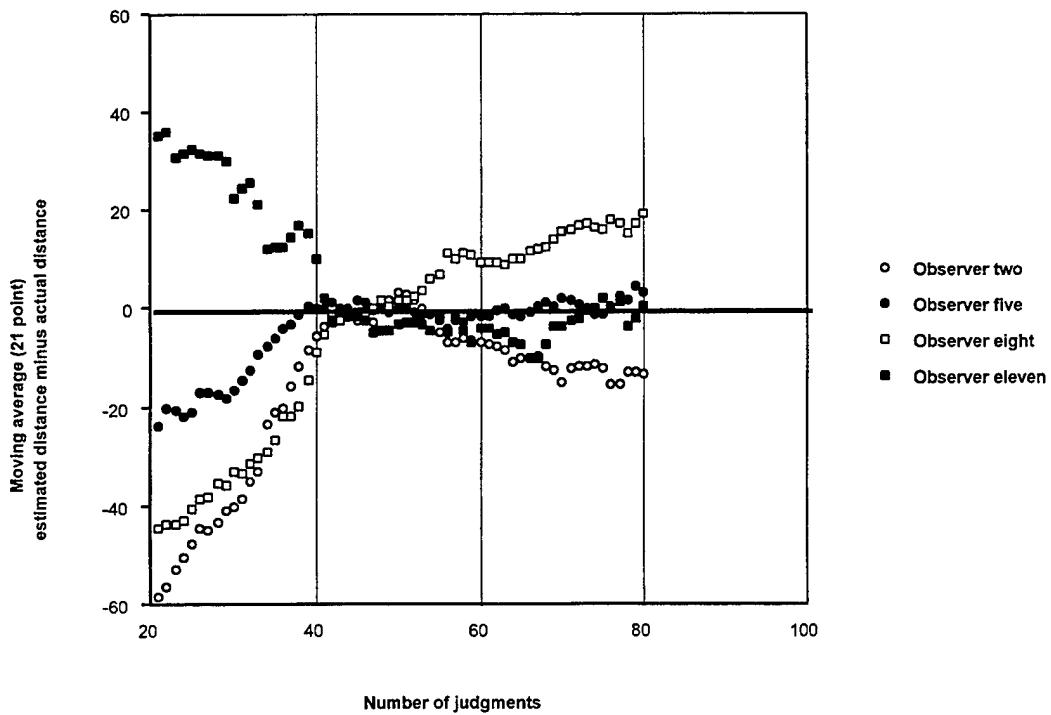
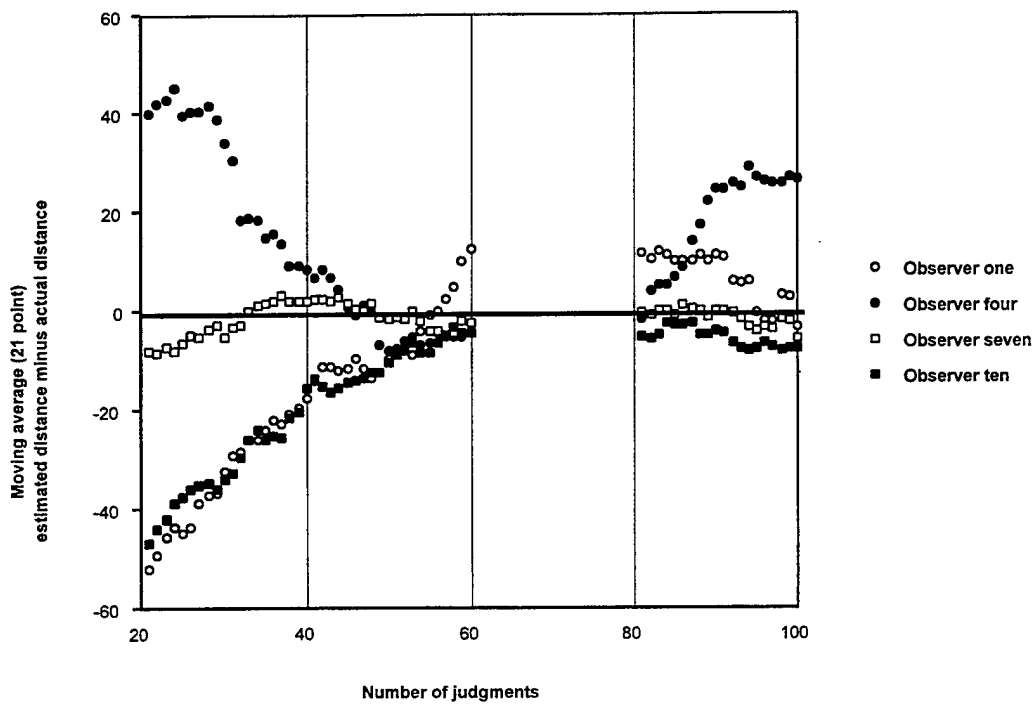
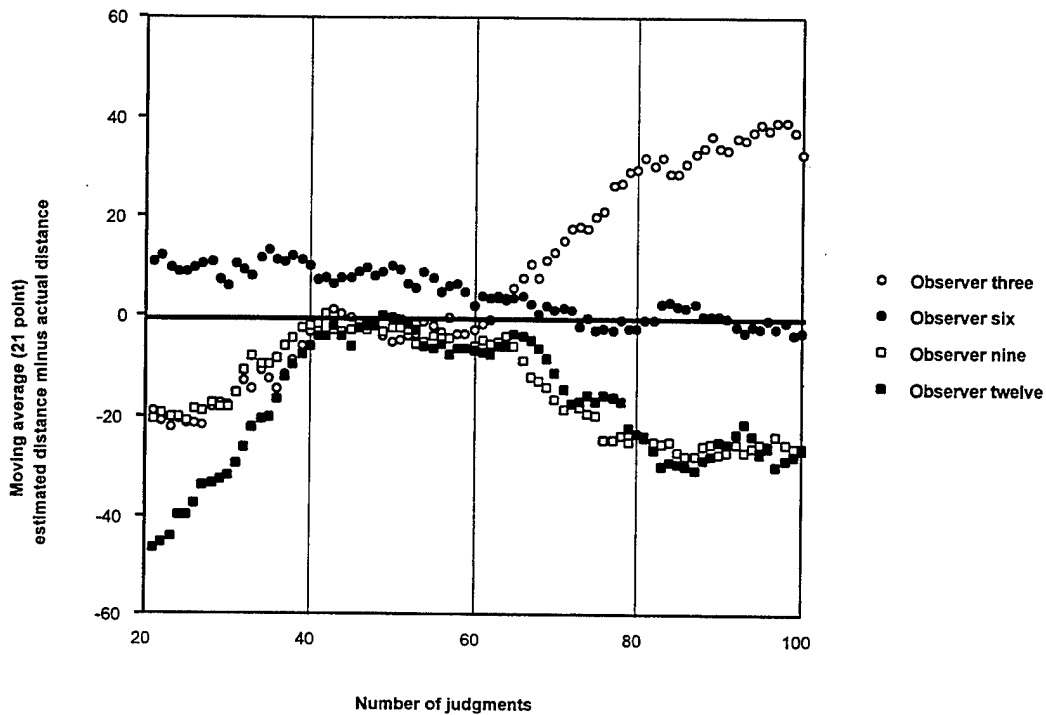


Figure 7. Moving Averages of Difference Scores for Individual Observers



**Figure 7. Concluded**

A moving average of the error scores can be computed. A 21-point moving average is computed as follows: The first 21 judgments are averaged—essentially the entire first trial. Then the first judgment is dropped, the 22nd judgment added, and a new mean calculated. Then the second judgment is dropped, the 23rd judgment added, and another new mean calculated, and so on. The moving average is used to indicate trends in time series. A 21-point moving average is plotted for the second through fourth trials of the experiment (the first training: judgments 21 to 40; second training: judgments 41 to 60; first posttest: judgments 61 to 80; and second posttest: judgments 81 to 100) by number of judgments made by each observer. The moving average is computed on the signed error score of estimated distance minus actual distance. Individual results are plotted; not all observers took part in all the posttest conditions. Judgments become accurate with feedback training; the judgments of some individuals do depart from precise performance in the posttest conditions.

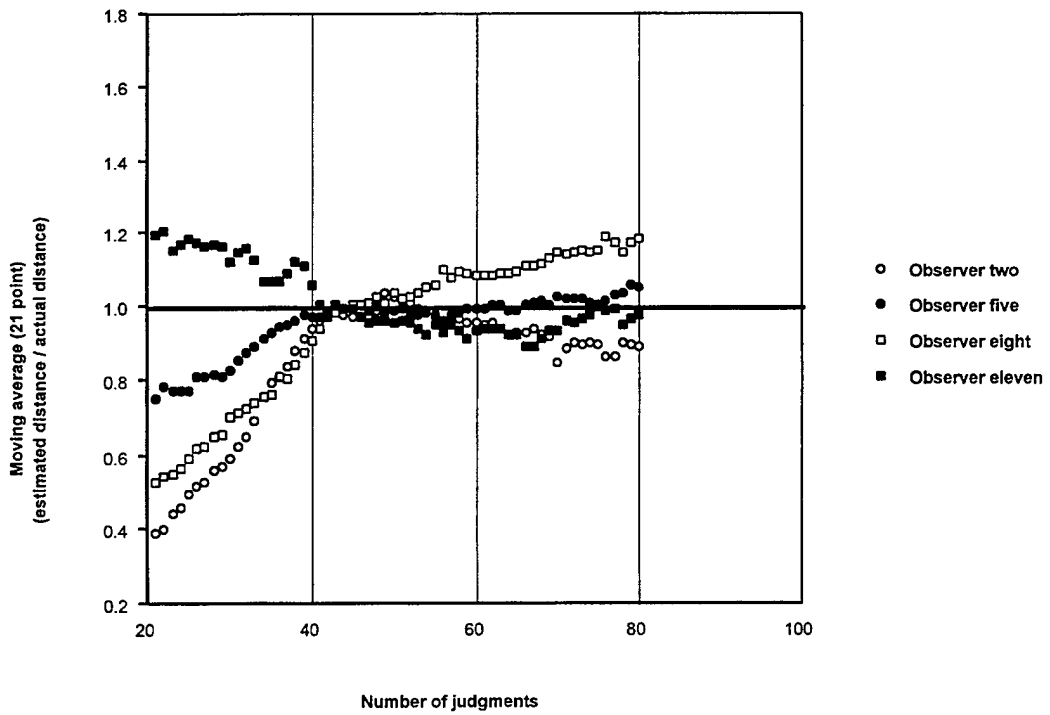
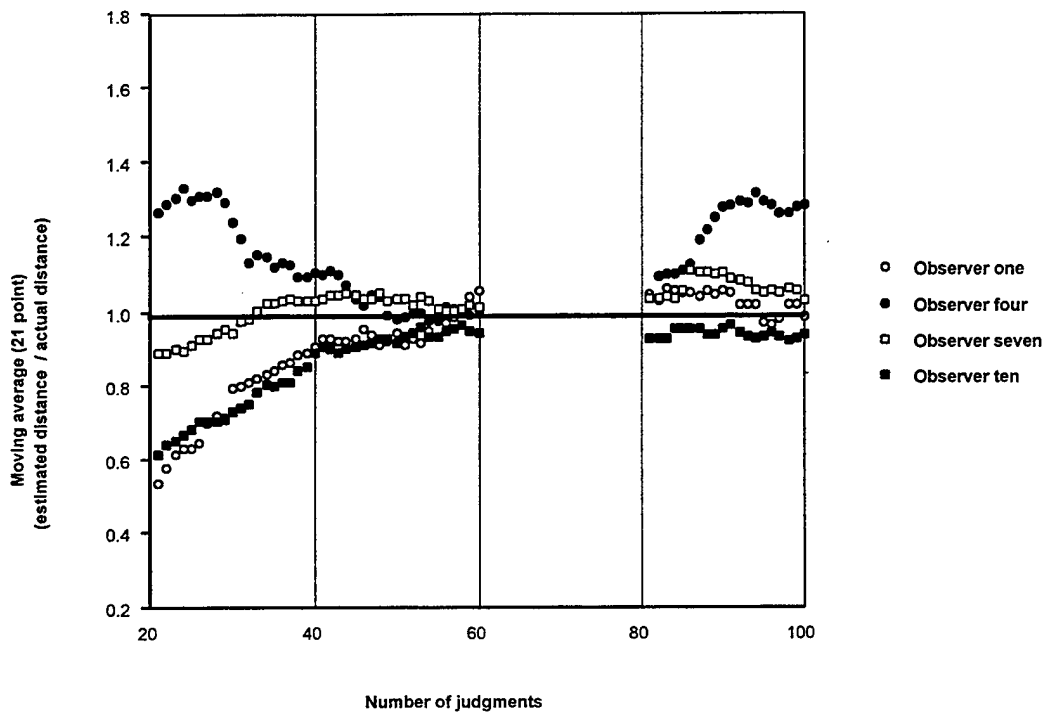
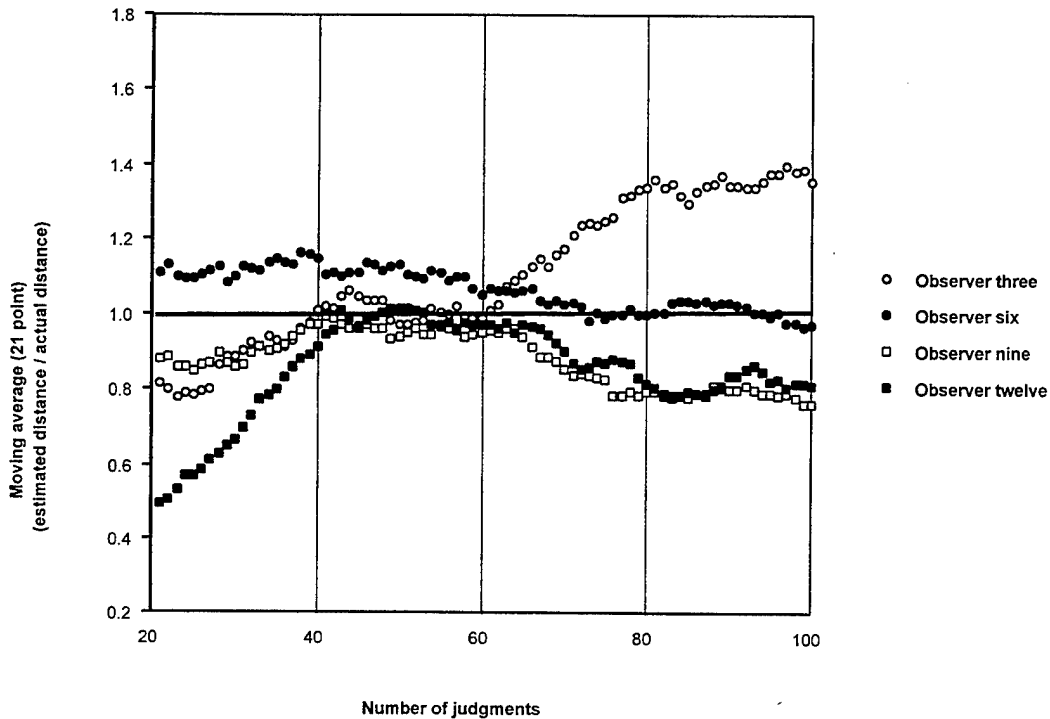


Figure 8. Moving Averages of Ratios for Individual Observers



**Figure 8. Concluded**

A 21-point moving average is plotted for the second through fourth trials of the experiment (the first training: judgments 21 to 40; second training: judgments 41 to 60, first posttest: judgments 61 to 80; and second posttest: judgments 81 to 100) by number of judgments made by each observer. The moving average is computed on the ratio of estimated distance to actual distance. Individual results are plotted; not all observers took part in all the posttest conditions.

condition of the experiment, estimated distances are not well predicted either by visual angle or the tangent of visual angle.

Visual angle is computed by considering the idealized eye position of the observer, and the two end locations of the distance in question. The eye height of the observer is considered to be 5 ft in the standing condition, and 12 ft 7 in. in the elevated condition. Three direction cosines from the eye position of the observer are computed to each of the two locations. (Direction cosines can be considered as the projected lengths of a given line length on the  $x$ ,  $y$ , and  $z$  axes of a coordinate system. Three direction cosines correspond to each length.) If the eye position at the origin of coordinates is designated by  $\underline{O}$ , and the ends of the distance in question are designated  $\underline{P}$  and  $\underline{Q}$ , then we wish to find the angle between lines  $\underline{OP}$  and  $\underline{OQ}$ . If  $\underline{OP}$  has direction-cosines  $\cos \alpha$ ,  $\cos \beta$ , and  $\cos \gamma$ , and  $\underline{OQ}$  has direction-cosines  $\cos \alpha'$ ,  $\cos \beta'$ , and  $\cos \gamma'$ , then the angle  $\theta$  that  $\underline{OP}$  makes with  $\underline{OQ}$  is given by:

$$\cos \theta = \cos \alpha \cos \alpha' + \cos \beta \cos \beta' + \cos \gamma \cos \gamma'$$

The experiment that has been reported includes a number of conditions including: standing observation, elevated observation, distances that are radial from the observer (egocentric distances), distances that are not radial from the observer (exocentric distances), and the three test conditions (pretest, trial 1; feedback, trials 2 and 3; and posttest, trials 4 and 5). For each of the combinations of these conditions, the relation of estimates of distance may be compared to both actual distance and visual angle. For the sake of brevity and clarity, instead of visual angle we use the tangent of visual angle in the present examples. (Boff, Kaufman, & Thomas, 1986, use cotangent from the visual horizon rather than the tangent of visual angle, but this is a superficial difference. Also, similar results are obtained with the raw measure of visual angle.)

Regression analyses (simple linear regressions) were performed for each of the conditions of the experiment, both for actual distance versus estimate of distance, and tangent of visual angle versus estimate of distance. Regression scatterplots can be drawn for 12 conditions: the combinations of two conditions or types of distances (egocentric, exocentric), two viewing heights (standing or elevated), and three test conditions (pretest, feedback, posttest). We may ask two simple yes-or-no questions of these results: (1) Is the slope of each regression line different from zero? i.e. if the regression coefficient is significant at a level of  $\alpha = .05$ ; and (2) If it is significant, we may ask if the statistical estimate of the regression coefficient could include one, i.e. if the confidence interval of the estimate of slope includes one. A regression coefficient of one indicates a perfect correspondence between the variables.

A simple pattern emerges from this mass of results (Table 6). All scatterplots that relate estimated distance to actual distance had a slope significantly different from zero. All of those scatterplots had another property: The estimate of slope was not significantly different from one. In conditions that involved exocentric distances, none of the scatterplots that relate estimated distance to the tangent of visual angle had a slope significantly different from zero. In conditions that involved egocentric conditions, all of the scatterplots that relate estimated distance to the tangent of visual angle had a slope significantly different from zero. In those conditions, all of the estimates of slope of the regression line were significantly different from one as well. In other words estimated distance could (possibly) be predicted perfectly by actual distance for both egocentric and exocentric distances. At the same time, estimated distance could not be predicted perfectly by the tangent of visual angle, which does not produce any significant prediction of estimated distance in the case of exocentric distances.

There is another way to consider the results, that leads to a similar conclusion. We have three variables, one dependent (estimated distance) and two independent (actual distance, visual angle). We can consider four conditions: direct feedback trials for egocentric distances (trials 2 and 3), direct feedback trials for exocentric distances (trials 2 and 3), posttest trials for egocentric distances (trials 4 and 5), and posttest trials for exocentric distances (trials 4 and 5). In each of these conditions, we can ask what the relation of two variables may be, discounting the effect of the third. We do this because the tangent of visual angle is correlated with actual distance in the experiment. (The relation between egocentric distance, exocentric distance, and visual angle is diagrammed in Figure 9 for the conditions of the present experiment.) We want to determine:

**Table 6. Summary of Regression Analyses**

<u>Independent var.</u>	<u>Condition</u>	<u>Height</u>	<u>Trial</u>	<u>Slope <math>\neq 0</math> ?</u>	<u>Estimate includes 1.0 ?</u>
actual	ego	low	1	✓	✓
actual	ego	low	2,3	✓	✓
actual	ego	low	4,5	✓	✓
actual	ego	high	1	✓	✓
actual	ego	high	2,3	✓	✓
actual	ego	high	4,5	✓	✓
actual	exo	low	1	✓	✓
actual	exo	low	2,3	✓	✓
actual	exo	low	4,5	✓	✓
actual	exo	high	1	✓	✓
actual	exo	high	2,3	✓	✓
actual	exo	high	4,5	✓	✓
tan theta	ego	low	1	✓	X
tan theta	ego	low	2,3	✓	X
tan theta	ego	low	4,5	✓	X
tan theta	ego	high	1	✓	X
tan theta	ego	high	2,3	✓	X
tan theta	ego	high	4,5	✓	X
tan theta	exo	low	1	X	
tan theta	exo	low	2,3	X	
tan theta	exo	low	4,5	X	
tan theta	exo	high	1	X	
tan theta	exo	high	2,3	X	
tan theta	exo	high	4,5	X	

(a) if estimated distance is correlated with the tangent of visual angle, once the effect of actual distance is held constant, and (b) if estimated distance is correlated with actual distance once the effect of visual angle is held constant. This is accomplished by taking a partial correlation, as in Table 7. Then a pattern is clear: Estimated distance is strongly and significantly correlated with actual distance when the effect of tangent of visual angle is held constant. Estimated distance is not significantly correlated with the tangent of visual angle--anywhere--when the effect of actual distance is held constant. The apparent effect of visual angle seems to be due to its dependence on actual distance, and not vice versa. In conclusion it seems unlikely that judgments of distance are formed by apprehending visual angles from which less reliable estimates of distance are formed. More likely, observers estimate distance when asked to estimate distance.

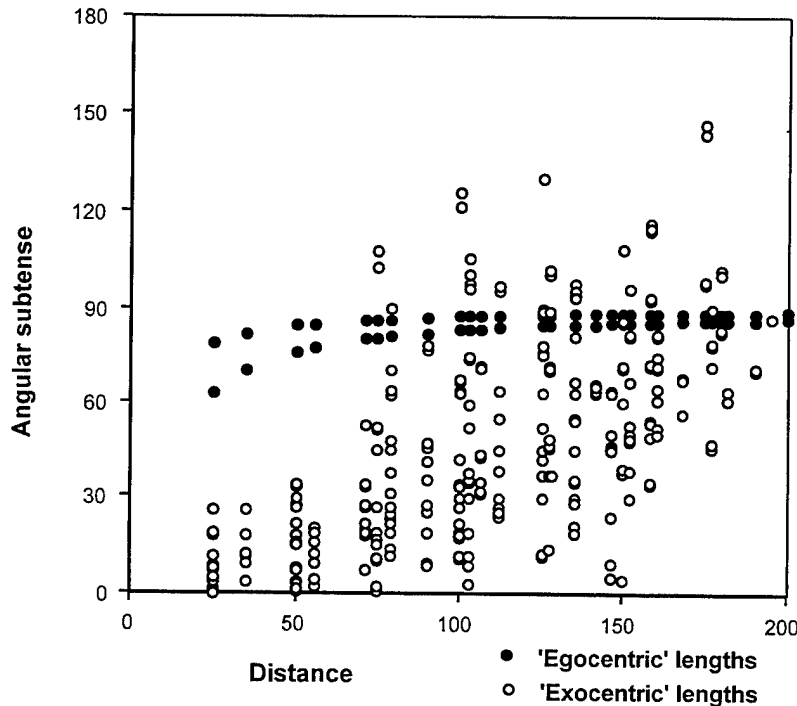
**Table 7. Partial Correlation of Distance and Visual Angle with Responses**

Partial correlations can be taken to gauge the relative contributions of actual distance and visual angle to the prediction of distance estimates. These correlations are tabled for the training trials and retention trials of the experiment. Separate correlations are drawn for distances from the observer to a target ("egocentric distances") and distances between targets ("exocentric distances"). The correlation of actual distance and estimated distance is high and significant, even when the effect of visual angle is taken into account. In contrast, the correlation between visual angle and estimated distance is nonsignificant and approaches zero when the effect of actual distance is taken into account. The data of the experiment are better explained by saying that observers base their estimates of distance on actual distance, and not on the magnitude of visual angle. (This seems a common-sense proposition: that when asked and able to judge distance, observers will judge distance, and not some other thing.)

Condition	Trials	R12.3	R23.1	n
Egocentric	2,3	0.85	-0.05	192
Egocentric	4,5	0.70	-0.10	128
Exocentric	2,3	0.85	0.00	287
Exocentric	4,5	0.80	0.04	192

A related question concerns the special status of so-called "egocentric" distances. These distances radial to the observer are distinguished by their geometry, as may be seen by the relation of distance to subtense of visual angle in the experiment (plotted in Fig. 9). Egocentric distances are distances most severely foreshortened (their angular subtense is nearest 90 deg, from the observer's feet to the horizon). Elevation of the observer does change this foreshortening somewhat (as can be seen from the parallel curves of black dots in the diagram), but the variation in angular subtense is not as great as that among the exocentric distances. The effect of foreshortening follows the cosine of this angular subtense. (Remember that the egocentric distances are close to being seen end-on, that is, close to not being seen at all.) It is the property of geometric foreshortening that distinguishes these stimuli; that is, they are distinguished by their geometric or optical properties, and not as the result of an automatic but unconscious computational process. Foreshortening is not a cue to distance, or an aid to the estimation of distance; it is a positive impediment to the estimation of distance, that is a fixed

part of the optical conditions of stimulation whose influence can be ameliorated by training. For the purposes of the estimation of distance, at the elevation angles we have studied, estimates of these distances are still best predicted by their associated distances. (One might consider, though, that an elevation of the observers over a full range, from standing position to bird's-eye view, might have had some effect on estimates of distance. The more elevated the eye point of the observer from the ground plane, the less will be the effect of foreshortening upon distances in the ground plane.)



**Figure 9. Distance versus Angular Subtense**

“Egocentric” distances are different from “exocentric” distances in the experiment: They are different in their geometry. The distances used in the experiment are plotted against the visual angle subtended by those distances. “Egocentric” lengths appear as solid dots, while “exocentric” distances appear as unfilled dots. While exocentric distances span a range of angles, egocentric distances fall close to  $90^\circ$  of visual angle. Egocentric distances are maximally foreshortened in contrast to other distances. The dots that indicate egocentric distances appear to form two curved lines; the two lines correspond to the standing and elevated conditions of observation used in the experiment.

## DISCUSSION

Observers estimated distance well on average in the present study. Yet in discussion on the psychology of vision, many reasons are offered why observers should not discern distances with accuracy. The greater number of those reasons involves consideration of foreshortening. The story of foreshortening begins as follows: Distances in a landscape are not generally preserved in a photograph of the landscape. That is, photogrammetry and mapping do not proceed by measuring

lengths in pictures taken from eye height. Instead, strict methods are applied in aerial photography to obtain pictures from a vantage directly above a portion of the landscape to be mapped. Pictures taken from oblique angles are susceptible to foreshortening, which is a general name for the compression of distances due to perspective in a picture. The effect of foreshortening can be described simply when, as in our experiment, the distances to be compared lie on a flat surface or ground plane.

The nature of foreshortening provides a clue to what has been thought to be a psychological difference between the judgment of egocentric distance and that of exocentric distance. The judgment of distance has been thought to depend on the apprehension of visual angle (or as the tangent of visual angle); we have seen in this experiment that the evidence runs contrary to that assumption. Under foreshortening, distances are shortened more in projection as the angle they make to the picture plane increases. That is, the picture image of a distance nearly end-on is severely shortened, and the picture image of the same distance taken broadside is less shortened. The relation can be expressed more exactly: The shortening of the distance varies according to the cosine of the angle that that distance makes with the picture plane. Now the rate of change of the cosine function is not great between  $0^\circ$  and  $15^\circ$ . The rate of change of the function is greater between  $80^\circ$  and  $85^\circ$ .

Contrast this with the tangent function of visual angle. The tangent function, or visual angle itself, has been considered important because psychologists have claimed that observers apprehend visual angle and, from there, they deduce or infer or interpret information about distances on that basis. That is an unnecessary assumption, a theoretical confusion that may have no foundation in fact. What may have encouraged psychologists in this matter is that sometimes foreshortening has an effect on the estimation of distance. Foreshortening varies as the cosine of the slant of a line length to the picture plane. Line lengths that are most severely foreshortened are not judged so well; hence, "egocentric" distances are badly judged in contrast to "exocentric" distances in general. But the distinction has little to do with any special status of egocentric distances in psychological terms. Rather, egocentric distances are special in geometric or optical terms, because they represent line lengths that lie closest to being "end-wise to the eye." This difference is not changed by training. (Nor was there a significant interaction of **Distance Type** and **Test** in the ANOVA that was reported.)

If the optical conditions are changed under which distances are judged, then performance may change as a consequence. Performance may not transfer adequately from one set of optical conditions to another, but this is not in itself a psychological matter (see Ferris, 1972; 1973). Many psychological effects on the untrained estimation of distance have been claimed. Higashiyama (1996) claims that distance estimation changes when observers are standing, lying on their sides, or lying on their bellies. Yet such differences may be malleable performance effects rather than a reflection of the observers' competence. In the study of competence, we catch subjects at their best. In the evaluation of distance, "best" simply means accurate performance. Whatever other objections there may be in psychology to the accurate estimation of distance by eye, the results of the experiment are that such estimates are accurate (precise in the sense of being dead-on in average) when observers are given simple feedback on their performance, even under NVG

viewing conditions (given the limits of the experiment in terms of range of distances, and other factors).

## CONCLUSION

Observers improved their ability to estimate distance and this improvement persisted for at least one week. It did not make a significant difference whether observers were tested at eye level, or slightly elevated on a B-1 stand. Distances between the observer and an object were less well estimated than distances between two objects, presumably because of the severe foreshortening due to perspective on ground distances viewed from eye height or nearby. The distances examined in this experiment have most relevance to the "close-in" judgments that are made in helicopter operations.

### Future Research

Providing immediate verbal feedback does produce accurate performance in the long run. There are many issues that remain to be addressed. A planned experiment will touch upon issues (a) of time restrictions, (b) of criterion-referenced training (that is, training to a stable level of proficiency), and (c) of transfer of training from unaided daylight conditions to estimates made under NVG conditions. In this prospective experiment, observers will be trained to criterion; they will be trained until they achieve a certain tolerance in terms of relative distance, i.e., until their performance in terms of the ratio of the distance they estimate to the actual distance is close to 1.0, for a number of estimates in a row. Though the testing will be done at night under conditions of NVG viewing as before, the training with immediate feedback that will be given before the testing will be either under daylight conditions or under NVG viewing conditions. It may be that a certain amount of training in daylight can substitute for a large amount of training under conditions of NVG viewing. The testing procedure in this experiment will have an additional constraint: Observers will be required to give their answers within a short interval of time. Responses that do not fall within the required interval (a variable interval measured in seconds) will be recorded by the experimenter, but counted as successful responses only if given in the time allotted. This condition parallels the many operational conditions in which relatively rapid judgments must be made.

## REFERENCES

- Antonio, J. C., & Berkley, W. E. (1993). Night vision goggle model F4949 preflight adjustment/assessment procedures. (AL/HR-TR-1993-0111, AD A271 079). Mesa, AZ: Armstrong Laboratory, Human Resources Directorate, Aircrew Training Research Division.
- Boff, K. R., Kaufman, L., & Thomas, J. P. (1986). Handbook of perception and visual performance. 2 vols. New York: John Wiley and Sons.
- Bourdy, C., Cottin, F., & Monot, A. (1991). Errors in distance appreciation and binocular night vision. Ophthal. Physiol. Optics, 11, 340-349.
- Crowley, J. S. (1990). Human factors of night vision goggle (NVG) helicopter accidents [abstract]. Aviation, Space, and Environmental Medicine, 61, 508.
- DeLucia, P. R., & Task, H. L. (1995). Depth and collision judgment using night vision goggles. International Journal of Aviation Psychology, 5(4), 371-386.
- Ferris, S. H. (1972). Improvement of absolute distance estimation underwater. Perceptual and Motor Skills, 35, 299-305.
- Ferris, S. H. (1973). Improving absolute distance estimation in clear and in turbid water. Perceptual and Motor Skills, 36, 771-776.
- Foyle, D. C., & Kaiser, M. K. (1991). Pilot distance estimation with unaided vision, night-vision goggles and infrared imagery. Society for Information Display International Symposium Digest of Technical Papers, 22, 314-317.
- Gibson, E. J., & Bergman, R. (1954). The effect of training on absolute estimation of distance over the ground. Journal of Experimental Psychology, 48(6), 473-482.
- Gibson, E. J., Bergman, R., & Purdy, J. (1955). The effect of prior training with a scale of distance on absolute and relative judgments of distance over ground. Journal of Experimental Psychology, 50(2), 97-105.
- Higashiyama, A. (1996). Horizontal and vertical distance perception: the discorded-orientation theory. Perception and Psychophysics, 58(2), 259-270.
- Higashiyama, A., & Shimono, K. (1994). How accurate is size and distance perception for very far terrestrial objects?: Function and causality. Perception & Psychophysics, 55(4), 429-442.
- Levin, C. A., & Haber, R. N. (1993). Visual angle as a determinant of perceived interobject distance. Perception & Psychophysics, 54(2), 250-259.

Reising, J. D., & Martin, E. L. (1994). Distance estimation training with night vision goggles: A preliminary study. (AL/HR-TR-1994-0090, AD A284 900). Mesa, Arizona: Armstrong Laboratory, Human Resources Directorate, Aircrew Training Research Division.

Reising, J. D., & Martin, E. L. (1995). Distance estimation training with night vision goggles under low illumination. (AL/HR-TR-1994-0138, AD A291 338). Mesa, Arizona: Armstrong Laboratory, Human Resources Directorate, Aircrew Training Research Division.