2D vs. 3D Visual Cues for Altitude Maintenance in Low-Altitude Flight

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Previous research on altitude maintenance in low-altitude flight has focused either on cues provided by 2D features in the visual scene (e.g., splay angle) or on visual cues provided by the presence of 3D objects in the scene (e.g., occlusion). Therefore, little is known about the relative importance of 2D and 3D cues in altitude maintenance. We systematically varied the position variability, height, and pattern of surface elements in a simulated low-level flight environment to vary the salience of 2D and 3D visual cues. For 2D objects, altitude variability increased as a function of object position variability indicating that splay and depression angles are not reliable cues for terrains with irregularly spaced objects. For 3D objects, altitude variability increased less (or not at all) as a function of position variability indicating that the cues provided by 3D objects such as occlusion and motion parallax are the dominant visual cues for altitude maintenance for natural terrains with irregularly spaced objects.

INTRODUCTION

Of all 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/sec (450 kts). 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.

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. Early research on altitude maintenance in LAF focused primarily on the visual information provided by a 2D texture on a flat terrain surface. For example, Flach, Hagen and Larish (1992) identified two visual cues that could be used by pilots: 1) the *depression angle*- the visual angle formed by the horizon and a terrain edge that is oriented perpendicularly to the direction of motion, and 2) 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. 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 3D objects of varying heights may reduce the effectiveness of those cues, however this has not been empirically tested

Another set of studies has focused on visual cues provided by the presences of 3D objects in the scene, such as buildings or trees. For example, Kleiss and Hubbard (1993) used an altitude-change detection task in which participants flew over a simulated ground terrain populated with different types of 3D objects. Altitude change detection was good even when there was no texture on the ground surface suggesting that changing object size was a reliable visual cue to altitude maintenance. More recently it has been shown that the presence of 3D objects provides motion parallax (Covas, Patterson, Geri, Akhtar, Pierce, & Dyre, 2005) and visual occlusion (Gray, Geri, Akhtar, & Covas, 2007) cues that can be used to maintain altitude.

Given that there are multiple visual cues that can be used for altitude maintenance in LAF, how are these different cues combined/weighted and how does their relative effectiveness vary as a function of terrain conditions? Unfortunately, it is difficult address these questions from previous research because; (i) most previous studies have used either exclusively 2D textures or exclusively 3D objects, and (ii) different experimental tasks have been used in the 2D and 3D studies. These limitations make it difficult to compare the relative effectiveness of the different visual cues described above.

In the present study we systematically varied the visual scene content (from simple 2D textures to 3D objects) in attempt to vary the salience of the 2D and 3D visual cues to altitude maintenance in LAF. Altitude maintenance performance was quantified using the wind disturbance task developed by Flach, Warren and colleagues. We hypothesized that as the layout of objects on the ground became more irregular, successful altitude maintenance would rely more heavily on the presence of 3D objects in the environment.

METHODS

Participants

Six participants completed the experiment. 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 Co., Inc., Chicago, IL).

Apparatus

The simulated ground terrain was a flat grey plane populated with black bars of varying heights, lengths, positions and orientations. As shown in Figure 1, the simulated image was displayed over three simulator-display channels [each 133 cm (H) x 111 cm (V)], and subtended a visual angle of 180° (H) × 63° (V). Each channel consisted of 1600 × 1200 pixels and was displayed using a rear-projection CRT (Barco Inc., Model 808). Flight over the terrain was simulated using a PC-based runtime system with a 60 Hz frame rate.

Figure 1: View of simulated ground terrain.

Three aspects of the black objects on the ground terrain were varied randomly across trials: (1) *pattern, (2), position variability,* and *(3) height.* Three patterns of objects were used: splay (all objects were oriented parallel to the path of travel), depression (all objects were oriented perpendicular to the path of travel), and grid (half of the objects were parallel, half were perpendicular). Within these patterns the positions and orientations of the bars were also varied. Three levels of position variability were used: none, medium or high. Three levels of object height were used: 0m (i.e., the object was 2D), 10m and 20m. Examples of some of these terrains are shown in Figure 2.

Procedure

Each trial began with simulated flight over the terrain with no simulated wind disturbance at an airspeed of 232 m/sec (450 kts) 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 when the wind disturbance began. Participants were able to control pitch and altitude by pulling back or pushing forward on a joystick. This portion of the flight lasted 8 sec after which simulated wind disturbances were initiated. The wind disturbance was in the up/down direction with amplitude determined by the sum of three sinusoids. Flight time during the wind disturbance lasted for 52 sec. Altitude was sampled every 0.25 sec. 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 one-minute trial, although there was a minimum of 7 sec between trials in order to reduce motion adaptation.

All participants completed 5 repeats of the 27 terrains (3 patterns X 3 levels of position variability x 3 heights). The order of terrains was counterbalanced across participants.

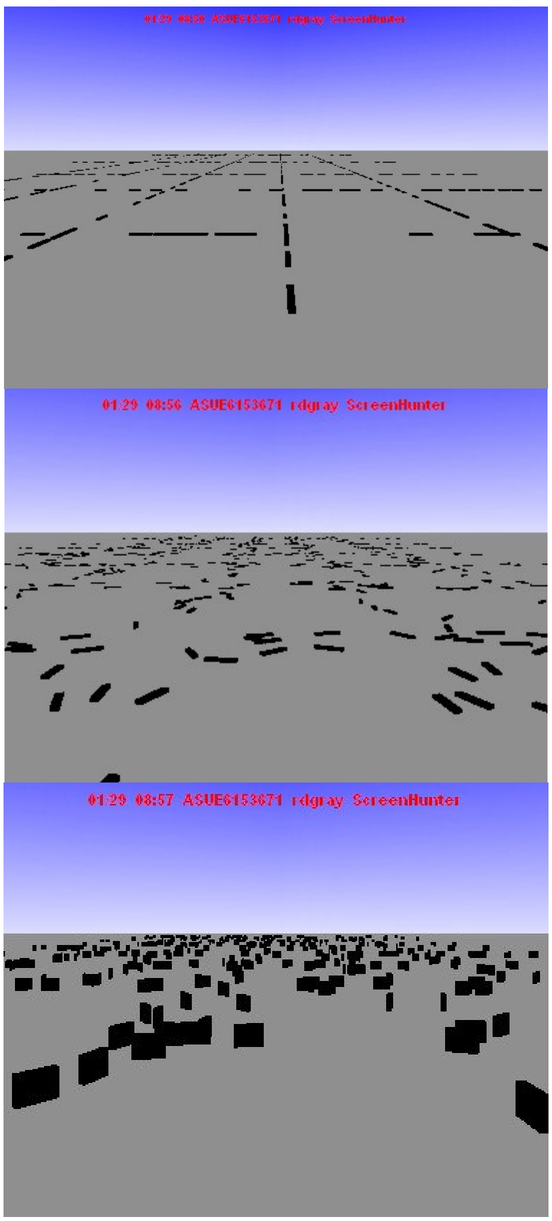

Figure 2: Example terrains. A: grid pattern, no position variability, 0m height. B: grid pattern, high position variability, 0m height. C: grid pattern, high position variability, 10m height.

Data Analysis

The primary dependent measure was the variability in altitude (VARalt) during the final 52 sec of each trial. Mean VARalt values were analyzed using a 3 x 3 x 3 repeated measures ANOVA.

RESULTS

Figure 3 shows the mean variance in altitude (averaged across the six participants) as a function of object position variability for the three object heights.

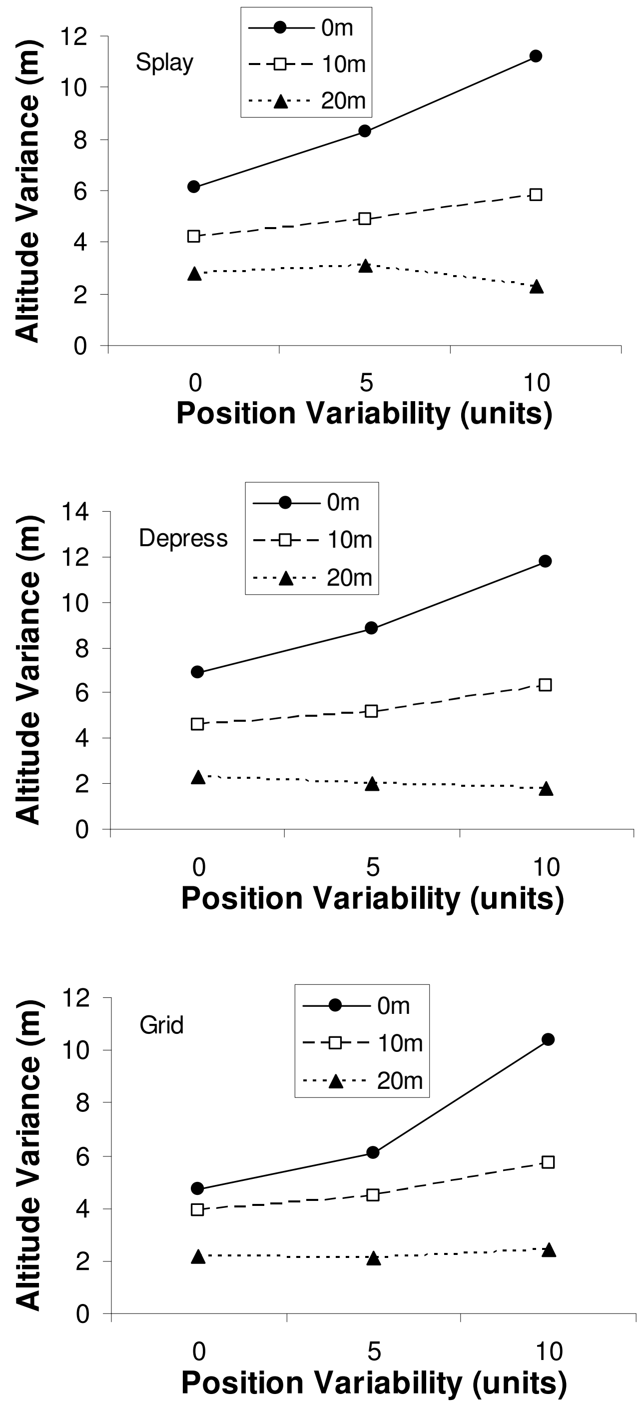

Figure 3: Variability in altitude as a function of object position variability. A: Splay pattern. B: Depression pattern. C: Grid pattern.

For all three terrain patterns, mean altitude variance increased as a function of position variability for the 0m and 10m tree heights but not for 20m tree height. The 3x3x3 ANOVA revealed significant main effects of Position Variability [$F(2,10)=15.6, p<0.01$] and Object Height [$F(2, 10)=9.3$, $p<0.01$]. There was also a significant Position Variability x Object Height interaction [$F(4,20)=23.6$, $p<0.01$]. None of the other effects were significant.

DISCUSSION

In the present study we found that varying the regularity and height of surface elements on the ground terrain had a substantial effect on altitude maintenance performance. For the 0m object height (i.e., 2D objects), variability in altitude increased as a function of object position variability for the splay, depression and grid terrain patterns. This finding indicates that splay and depression angles are not reliable cues to altitude maintenance for terrains with irregularly spaced elements. This decline in altitude maintenance performance with increasing element irregularity was strongly mediated by object height: for the 10m objects there was only a slight increase in altitude variability while for the 20m objects there was no significant effect of position variability on altitude maintenance performance. This later finding suggests that when tall 3D objects are present in the visual scene observers effectively ignore splay and depression angle and rely on visual cues provided by 3D objects.

We conclude that splay and depression angles are only effective cues for altitude maintenance when the elements in scene are 2D (or very short) and are regularly spaced. For more commonly encountered terrains with irregularly spaced 3D objects occlusion and/or motion parallax will be the dominant cues used for altitude maintenance.

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