

The Role of Visual Occlusion in Altitude Maintenance During Simulated Flight

R. Gray

Arizona State University and Link Simulation and Training

G. A. Geri

Link Simulation and Training

S. C. Akhtar

The Boeing Co.

C. M. Covas

Arizona State University and Air Force Research Laboratory

The use of visual occlusion as a cue to altitude maintenance in low-altitude flight (LAF) was investigated. The extent to which the ground surface is occluded by 3-D objects varies with altitude and depends on the height, radius, and density of the objects. Participants attempted to maintain a constant altitude during simulated flight over an undulating terrain with trees of various heights, radii, and densities. As would be predicted if participants used occlusion, root-mean-square error was related to the product of tree height and tree density (Experiment 1) and to the product of tree radius and tree density (Experiment 2). This relationship was also found for simulated terrains with a more realistic mixture of tree heights (Experiment 4). The authors present a modification to an occlusion model (T. Leung & J. Malik, 1997) that can be used to approximate occlusion in the context of LAF, and they evaluate the modified model using the present LAF data. On a practical level, simulating 3-D objects is computationally expensive. The present results suggest that performance may be maintained with fewer objects if their size is increased.

Keywords: aviation, perception and action, visual occlusion, simulation

The ability to effectively control movement through the environment is one of the most important perceptual–motor skills humans possess. Whether walking, cycling, driving, or flying we must control our rate and direction of travel in a manner that will allow us to reach our goal while avoiding collisions with obstacles. Safe performance of these actions frequently requires that we regulate our position relative to some object or feature in the environment—for example, maintaining a safe distance behind a lead car in driving or keeping a safe distance from the road edge when cycling. In the present article we consider a particular example of this ability: regulating height above the ground in simulated aircraft flight.

Of all of the perceptual–motor tasks performed by military pilots, low-altitude flight (LAF) is one of the most demanding and potentially the most dangerous. LAF can involve maintaining an

altitude of less than 40 m while traveling at speeds up to 232 m/s (450 knots). Not surprisingly, this flight task accounts for disproportionately high numbers of accidents relative to the total number of flight hours (Wiener, 1988). Given this high level of risk, flight simulators are now used extensively to provide a training environment for pilots to acquire LAF skills.

In order for simulator training of any flight skill to transfer positively to the real world, it is critical that the simulation include the necessary visual cues. Owing to both computational and display limitations, current flight simulators cannot provide all of the cues associated with LAF. The questions then become, to what extent can LAF tasks be performed given the cues that are available, and to what extent can those cues be traded off so as not to exceed limited simulator capabilities? Answering these questions requires empirical research to identify the visual cues used to perform various flight simulator tasks.

A minimum requirement for successful LAF is that the pilot be able to keep the aircraft's altitude near a specified value—flying too high can lead to radar detection, for example, whereas flying too low can lead to ground contact. The goal of the present study was to investigate some of the image properties that may underlie the visual cues used to maintain altitude during LAF. In particular, we were interested in how pilots use information provided by the size and number of 3-D objects in the visual scene. We next review the various visual cues that may be used in LAF. In this article we consider only those visual cues that can be used to judge relative altitude (i.e., whether the aircraft is higher or lower than in the previous instant). In general, the visual scene does not provide effective cues for judgment of absolute altitude (i.e., how many feet or meters the aircraft is above the ground), and so pilots

R. Gray, Department of Applied Psychology, Arizona State University, and Visual Research Laboratory, Link Simulation and Training, Mesa, Arizona; G. A. Geri, Visual Research Laboratory, Link Simulation and Training; S. C. Akhtar, The Boeing Co., Mesa, Arizona; C. M. Covas, Department of Applied Psychology, Arizona State University, and Air Force Research Laboratory, Mesa, Arizona.

This work was supported by the National Science Foundation Faculty Early Career Development Program (Award 0239657 to R. Gray) and U.S. Air Force Contracts F41624-97-D-5000 and FA8650-05-D-6502 to Link Simulation and Training, a division of L-3 Communications.

Correspondence concerning this article should be addressed to R. Gray, Department of Applied Psychology, Arizona State University, 7001 East Williams Field Road, Sutton 340J, Mesa, AZ 85212. E-mail: robgray@asu.edu

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE APR 2008		2. REPORT TYPE Journal Article		3. DATES COVERED 01-01-2007 to 01-01-2008	
4. TITLE AND SUBTITLE The role of visual occlusion in altitude maintenance during flight				5a. CONTRACT NUMBER FA8650-05-D-6502	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62202F	
6. AUTHOR(S) Rob Gray; George Geri; Shama Akhtar; Christine Covas				5d. PROJECT NUMBER 1123	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arizona State University, Department of Applied Psychology, 7001 East Williams Field Road, Bldg 140, Mesa, AZ, 85212				8. PERFORMING ORGANIZATION REPORT NUMBER ; AFRL-RH-AZ-JA-2008-0001	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory/RHA, Warfighter Readiness Research Division, 6030 South Kent Street, Mesa, AZ, 85212-6061				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL; AFRL/RHA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RH-AZ-JA-2008-0001	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Published in the Journal of Experimental Psychology: Human Perception and Performance, Apr 2008, Vol 34(2), 475-488					
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15. SUBJECT TERMS Visual occlusion; Altitude maintenance; Flight simulation; Occlusion model; Experimental psychology; Human perception; Human performance					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	unclassified	unclassified	Public Release	13	

generally rely on cockpit instrumentation for that information (Wiener, 1988).

Early research on altitude maintenance in LAF focused primarily on the visual information provided by a 2-D texture on a flat terrain surface. For example, Flach, Hagen, and Larish (1992) identified two visual cues that could be used by pilots: (a) the *depression angle*, the visual angle formed by the horizon and a terrain edge that is oriented perpendicularly to the direction of motion, and (b) the *splay angle*, the visual angle formed by the motion path and a terrain edge oriented parallel to the direction of motion at the convergence point on the horizon. Flach et al. (1992) and Flach, Warren, Garness, Kelly, and Stanard (1997) used simple terrain textures composed of lines and grids and an experimental task that required maintenance of a constant altitude in the presence of simulated fore-aft, up-down, and right-left wind disturbances. They found that either depression angle or splay angle could be used for altitude maintenance during simulated LAF and that their relative effectiveness varied across flying conditions. Although depression angle and splay angle have proven important for altitude maintenance (see also Johnson, Tsang, Bennett, & Phatak, 1989, and Wolpert, Owens, & Warren, 1983), it should be noted that the simulated ground textures used in those studies were specifically designed to optimize those cues. A more natural terrain with irregularly spaced 3-D objects of varying heights may reduce the effectiveness of those cues, but this has not been empirically tested.

Another visual cue that could be used for altitude maintenance is the rate of change of the angular size of either 2-D features, such as terrain texture elements, roadways, and rivers, or 3-D objects, such as buildings and trees. The rate of change of size is proportional to the rate of change of altitude (Regan, Beverley, & Cynader, 1979). Kleiss and Hubbard (1993) and Kleiss (1995) used an altitude-change detection task to investigate the role of changing size in altitude maintenance. Participants flew over a simulated ground terrain populated with different types of 3-D objects positioned randomly and with varied density. Participants first actively controlled their altitude; the display was then blanked and the altitude was changed. The participants' task was to indicate whether their perceived altitude was higher, lower, or the same as before the display was blanked. Those authors found that perceived altitude was determined primarily by object density (see Martin & Rinalducci, 1983, for a similar finding). In separate experiments, Kleiss and Hubbard (1993) also found that the absence or presence of detailed texture on the 3-D objects and the absence or presence of 2-D texture on the ground surface did not significantly affect judgment accuracy. Finally, Winterbottom, Geri, Pierce, and Harris (2001) used an active-control task in a flight simulator to investigate the effects of texture density on altitude-maintenance performance. In that study, terrain textures were obtained from random noise patterns, so that edges, which could be used to detect changes in splay and depression angle, were minimized. After flying over a flat portion of the terrain for 10 s at an altitude of 50 m, participants were required to maintain that altitude as they flew over a sloped section of terrain. The mean altitude deviations ranged from 4 to 10 m (depending on airspeed), suggesting that participants can use changes in perceived texture density to maintain altitude.

Finally, motion parallax is another cue that may be relevant to altitude control in LAF. Motion parallax refers to the relative

movement of objects that occurs when the observer moves and is a consequence of the fact that nearer objects move faster across the retina than do farther objects. In the context of movement over a textured surface, as in LAF, motion parallax is often referred to as motion perspective (see, e.g., Hershenson, 2000). In the case of movement over a textured surface or a scene containing 3-D objects, the most salient perceptual cue is the motion gradient formed by differential movement of the texture elements or the 3-D objects (Sedgwick, 1986). This motion gradient is a visual cue that could be used for altitude maintenance (Patterson et al., 2003). Horizontal motion perspective has been shown to be used for lateral control, such as in the control of heading (see, e.g., Li & Warren, 2000; Longuet-Higgins & Prazdny, 1980; Rieger & Lawton, 1985), and there is some evidence that vertical motion-perspective cues may also be used for altitude control (Covas et al., 2005).

Present Study

In the present study, our primary goal was to investigate the role of occlusion as a visual cue to relative altitude in LAF. Visual occlusion may be manifested in two independent ways, both of which require the presence of 3-D objects. The more common case is the occlusion of objects by other objects (Gibson, 1979; Kaplan, 1969). In the case of a moving observer, the time course of occlusion (and disocclusion) is a cue to both the relative distance among objects and the relative distance from the observer to the various objects. As described above, this form of occlusion is an inherent component of the motion parallax associated with 3-D objects. A less often considered case of visual occlusion that may be relevant for altitude maintenance is that involving occlusion of the ground plane by 3-D objects. As illustrated in Figure 1, the amount of ground surface that will be occluded from a pilot's view by 3-D objects is inversely related to eyeheight (compare Figure 1A and 1B) and directly related to the width, height (compare Figure 1A and 1D), and density (compare Figure 1A and 1C) of the 3-D objects. The relationship among these variables, as well as the magnitude of occlusion, has been modeled by Leung and Malik

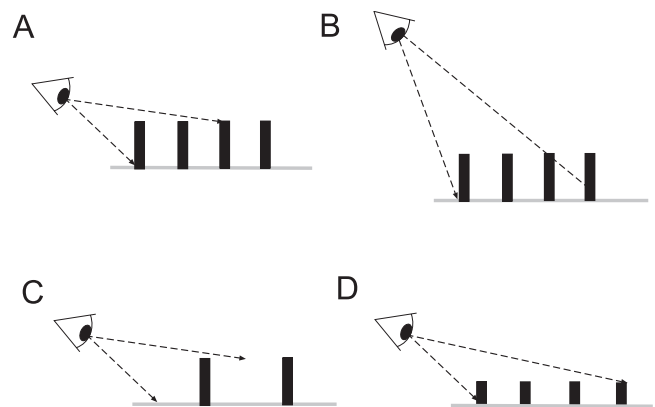


Figure 1. Visual occlusion and altitude maintenance. When 3-D objects (black posts) are present in the visual scene, the ground surface between them will be partially occluded (A). The magnitude of this occlusion decreases with increases in altitude (B) or decreases in either object density (C) or object height (D).

(1997). In their model, the degree of occlusion is represented by the probability that the ground surface (i.e., the space between objects) is not visible within a window through which the terrain is viewed. Thus, a low probability of seeing the ground is associated with a high degree of occlusion, and vice versa. This probability can be estimated using the following equation from Leung and Malik (1997):

$$p(\text{ground}) \approx e^{-2hdr \tan \sigma} - d\pi r^2, \quad (1)$$

where h is the object height, d is the object density, r is the object radius, and σ is the angle formed by the line of sight and a line that is perpendicular to the ground surface and proportional to the eyeheight or altitude. The exponential factor in Equation 1 arises from Leung and Malik's use of a Poisson probability function to model the spatial distribution of 3-D objects in the visual field. The subtractive term in the equation is effectively the total area of the ground surface that is occluded when the 3-D objects are viewed from above (i.e., when $\sigma = 0$). This model was derived under the assumption that the 3-D objects are cylindrical in shape and are perpendicular to the ground plane.

Application of the Occlusion Model to Altitude Maintenance

One of the main goals of the present study was to determine to what degree Leung and Malik's (1997) computational model of visual occlusion can be used to explain performance in altitude maintenance for different simulated terrain conditions. We chose to use this particular model because it specifically relates the magnitude of occlusion to some of the primary 3-D object parameters that vary in natural scenes and that are typically varied in flight simulator displays—namely, object height, width, and density. Thus, the model provides a relatively clear quantitative test of whether visual occlusion is used during altitude maintenance. That is, if the effect of varying these 3-D object parameters is similar for flight performance and for the magnitude of visual occlusion as computed by the model, we can infer that visual occlusion is used. By using this model we are not proposing that humans compute the magnitude of visual occlusion in a scene by first detecting height, width, and density; we are suggesting only that these variables influence the magnitude of occlusion and therefore should also affect flight performance. Thus, we consider occlusion, as described here, to be an elementary perceptual quantity that is perceptually processed in a way consistent with existing models of depth perception (e.g., Grossberg, 1993; Marshall & Alley, 1993).

In order to apply Equation 1 to data obtained from the LAF task used in the present study, we had to make two modifications. First, Equation 1 was derived assuming a flat surface, whereas curved surfaces were used in the present study. Second, Equation 1 assumes that the 3-D objects are parallel to the surface normal, whereas in a natural setting the angle of trees relative to the ground varies as the slope of the ground varies. The extension of Equation 1 to curved surfaces is both conceptually and mathematically complex. Leung and Malik (1997) attempted to extend their model to curved surfaces, and their results, as well as a discussion of their simplifying assumptions, are presented in their paper. They did not, however, consider the case of parallel objects on a curved surface. The modifications to the model described here are pre-

sented not as improvements to the Leung and Malik model but rather as first-order approximations for applying the model to an LAF task.

The first modification to Equation 1 was made to better account for the ground occlusion that results when the ground is not flat. We assume here that the terrain surface is a slanted plane rather than a more complex curved plane. This is justified because in the present application the radius of curvature of the ground plane was much greater than the mean flight altitude. Figure 2A depicts a surface, with y representing altitude. Shown in Figure 2B and 2C are ground surfaces sloping upward and downward, respectively, at an angle θ . An upward sloping terrain effectively decreases the value of σ in the Leung and Malik model, and a downward sloping terrain effectively increases the value of σ (see Equations 2 and 3 below).

The second modification to Equation 1 was made in order to better account for the fact that for many collections of real trees and for virtually all tree models used in flight simulation, trees are parallel to each other and the angle the trees form with the ground varies as the slope of the ground varies. (Note that this is a simplifying assumption, as one can think of many cases in the real world where trees are not perfectly parallel to each other.) In

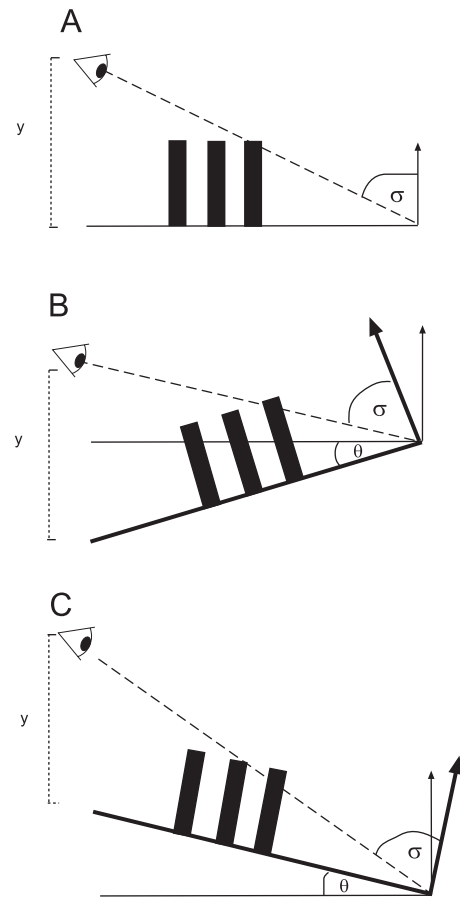


Figure 2. Visual occlusion for flat (A), upward sloping (B), and downward sloping (C) terrains. The variable y is the flight altitude. The variable σ is the angle formed by the line of sight and a line perpendicular to the ground surface. The angle θ represents the slope of the terrain.

addition, we are considering only tree trunks and not branches, leaves, and so forth. The second term in Equation 1 (i.e., $d\pi r^2$) is the cross-sectional area of the 3-D object (in this case a cylinder perpendicular to the ground) as viewed from directly overhead. We have made a first-order approximation to account for the angle between our trees and the ground by modifying this term to represent the slope-dependent, projected (onto the ground surface) area of the tree model (see Figure 3).

The two modifications to the Leung and Malik (1997) model described above result in the following modifications to Equation 1:

$$p(\text{ground}) \approx e^{-2hdr \tan(\sigma-\theta)} - d\pi r \left(\frac{h \sin \theta}{2} + r \right) \quad (2)$$

for upward-sloping terrain and

$$p(\text{ground}) \approx e^{-2hdr \tan(\sigma+\theta)} + d\pi r \left(\frac{h \sin \theta}{2} + r \right) \quad (3)$$

for downward-sloping terrain.

Shown in Figure 4 is the relationship between $p(\text{ground})$, in Equation 1, and altitude for various values of the product of object density (d), height (h), and radius (r) used in the present study. In general, the functions become flatter as this product decreases. Specifically, for the lowest value of $d \times h \times r$ shown, a change in altitude from 30 to 35 m, for instance, results in about a 0.1% increase in $p(\text{ground})$, whereas for the highest value, the same change in altitude results in a 20% increase. These data show that higher values of any of the three variables, d , h , and r , result in a greater change in the degree of visual occlusion for a given altitude change and, hence, the expectation that altitude change will be better perceived. For the three largest values of $d \times h \times r$ in Figure 4, the percentage change in the value of $p(\text{ground})$ for a 5-m change in altitude is roughly equal to or larger than the Weber fractions of .05–.10 observed for surface slant discrimination from texture cues (Knill, 1998). This suggests that human observers would be sensitive to changes in the magnitude of occlusion under most conditions.

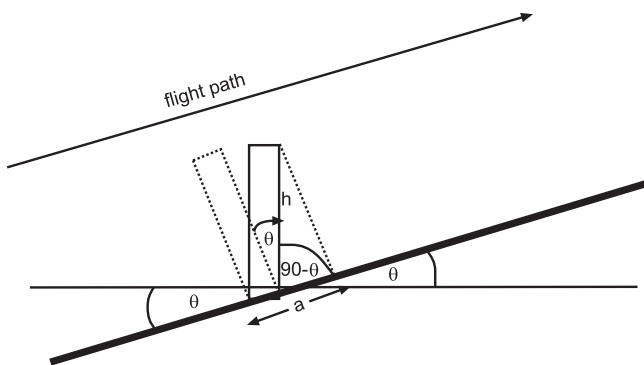


Figure 3. Change in the projected area of a cylindrical 3-D object on the ground plane caused by changing the angle between the object and the ground plane. The projected area represents the ground area occluded by the 3-D object as viewed from directly overhead. The projected area is an ellipse whose minor axis is the diameter of the cylinder and whose major axis is a . The projected area is a function of the slope of the ground plane and is given by the second term in Equations 2 and 3.

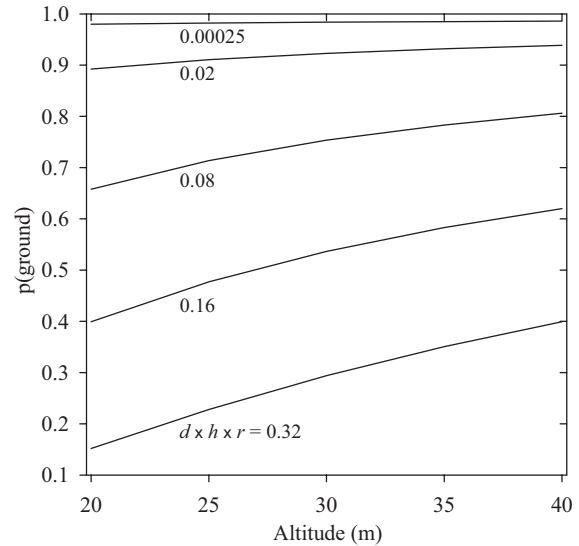


Figure 4. The value of $p(\text{ground})$, calculated from Equation 1 as a function of altitude, for five values of the product of object density, object height, and object radius ($d \times h \times r$) similar to those used in the present study.

Rationale for the Present Study

The rationale for the present study was to systematically vary the quantities h , d , and r in Equations 2 and 3 and determine the effect on altitude maintenance, where altitude is inversely related in the equations to the variable σ . In Experiment 1, we varied object density and object height across experimental blocks. We hypothesized that altitude-maintenance performance would improve as the value of $d \times h$ in our display increased (as predicted by Equations 2 and 3) and that this product would better predict altitude-maintenance performance than would either variable alone. In Experiment 2, we varied object density and object radius across experimental blocks. We hypothesized that altitude-maintenance performance would improve as the value of $d \times r$ in our display increased (as predicted by Equations 2 and 3) and again that the product would best predict performance. Because under real-world conditions 3-D objects do not typically all have the same height, in Experiment 4 we investigated the more ecologically valid condition where object height varied across the terrain. In this final experiment we again hypothesized that altitude-maintenance performance would be best related to the value of $d \times h$ in our display. For Experiments 1, 2, and 4, we used Equations 2 and 3 to model altitude-maintenance performance.

Visual occlusion has primarily been considered as a cue for passive perceptual judgments (e.g., the relative depth of objects). The present data may be relevant to the question of whether and to what extent visual occlusion can be used as a cue for an active control task. Furthermore, as discussed above, the vast majority of previous research on the use of visual occlusion in perceptual tasks has considered the occlusion of objects by other objects. In the present study, we investigated whether humans are sensitive to a less-studied type of visual occlusion: occlusion of the ground plane by 3-D objects.

Experiment 1: The Effect of 3-D Object Height and Density

Purpose

In Experiment 1, we investigated altitude-maintenance performance during simulated LAF for different combinations of 3-D object density (d) and height (h) to determine whether these variables influence altitude maintenance in a manner consistent with changes in the magnitude of visual occlusion. These two variables were initially chosen for study because they are the object characteristics typically varied when databases are constructed for LAF training. As discussed above, it has previously been shown that perceived changes in altitude vary with both object height and object density (Kleiss & Hubbard, 1993); however, these variables have not been varied systematically. Further, we sought to determine whether the product $d \times h$ is a better predictor of altitude-maintenance performance than is either d or h alone.

Method

Stimuli and apparatus. The simulated ground terrain was created by mapping a gray texture onto a flat height map. Three flight paths with hills and valleys were then constructed by varying terrain height using three different combinations of the sum of three sinusoids. The resulting three flight paths, each 9,600 m in width, were placed adjacent to each other on each of the databases. Databases were then constructed by adding tree models to the flight-path height maps. A total of 17 databases were constructed using selected combinations of five tree densities (0.25, 1, 2, 4, and 64 trees/km²) and five tree heights (0, 2.5, 5, 10, and 20 m). The tree width decreased proportionally as the tree height decreased (see Figure 5, top panel). (See Experiment 3 for conditions in which tree width and height were not correlated.) The 0-m tree was an elliptical 10 × 10-m patch on the terrain. Each flight path began with an initial flat section that extended for 1,856 m followed by 12,064 m of undulating terrain. The mapping was done by commercial database-generation software (World Perfect 2.0, MetaVR, Brookline, MA).

The tree models were black in color. Each tree was made up of two polygons that intersected at right angles, ensuring that a silhouette of the tree was visible at all times. Thus, they were somewhat simplified representations of real trees that have branches, leaves, and so forth. The trees were randomly distributed within a strip along the center of the three flight paths. The width of the strip was limited to 1,600 m, in order to allow a 60-Hz frame rate while still filling the simulated field of view. The tree models were visible while viewing at distances from 0 to 4,500 m.

The simulated image was displayed over three simulator-display channels (each 133 cm [H] × 111 cm [V]) and subtended a visual angle of 180° (H) × 63° (V). Each channel consisted of 1,600 × 1,200 pixels and was displayed using a rear-projection CRT (Barco, Model 808). The simulated view of the front channel as seen by the participants is shown in Figure 6 for one of the tree densities. Flight over the terrain was simulated using a PC-based runtime system (Meta VR, Virtual Reality Scene Generator) with a 60-Hz frame rate. The simulation did not provide stereo information.

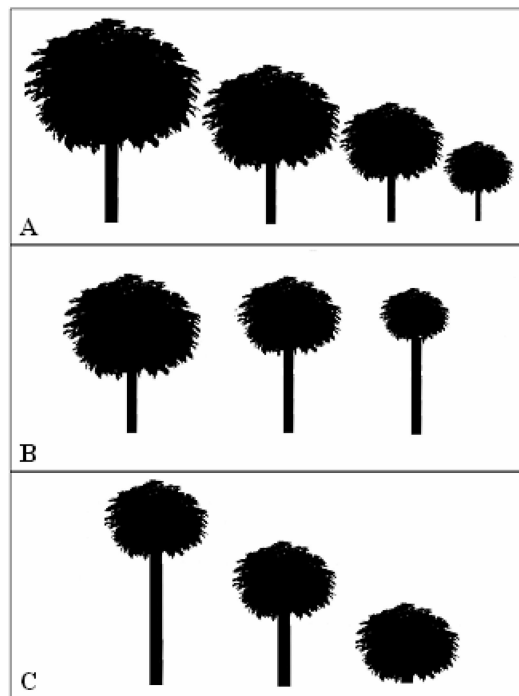


Figure 5. Illustration of the various tree heights and radii used in Experiments 1–4. In Experiment 1, there were five tree heights, 0, 2.5, 5, 10, and 20 m, and the radii were scaled proportionally (top panel). The 0-m tree was an elliptical 10 × 10-m patch on the terrain and is not shown here. In Experiment 2, tree height was held constant at 10 m, and tree radii were 0, 0.5, 2.5, and 5 m, but the trunk radius was held constant at 0.5 m (middle panel). In Experiments 3 and 4, the tree heights were 2.5, 10, and 20 m, treetop radius was held constant at 1.25 m, and the tree trunk radius was held constant at 0.5 m (bottom panel).

Procedure. Each trial began with simulated flight over the flat portion of the terrain at a simulated airspeed of 232 m/s (450 knots) and an altitude of 30 m. The participants were instructed to note their altitude as they flew over the flat portion of the terrain and to maintain that altitude as they flew over the series of hills and valleys. Participants were able to control pitch and altitude by pulling back or pushing forward on a joystick. Each participant was tested on all conditions.

Flight time over the flat portion of the database was 8 s, and flight time over the hills and valleys was 52 s. Altitude was sampled every 0.25 s. Feedback in the form of a warning tone was presented if participants flew more than 10 m above or below the target altitude of 30 m. The participants controlled the start of each 1-min trial, although there was a minimum of 7 s between trials in order to reduce motion adaptation. Participants were initially given 2–3 practice sessions, with experimental sessions beginning after their responses had stabilized.

Data for the different combinations of tree height and tree density were collected in two separate experimental blocks. Block 1 had nine conditions corresponding to all combinations of three tree heights (0, 10, and 20 m) and three tree densities (0.25, 4, and 64 trees/km²). Block 2 had nine conditions corresponding to all combinations of three tree heights (2.5, 5, and 20 m) and three tree densities (1, 2, and 64 trees/km²). Each participant completed three

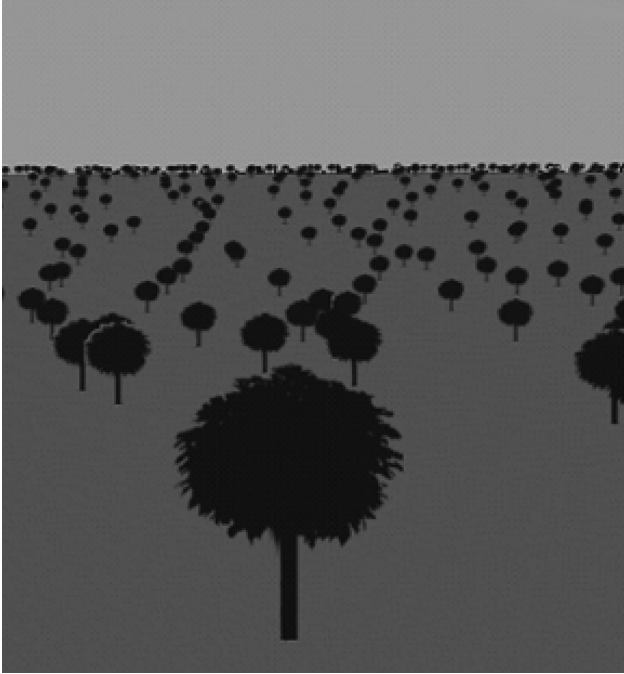


Figure 6. Simulated view of a portion of a database with 3-D objects (trees) whose height and density are 20 m and 64 objects/km², respectively. Only the front simulator channel is shown.

runs for each condition. Each run consisted of nine trials, resulting in a total of 27 observations per condition for each participant. We collected the data in this manner because the limited availability of the simulator did not permit the collection of data in one block of 18 conditions and did not permit a fully crossed design. The 20-m tree height with 64 trees/km² condition was included in both blocks in order to minimize participant frustration with the experimental task (i.e., to ensure that on at least some of the trials in each block altitude could be easily maintained). This is analogous to using stimuli for which participants achieve near 100% correct in the method of constant stimuli. Because such stimuli contribute very little to the estimation of the psychometric function (see, e.g., McKee, Klein, & Teller, 1985), their main purpose is to prevent the task from being too difficult for the participant.

Participants. The 6 participants were between 19 and 32 years of age. All had normal or corrected-to-normal vision as determined by the acuity, binocular vision, color vision, and phoria tests of the Optec Vision Tester (Stereo Optical, Chicago). Participant 3 was author R.G. All other participants were naive to the aims of the experiment and were paid an hourly rate.

Data analysis. In the present study, participants were asked to maintain an altitude of 30 m above an undulating terrain. For tasks of this kind, it is often useful to separate the total error in performing the task into variable and constant errors as follows:

$$\sum_1^n \frac{(x_i - t)^2}{n} = \sum_1^n \frac{(x_i - \bar{x})^2}{n} + \frac{(\bar{x} - t)^2}{n}, \quad (4)$$

where x_i are the n measured altitudes, t is the target altitude (in this case 30 m), and \bar{x} is the mean of the measured altitudes. The total

error is the mean-squared deviation of the altitude measurements from the target altitude. The variable error is the mean-squared deviation of the altitude measurements from their mean (i.e., the variance of the measurements). And, finally, the constant error is the deviation of the mean of the altitude measurements from the target altitude. The variable and constant errors may be taken as measures of the precision and accuracy, respectively, with which altitude maintenance was performed.

In the present study, the dependent variables were the square roots of the variable and constant errors described above. These quantities are referred to here as the *variable root-mean-square (RMS) error* and the *constant RMS error*. Although we have attempted to distinguish these variables when they are used, it should be noted that because of the square root operation, and unlike the quantities shown in Equation 4, the sum of the variable and constant RMS errors does not equal the total RMS error. The variable and constant RMS errors were calculated using the altitude samples from the final 52 s of each trial and were analyzed in separate repeated measures analyses of variance (ANOVAs) with tree height and tree density as independent variables. For the ANOVA, we did not include the conditions involving the 20-m tree height and 64 trees/km² tree density. Instead we ran a 4 × 4 repeated measures ANOVA with incompletely crossed factors (Myers & Well, 1995) using tree heights of 0, 2.5, 5, and 10 and tree densities of 0.25, 1, 2, and 4.

Because previous research has shown that performance in simulated LAF tasks is related to variations in both object density and object height (Kleiss & Hubbard, 1993; Martin & Rinalducci, 1983), we determined the extent to which height alone or density alone could explain performance in the present study. As shown in Equation 1, the magnitude of visual occlusion depends on the product of height and density. Therefore, we next examined the extent to which performance in Experiment 1 could be explained by this product.

Results and Discussion

Shown in Figure 7 (A–F) is the log₁₀(variable RMS error) plotted as a function of log₁₀(tree height) for each of the 6 participants. Solid lines show the best linear fit for each data set. Also shown with each data set are the slopes and y-intercepts of the fitted linear functions, as well as associated R^2 values. The linear functions correspond to power law relationships between variable RMS error and tree height. Using an algorithm developed by Newell and Rosenbloom (1981) for approximating the asymptote for a power law relationship between two variables, we estimated that the variable RMS error decreased up to a tree height of about 3–5 m (log₁₀(tree height) of 0.5–0.7 m), after which it remained roughly constant. R^2 values indicate that tree height accounts for 13%–39% of the variance in the performance data. R^2 values are compared statistically below.

Shown in Figure 8 (A–F) is the log₁₀(variable RMS error) plotted as a function of log₁₀(tree density) for the 6 participants. Solid lines again show the best linear fit for each data set. It was determined by the Newell and Rosenbloom algorithm that the variable RMS error decreased up to a tree density of 10–12 trees/km² (log₁₀(tree density) of 1.0–1.1 m), after which it re-

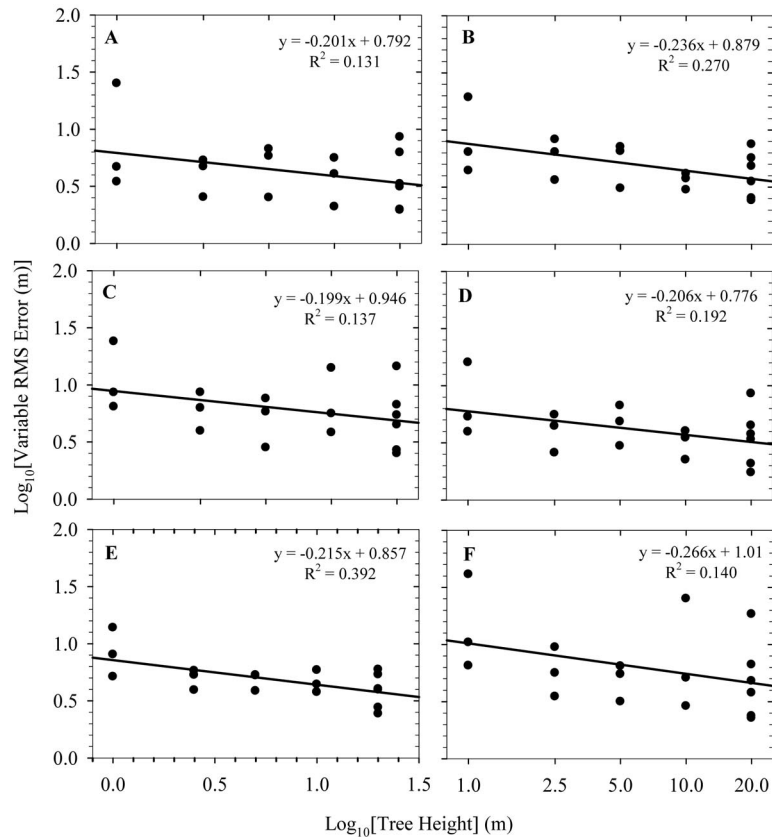


Figure 7. Effect of tree height on altitude-maintenance performance. The \log_{10} (variable RMS error) is plotted as a function of \log_{10} (tree height). Panels A–F are data from Participants 1–6, respectively. Solid lines are linear, best fit functions whose slopes, y-intercepts, and associated R^2 values are shown in each panel.

mained roughly constant. As shown by the R^2 values presented in the figure, tree density explained 48%–71% of the variance in these data.

Variable RMS error, which may be taken as a measure of the precision of the altitude-maintenance performance, was analyzed using a 4×4 repeated measures ANOVA with incompletely crossed factors. The main effects of tree density, $F(3, 15) = 17.2$, $p < .01$, and tree height, $F(3, 15) = 73.2$, $p < .001$, and the Density \times Height interaction, $F(9, 45) = 33.8$, $p < .001$, were all significant

If our participants were using the change in magnitude of occlusion as a cue to altitude maintenance, then we would predict from Equation 1 that variable RMS error would depend more strongly on the product of tree height and tree density than on either variable alone. Shown in Figure 9 (A–F) is the \log_{10} (variable RMS error) plotted as a function of $\log_{10}(h \times d)$. Once again, solid lines show linear curve fits to the data. The product $h \times d$ accounted for more of the variance in the data (76%–84%) than either h or d alone. The R^2 values from the data of Figures 7–9 were compared statistically using pairwise t tests. This analysis revealed that the variance in variable RMS error explained by the product $h \times d$ was significantly greater than the variance explained by either h alone, $t(5) = -13.2$, $p < .001$, or d alone, $t(5) = -5.6$, $p < .01$.

As discussed above, the relationship between variable RMS error and the product $h \times d$ is what would be predicted if participants were using the magnitude of visual occlusion as described in Equations 2 and 3. Specifically, we can use Equations 2 and 3 to calculate the value of $p(\text{ground})$ for each combination of tree height and tree density used in Experiment 1. We first describe this calculation for a tree height of 1 m and a tree density of 0.25 trees/km². For each of the three flight paths used in Experiment 1, we calculated the instantaneous terrain slope (θ) as a function of the distance traveled at 50-m intervals (not including the initial 1,856-m flat section of terrain for each height map). Using the value of θ at each distance interval and $h = 1$, $d = 0.25$, and $r = 1$, we next calculated the instantaneous value of $p(\text{ground})$ for an altitude of 25 m and the instantaneous value of $p(\text{ground})$ for an altitude of 35 m, using Equation 2 or 3. The instantaneous values for each of the three height maps were next averaged to calculate the mean value of $p(\text{ground})$ for an altitude of 25 m (denoted $p(\text{ground})_{25}$) and the mean value of $p(\text{ground})$ for an altitude of 35 m (denoted $p(\text{ground})_{35}$). Note that the two altitudes used do not affect the calculation as long as they are equal intervals from the target altitude of 30 m. For $h = 1$ and $d = 0.25$, $p(\text{ground})_{25}$ was .989 and $p(\text{ground})_{35}$ was .909. Finally, from these two values we calculated the slope relating $p(\text{ground})$ to altitude using the formula

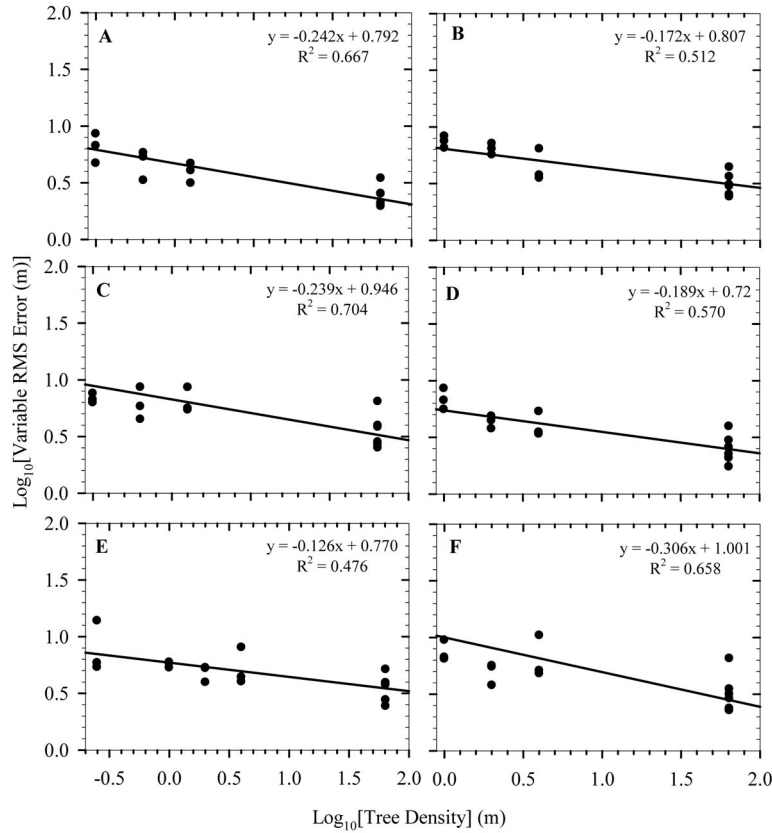


Figure 8. The effect of tree density on altitude-maintenance performance. The \log_{10} (variable RMS error) is plotted as a function of \log_{10} (tree density). Panels A–F are data from Participants 1–6, respectively. Solid lines are linear, best fit functions whose slopes, y-intercepts, and associated R^2 values are shown in each panel.

$$p(\text{ground})_{\text{slope}} = \frac{p(\text{ground})_{25} - p(\text{ground})_{35}}{35 - 25}. \quad (5)$$

For $h = 1$ and $d = 0.25$, $p(\text{ground})_{\text{slope}}$ was found to be .008. The value $p(\text{ground})_{\text{slope}}$ was calculated for all other combinations of tree height and tree density in a similar fashion. These slopes give a quantitative measure of the effectiveness of visual occlusion as a cue to altitude maintenance for each combination of these variables.

If the participants in Experiment 1 were using visual occlusion to maintain altitude, then we should be able to predict the measured variable RMS error for each participant from the $p(\text{ground})_{\text{slope}}$ values for each combination of tree height and tree density (i.e., when the value of $p(\text{ground})_{\text{slope}}$ is larger, variable RMS error should be smaller). Because we predicted an inverse relationship between variable RMS error and $p(\text{ground})_{\text{slope}}$, we used the inverse of the $p(\text{ground})_{\text{slope}}$ values in our model. The solid circles in Figure 10 plot $\log_{10}[1/p(\text{ground})_{\text{slope}}]$ as a function of $\log_{10}(h \times d)$. Also plotted in Figure 10 is mean \log_{10} (variable RMS error) for each of the participants (1–6) in Experiment 1. Predictions from the visual occlusion model provided a good fit to the experimental data, indicating that the magnitude of visual occlusion in the display was related to altitude-maintenance performance. Correlations between the model predictions and the observed data ranged from .82 to .91 for the 6 participants. These

correlations were significant for all 6 participants: Participant 1, $r(16) = .91, p < .001$; Participant 2, $r(16) = .87, p < .001$; Participant 3, $r(16) = .87, p < .001$; Participant 4, $r(16) = .89, p < .001$; Participant 5, $r(16) = .86, p < .001$; Participant 6, $r(16) = .84, p < .001$. As can be seen in Figures 7–9 and in the correlations above, similar results were found for author R.G. (Participant 3) and for the 5 naive participants.

Constant RMS errors, which may be taken as a measure of accuracy of altitude-maintenance performance, were analyzed using two separate 3×3 repeated measures ANOVAs corresponding to experimental Blocks 1 and 2. For both Block 1 and Block 2, neither the main effects of height or density nor the Height \times Density interaction was significant.

Consistent with the previous work of Kleiss and Hubbard (1993) and Kleiss (1995), we found in Experiment 1 that the precision of altitude-maintenance performance was significantly influenced by the density of 3-D objects on the terrain surface. Variable RMS error decreased significantly up to a tree height of about 3–5 m and up to a tree density of about 12 trees/km². Although both tree height and tree density produced significant main effects, a stronger predictor of performance in Experiment 1 was the product of these two variables, which explained a significantly larger proportion of the variance in the variable RMS error data than did either variable alone.

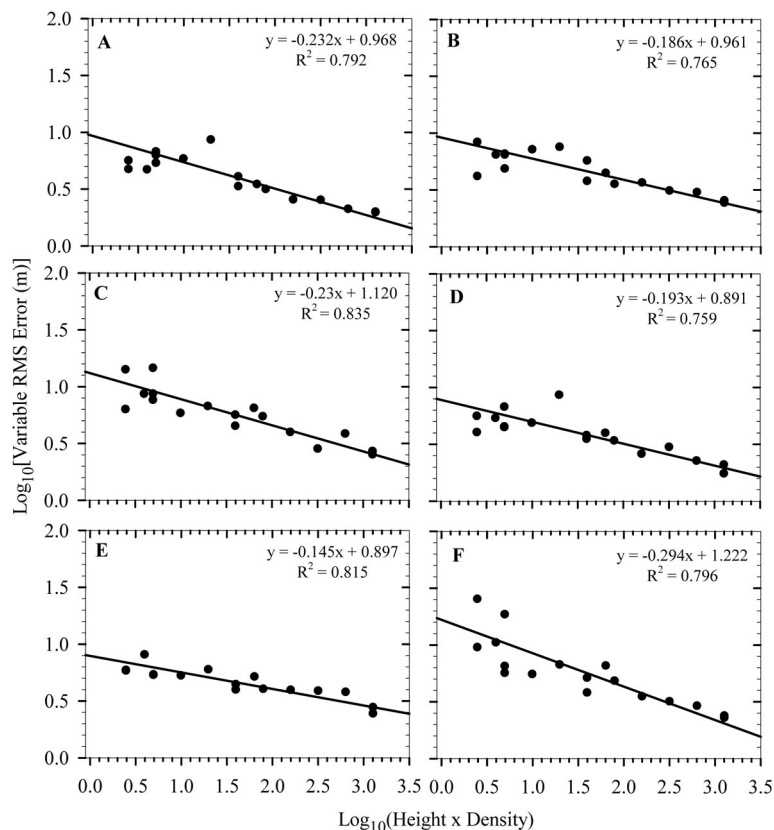


Figure 9. $\text{Log}_{10}(\text{variable RMS error})$ in altitude maintenance is plotted as a function of $\text{log}_{10}(\text{height} \times \text{density})$. Panels A–F are data from Participants 1–6, respectively. Solid lines are linear, best fit functions whose slopes, y-intercepts, and associated R^2 values are shown in each panel.

Experiment 2: The Effect of 3-D Object Radius and Density

Purpose

In Experiment 1, we found a strong interaction between object height and object density on altitude-maintenance performance. This interaction was also reflected in high R^2 values for curve fits between the product of height and density and the variable RMS error in altitude maintenance. We also applied a visual occlusion model of altitude-maintenance that explicitly incorporates object height and density and correlated highly with the altitude-maintenance data. The product of 3-D object height and density is directly related to the total area of the 3-D objects and hence is a direct measure of the terrain area occluded by those objects. However, the same is true of the product of 3-D object width and density. Whereas there is no distinction between object height and object width in the occlusion model of Equations 1–3, these two variables may be expected to have different effects on motion perspective and hence on altitude-maintenance performance. The available experimental evidence suggests that motion-perspective cues are affected by vertically extended contours (Patterson et al., 2003) but not horizontally extended contours (Covas et al., 2005). In Experiment 2, we varied the radius (width) of 3-D objects in order to determine whether increasing horizontally extended oc-

clusions affected altitude-maintenance performance differently than did the increase in vertically extended occlusions, which was tested in Experiment 1.

Method

Stimuli and apparatus. The apparatus was as described for Experiment 1. In Experiment 2, nine databases were constructed using combinations of three tree densities (2, 4, and 64 trees/ km^2) and four tree radii (0, 0.5, 2.5, and 5 m). The radius of the tree trunk was held constant at 0.5 m. Tree height was 10 m for all trials (see Figure 5, middle panel).

Procedure. The procedure was identical to that described for Experiment 1. Tree radius and density were held constant during each run. Each participant completed three repetitions for each of the nine conditions for a total of 27 trials per session.

Participants. Four participants (designated 7–10) between the ages of 18 and 47 participated in the experiment. None of these participants had participated in Experiment 1. All participants had normal or corrected-to-normal vision as determined by the acuity, binocular vision, color vision, and phoria tests of the Optec Vision Tester. Participant 7 was author C.C. All other participants were naive to the aims of the experiment and were paid an hourly rate.

Data analysis. Because we found in Experiment 1 that tree height and density did not have a significant effect on constant

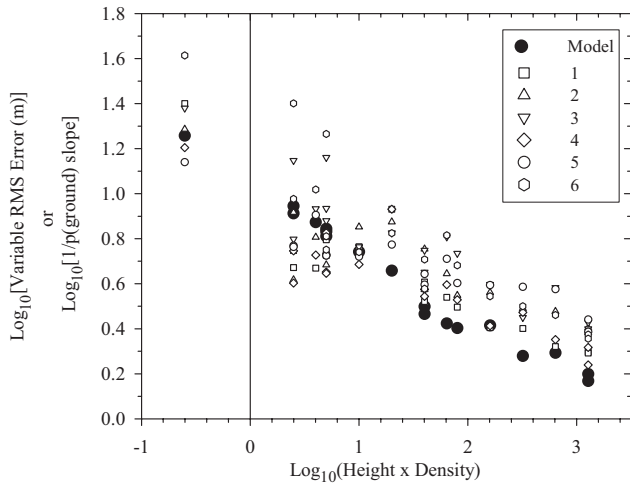


Figure 10. Model predictions ($\log_{10}[1/p(\text{ground})_{\text{slope}}]$) and experimental data ($\log_{10}(\text{variable RMS error})$) for the 6 participants are plotted as a function of $\log_{10}(\text{height} \times \text{density})$.

RMS error, we chose to analyze only variable RMS error in Experiment 2. We compared the amount of response variance that could be explained by either tree radius (r) or tree density (d) alone with the amount that could be explained by the product $r \times d$.

Results and Discussion

Shown in Figure 11 (A–D) is $\log_{10}(\text{variable RMS error})$ plotted as a function of $\log_{10}(\text{tree radius} \times \text{tree density})$ for Participants 7–10. Solid lines again show linear curve fits to the data. For the product of tree radius and tree density ($r \times d$), R^2 ranged from .62

to .83. For radius alone, R^2 ranged from .01 to .06, and for density alone, R^2 ranged from .39 to .61. R^2 values were compared statistically using pairwise t tests. This analysis revealed that the variance in variable RMS error explained by the product $r \times d$ was significantly greater than the variance explained by r alone, $t(3) = -12.4, p < .01$, or by d alone, $t(5) = -6.0, p < .01$.

A 3×3 repeated measures ANOVA performed on the variable RMS error data revealed significant main effects of tree density, $F(2, 6) = 33.8, p < .001$, and tree radius, $F(2, 6) = 7.9, p < .05$, and a significant Density \times Radius interaction, $F(4, 12) = 3.5, p < .05$.

To allow for comparison between predictions from our visual occlusion model and the data of Experiment 2, we performed the slope calculations described in Experiment 1, in this case using the various combinations of tree density and tree radius. Figure 12 shows $\log_{10}[1/p(\text{ground})_{\text{slope}}]$ and mean $\log_{10}(\text{variable RMS error})$ plotted as a function of $\log_{10}(r \times d)$ for each of the 4 participants in Experiment 2. The correlation between model predictions (i.e., r values) and mean variable RMS errors ranged from .77 to .87 for the 4 participants in Experiment 2, indicating that the visual occlusion model again provided a good fit to the experimental data. These correlations were all significant: Participant 7, $r(16) = .82, p < .001$; Participant 8, $r(16) = .86, p < .001$; Participant 9, $r(16) = .77, p < .001$; Participant 10, $r(16) = .87, p < .001$. As can be seen in Figures 11 and 12, similar results were obtained for author C.C. (Participant 7) and the 3 naive observers in Experiment 2.

Experiment 3: Control Experiment—Dissociation of Object Height and Object Area

Purpose

In Experiment 1, tree width was proportional to tree height, and therefore changes in height also resulted in changes in the total

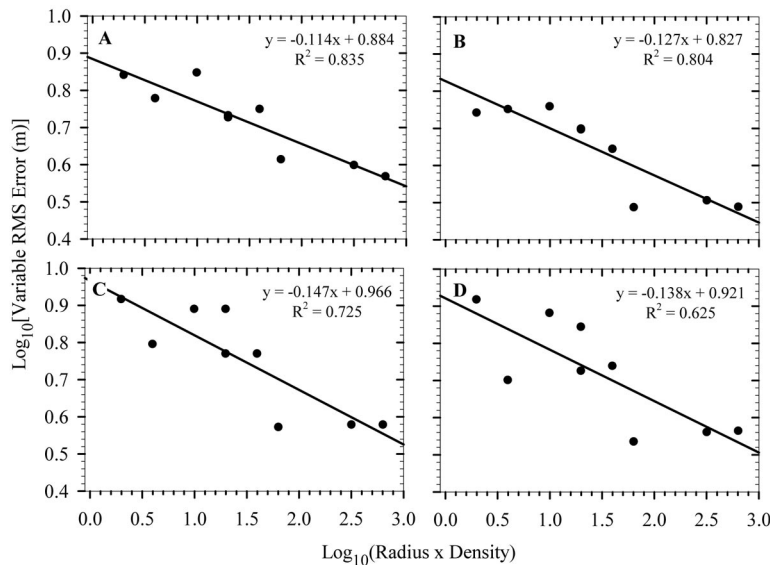


Figure 11. $\log_{10}(\text{variable RMS error})$ in altitude maintenance is plotted as a function of $\log_{10}(\text{radius} \times \text{density})$. Panels A–D are data from Participants 7–10, respectively. Solid lines are linear, best fit functions whose slopes, y-intercepts, and associated R^2 values are shown in each panel.

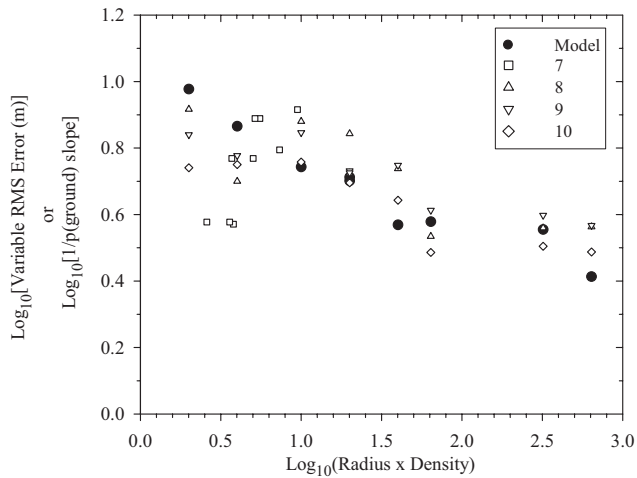


Figure 12. Experimental data ($\log_{10}(\text{variable RMS error})$) for the 4 participants and model predictions ($\log_{10}[1/p(\text{ground})_{\text{slope}}]$) are plotted as a function of $\log_{10}(\text{radius} \times \text{density})$.

angular subtense of the tree (i.e., its area). In Experiment 2, we dissociated object width and object area in order to assess their relative effect on altitude-maintenance performance. In Experiment 3, we attempted to dissociate object height and object area. We did this by replacing the trees used in Experiment 2 with trees of different heights but whose tops (foliage) were constant in size.

Method

Stimuli and apparatus. The apparatus was identical to that described for Experiments 1 and 2. Three databases were created using combinations of the tree density of 64 trees/km² and each of the three tree heights of 2.5, 10, and 20 m. Treetop radius was held constant at 1.25 m, and trunk radius was held constant at 0.5 m (see Figure 5, bottom panel). Object height was varied by changing the length of the trunk.

Procedure and participants. The experimental procedure and participants were identical to those described for Experiment 1. Tree height and density were held constant during each run, which consisted of nine trials. Each participant completed three repetitions for each of the nine combinations of tree height and tree density, for a total of 27 trials per session.

Results and Discussion

The mean variable RMS error (averaged across the four blocks of trials) and standard errors of the mean for each of the 6 participants are 3.20, 2.95, 2.96, 2.41, 2.40, and 3.02 m and 0.25, 0.30, 0.19, 0.23, 0.35, and 0.31 m, respectively. *T* tests (with a Bonferroni correction for inflation of Type I error) revealed no significant differences among the mean variable RMS errors of Experiments 1 and 3 ($p > .5$ for all). Therefore, we argue that the variations in altitude-maintenance performance associated with changes in tree height in Experiment 1 cannot be explained by the associated changes in the tree area, because removing the latter cue did not significantly alter performance.

Experiment 4: The Effect of Mixed 3-D Object Heights

Purpose

In Experiments 1 and 3, we simulated the special case where all 3-D objects in a given scene had the same height (i.e., tree height was varied only across trials). In Experiment 4, we further tested the visual occlusion model by investigating altitude maintenance in the more ecologically valid condition of LAF over simulated terrains with a mixture of different tree heights.

Method

Stimuli and apparatus. The apparatus was identical to that described for Experiments 1–3. One database was created with a tree density of 64 trees/km² and the three tree heights of 2.5, 10, and 20 m. Trees of different heights were randomly placed along the flight path.

Procedure, participants, and data analysis. The experimental procedure was identical to that described for Experiment 1, except that all tree heights were presented intermixed during each trial. All participants completed four runs. The 6 participants of Experiment 1 also participated in Experiment 4. Variable RMS error was analyzed as described for Experiment 1.

Results and Discussion

$\log_{10}(\text{variable RMS error})$ and associated \log_{10} of the standard errors of the mean for each of the 6 participants are shown in Figure 13. The horizontal line in the figure is $\log_{10}[1/p(\text{ground})_{\text{slope}}]$, calculated as described for Experiment 1. The $\log_{10}(\text{variable RMS error})$ averaged across the 6 participants was 0.44 m ($SEM = 0.02$ m), which was not significantly different from the predicted value of 0.43 for the slope of $\log_{10}[1/p(\text{ground})]$: $t(5) = 0.5$, $p > .5$. Again, results were similar for author R.G. (Participant 3) and the 5 naive participants in this experiment.

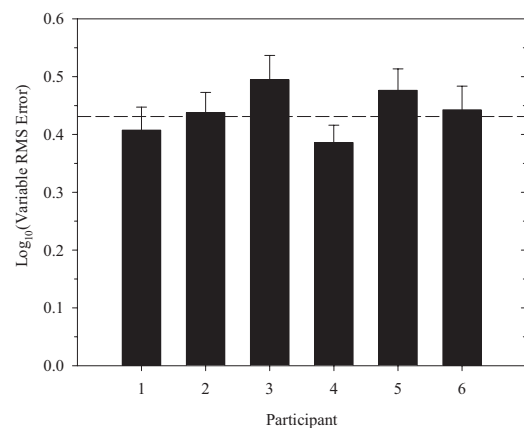


Figure 13. $\log_{10}(\text{variable RMS error})$ is plotted as a function of $\log_{10}(\text{height} \times \text{density})$ for the 6 participants of Experiment 4. The dashed horizontal line shows the value of $\log_{10}[1/p(\text{ground})_{\text{slope}}]$ predicted from the visual occlusion model. Error bars are standard errors of the mean.

General Discussion

Evidence for Visual Occlusion as a Cue to Altitude Maintenance

There are several visual cues that pilots could use for altitude maintenance in LAF. In the present study we chose to focus on one of these cues, visual occlusion, which has not been investigated previously. Leung and Malik (1997) showed that the amount of visual occlusion present in a scene made up of 3-D objects oriented perpendicularly to the ground (as expressed by the amount of ground surface that is visible to the observer) is related to the product of object height, object density, and object radius (see Equation 1). Therefore, if occlusion is used as a cue to altitude, we would expect altitude-maintenance performance to be related to interactions between and among these variables. In Experiment 1, we found that in our simulated altitude-maintenance task, significantly more performance variance was explained by the product of height and density than by either of these variables alone. In Experiment 2, we found that significantly more performance variance was explained by the product of radius and density than by either of these variables alone. These findings are consistent with the idea that our participants were using changes in the magnitude of visual occlusion (e.g., changes in the amount of visible ground surface between trees) as a visual cue to altitude maintenance.

Even stronger evidence for the role of visual occlusion in altitude maintenance comes from an analysis of the data of Experiments 1, 2, and 4. Using an equation derived by Leung and Malik (1997), we suggest a perceptually plausible, quantitative description of the role of visual occlusion in altitude maintenance (see Equations 2 and 3). These equations predicted altitude-maintenance performance that was significantly correlated with actual performance when object height and density were varied across experimental blocks (Experiment 1), when object radius and density were varied across experimental blocks (Experiment 2), and when object height was randomized in each database (Experiment 4).

Although visual occlusion has been studied primarily using passive perceptual judgments (e.g., the judgment of relative depth; Anderson, 2003), it has also been shown to be used for the control of motor actions such as reaching (Bingham, Bradley, Bailey, & Vinner, 2001). Here we provide further evidence that this visual cue is important for the control of action. It has been previously suggested that the visual occlusion created by objects oriented perpendicularly to a surface may be a useful cue for the judgment of surface slant (Saunders, 2003; Stevens, 1981). However, in a slant-matching task, Saunders (2003) reported that there was no evidence that the addition of occlusion cues improved the accuracy of slant judgments.

The Use of Other Visual Cues to Altitude Maintenance

Previous research on altitude maintenance in LAF has primarily used simulated terrains with only 2-D textures (e.g., Flach et al., 1992; Johnson et al., 1989; Wolpert et al., 1983). The few studies that have used simulated terrains with 3-D objects have found that the addition of objects oriented perpendicularly to the terrain does improve performance (Kleiss, 1995; Kleiss & Hubbard, 1993). However, it is not clear from these studies which visual cues are

being used. As discussed in the introduction, there are numerous 2-D and 3-D visual cues that a pilot could use for altitude maintenance. Next, we discuss the implications of the present findings for each of these visual cues.

Splay and depression angles. As discussed earlier, it is unclear how to define splay and depression angle when the terrain consists of randomly placed 3-D objects. For the simulated terrain shown in Figure 6, there are no clear "terrain edges" oriented perpendicularly or parallel to the path of travel. The optical flow lines (Gibson, 1958) produced by forward motion could potentially be used to compute a type of splay angle (i.e., the angle between the path of travel and an optic flow vector); however, this optic-flow/splay angle would be unaffected by changes in object height and radius for a given object density. Given that tree height and radius significantly affected the performance of our participants, the present study does not provide support for the use of splay and depression angles as the primary visual cues for altitude maintenance over simulated terrains and objects similar to those tested here.

Perceived object density. In Experiment 3, we created simulated imagery in which the area of 3-D objects was constant for all object heights. In this experiment, the texture density provided by the 2-D terrain would be the same for all object heights. Because a significant effect of tree height was still observed in Experiment 3, it appears that, at least for relatively sparse objects, perceived density is not a primary cue for altitude maintenance in the context of the present study.

Change in angular size of objects. The change in the angular size of objects is potentially a salient cue to altitude (Fitzpatrick, Pasnak, & Tyler, 1982). This cue would be expected to vary with object density, but if objects are large enough such that altitude-related size changes are above threshold, we would not expect it to be affected by either object height or object radius. The strong effect of the product of object height and object radius on altitude maintenance found in the present study suggests that visual occlusion is a more salient cue to relative altitude than is changes in angular size.

Motion perspective. Motion perspective, as conceptualized by Gibson (1950, 1979), is a fundamental component of the moving imagery used to simulate LAF. In fact, Gibson's work was initiated in the context of pilot training and specifically the training of aircraft takeoff and landing (see, e.g., Bruce, Green, & Georgeson, 1997).

Motion perspective is defined by the movement of objects (2-D or 3-D) relative to each other and to the moving participant. Although we have assessed the Leung and Malik (1997) model by comparing the degree of ground occlusion in successive temporal views of the visual scene, observer motion per se was not required for that assessment. Furthermore, changes in the degree of ground occlusion have not been studied in the context of motion perspective. Therefore, the Leung and Malik model, as well as our Equations 2 and 3, cannot be used to assess the relative role of motion perspective and visual occlusion in LAF.

The Role of Learning in the Use of Visual Occlusion

A question that arises from our findings concerns the degree to which our participants learned to use visual occlusion for altitude maintenance as opposed to other cues in the visual scene, such as

angular size. Because we used the same set of participants in Experiments 1, 3, and 4, one could argue that the visual occlusion model explained a large degree of performance variance in Experiments 3 and 4 primarily because participants learned to use this visual cue in Experiment 1 (perhaps owing to the limited range of stimulus parameters). We would argue that this learning explanation is not likely to have contributed to our results given that the order of the experimental conditions was biased in favor of participants learning to use angular subtense. In Experiment 1 the total angular subtense of the objects (i.e., area) was varied for the different simulated terrains, whereas in Experiment 3 object area was constant. Therefore, object area was a more salient visual cue for altitude maintenance in the first set of conditions participants completed. Similarly, in Experiment 1 tree height was constant within each trial, whereas in Experiment 4 tree height varied across the terrain for each trial. Therefore, angular tree height was a more salient cue in the first set of conditions participants completed. The fact that participants in Experiment 2, who did not complete any of the other experiments, also appeared to use visual occlusion for altitude regulation is also inconsistent with the notion that our participants learned to use visual occlusion because of the stimulus set used in Experiment 1.

Practical Implications

Owing to both computational and display limitations, flight simulator designers must often make trade-offs in display design, which may have important implications for training. For example, in order to achieve a high level of detail on the surface of objects and on the ground terrain while at the same time keeping the frame rate sufficiently high, one must keep object density sufficiently low. Therefore, it is critical to identify the relative importance of the different display parameters (e.g., object detail vs. object density) to flight performance to ensure that these trade-offs result in positive transfer of training between simulated and actual flight. From the results of the present study, there appears to be an important trade-off between both object height and object density, and object radius and object density. If it is necessary to have a simulation with low object density, the results of the present study suggest that good LAF performance can be maintained by using taller and/or wider objects.

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Received April 12, 2006

Revision received August 23, 2006

Accepted August 25, 2006 ■

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