Low-Altitude Database Development Evaluation and Research (LADDER)

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ABSTRACT

Singer-Link and the Air Force Human Resources Laboratory (AFHRL), Williams Air Force Base, combined efforts to investigate specific visual requirements during low-level, high-speed flight. Visual information requirements were hypothesized, and an experiment was designed to systematically test the effects of various visual cues upon flight performance. The experiment tested the effects of visual scene elements in supporting simulator flight tasks of experienced Air Force fighter pilots. Specific visual factors studied were: 1.) the importance of surface texture, 2.) the importance of 3-D objects and object type, and 3.) the effect of turning and bank angle upon flight performance. Pilot subjects were able to control flight at a mean altitude of 198 feet and at an airspeed of 480 knots. Test results indicate that both 3-D objects and 2-D terrain surface texture aid controlled low-altitude flight.

INTRODUCTION

Effective air defense systems require tactical and strategic aircraft to fly at very low altitudes and high airspeeds. These altitudes and airspeeds enable the aircraft and crew to use terrain masking and the element of surprise to evade hostile threats. The crew of today's tactical and strategic aircraft must balance the probability of destruction from hostile air defense systems with the probability of destruction from the terrain. A segment of a combat mission route that has a high air defense threat level will cause the aircrew to fly closer to the terrain and to accept a greater hazard from impact with the ground.

Experienced pilots have little difficulty flying at low altitudes. Unfortunately, during a combat mission the pilot must also navigate, monitor the aircraft systems, manage the weapon systems, evade the hostile threats, and perform many other critical tasks. The pilot must practice continually until these tasks can be performed almost automatically.

The amount of aircraft low-altitude, high-speed flight training necessary to attain this performance level is difficult to obtain because of cost, safety, noise, and pollution. Simulators equipped with Computer Image Generation (CIG) visual systems could safely provide the needed training at much lower cost with no environmental impact. The potential of this type of training has been demonstrated and the savings in aircraft and pilots can be predicted (3, 4). However, low-altitude, high-speed combat mission training in simulators is not presently being conducted on a large scale.

A key factor inhibiting the large-scale development of Combat Mission Simulator (CMS) facilities is visual scene content. Present terminology is not adequate to describe scenes, and there is little agreement on the relevant characteristics of a scene (10). In addition, data concerning scene content requirements is scarce (9).

The Low-Altitude Database Development Evaluation and Research (LADDER) study was initiated to examine visual scene content for low-altitude, high-speed flight training, and to gather experimental data that relates experienced pilot performance to visual scene content. To obtain this data, a generic cockpit trainer equipped with a CIG visual system was developed, and a visual database was produced to manipulate several scene content variables throughout a high-speed, low-altitude flight route. The performance of experienced military pilots was recorded during simulated flight and subjected to statistical analysis.

APPARATUS

A special-purpose research simulator was designed and assembled at the Air Force Human Resources Laboratory (AFHRL). The simulator consisted of a modified T-38 instrument trainer cockpit, a modified F-111 Computer Image Generation (CIG) visual system, a special-purpose low-altitude database, and the Advanced Simulator for Pilot Training (ASPT) F-16 flight dynamics and performance measurement systems.

Cockpit

The cockpit was part of a surplus T-38 instrument trainer. Since the LADDER study was concerned only with pilot performance relative to visual imagery, only the airspeed and percent-RPM instruments were functional. All other instruments within the cockpit were static during the experiment.

The T-38 control stick was fixed in the center position, and the pilot's control inputs were sensed by strain gauges. This control system is a hybrid of the F-16 force stick controller and the T-38 center displacement stick. The pilot subjects controlled the simulated aircraft by varying the force applied to the nonmoving stick. The T-38 force stick inputs were directed to the ASPT F-16 flight dynamics simulation program. The program processed the control inputs and generated the appropriate visual system eyepoint movement to simulate an F-16 aircraft flight path.

Visual System

The LADDER visual system consisted of a Singer-Link F-111 Digital Image Generator (DIG) and Wide-Angle Collimated (WAC) displays.

The F-111 DIG is capable of generating three channels of day-dusk-night, full-color scenes. A few modifications were made to increase its scene generation capacity. Each channel presented a computed scene via an array of 875 by 1024 picture elements. The imagery was updated at a rate of 30 Hz.

The WAC displays consist of high-resolution color monitors matched to collimating optics. The displays present a near-infinity virtual image of the computed scene to the pilot. The three displays were oriented as they exist in the F-111 simulator: to the left, center, and right of the aircraft centerline. The total field of view is approximately 36 by 120 degrees.

Low-Altitude Database

The visual system database was specifically designed to evaluate the contribution of different levels of scene content. The basic database consisted of a valley corridor 3000 ft wide, which was bordered by 900- to 1100-ft mountains. Within the valley there were 200-ft transverse level and sloping ridges, and 500-ft hills. The corridor permitted pilots to fly a continuous 420-mile route. The corridor construction forced pilots to continually change their altitude and heading to avoid impact with the terrain.

The experimental database content was chosen for its anticipated importance to the low-level flight task. Previous research and experience of Singer-Link (5, 8), and HRL (1, 2, 6, 7) with CIG database features indicated that some features were expected to have a significant effect upon low-level flight performance. Scene content features were agreed upon by Singer-Link and HRL.

Visual database content was studied for flight at approximately 100-ft AGL and a true airspeed of 480 kt. The visual factors selected were:

1.) Importance of texture and texture size. Four texture conditions were studied: no texture, 150-ft, 300-ft, and 450-ft square texture patterns. Texture was placed only on the floor of the flight corridor.

2.) Importance of 3-D objects and their sizes and shapes. Five object conditions were studied: no 3-D objects; houses, warehouses, or trees alone; and a mixture of all three types of objects.

3.) 90-degree shallow-turn versus 180-degree steep-turn corridor sections. Previous research at HRL indicated that there are significant differences between pilot performance in straight and turning (over 30-degree bank angle) flight. This experiment was designed with two types of corridor configuration to attempt to determine whether there is a difference in visual requirements between the two flight tasks. The 90-degree shallow turn segment did not require a bank angle over 30 degrees, while the 180-degree steep-turn segment required at least a 30-degree bank turn for the entire segment.

All combinations of the 2-D and 3-D database features were placed in steep- and shallow-turning modular sections of a corridor (Table 1). The corridor sections were joined to form a continuous 420-mile flight test corridor (Figure 1). The placement of each section with its particular combination of database features was randomly assigned. Several sections of the corridor were repeated to permit checking the reliability of performance data. The corridor mountains were deleted in two sections to assess their contribution to pilot performance.

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STEEP- and SHALLOW-TURNING FLIGHT

3-D OBJECTS	2-D TEXTURE NONE	150 ft	300 ft	450 ft
NONE	X	X	X	X
HOUSES	X	X	X	X
WARE HOUSES	X	X	X	X
TREES	X	X	X	X
MIXTURE	X	X	X	X

TABLE 1 - TEST CONDITION MATRIX

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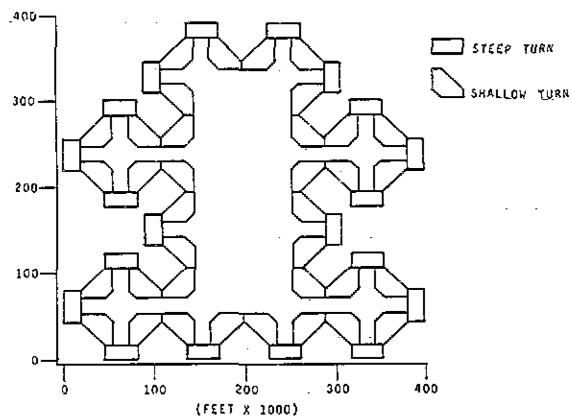

FIGURE 1 - LADDER TEST CORRIDOR

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Subjects

Eighteen experienced fighter pilots with low-level flight experience participated in the experiment. Ten were pilots in F-16 training, and eight were training to be fighter test pilots. The mean age of the pilots was 34.6 years, their mean total flight time was 2,513 hours, and their mean time in fighter/attack aircraft was 1541 hours.

Performance Measurement

The performance sample and measurement capability of the ASPT simulator were used to measure and record flight path parameters. Performance parameters during flight following the practice period were sampled and recorded at a 30-Hz rate. At a prespecified distance in each segment, recording was stopped so that flight performance measurements would not reflect the effect of visual information seen by the pilot when the next corridor segment came into view.

When a crash occurred during flight through a segment, that condition was terminated. The display and cockpit were initialized to the beginning of the subsequent corridor segment, and flight was resumed.

The primary flight parameters recorded at 30 Hz included position, heading, airspeed, altitude, angle of attack, angle of bank, angle of pitch, and crash. Many other parameters were also recorded for possible use in analysis.

Experimental Procedure

Each pilot flew the entire corridor with the starting condition randomly selected. Pilots were instructed to attempt to maintain an altitude of 100 ft above the corridor floor. A few minutes of practice flight were given to each subject, enabling him to accustom himself to the controls and visual system. During the practice flight, altitude and airspeed were announced verbally to the pilot to enable him to visually determine an altitude of 100 ft in reference to the corridor.

Comments made by the pilots and significant flight events were noted by the experimenter throughout the experiment. Each pilot was interviewed following the data collection.

RESULTS

Terrain Crashes

There were a total of 33 crashes with the terrain. The distribution of crashes among the corridor segments are provided in Table 2; 58% of the crashes occurred in steep-turn sections and 42% occurred in shallow-turn sections. Most of the crashes (61%) occurred in sections without 2-D texture on the valley floor. The rest of the crashes were distributed throughout the remaining sections with 2-D texture.

A relatively large number of crashes occurred in two separate corridor sections that had 2-D texture and 3-D objects but no mountain borders.

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STEEP-TURNING FLIGHT

3-D OBJECTS	TEXTURE NONE	450	300	150	SUM	%
NONE	5	0	2	1	8	42
HOUSES	3	1	0	0	4	21
WARE-HOUSES	2	0	0	0	2	11
TREES	2	0	1	1	4	21
MIXTURE	1	0	0	0	1	5
SUM	13	1	3	2	19	
PERCENT	68	5	16	11		

SHALLOW-TURNING FLIGHT

3-D OBJECTS	TEXTURE NONE	450	300	150	SUM	%
NONE	4	0	0	1	5	36
HOUSES	2	0 (3*)	0	0 (7*)	2	14
WARE-HOUSES	0	0	1	0	1	7
TREES	0	0	1	1	2	14
MIXTURE	1	0	2	1	4	29
SUM	7	0	4	3	14	
%	50	0	29	21		

* Section without mountain border

TABLE 2 - NUMBER OF TERRAIN CRASHES

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Altitude Control

The average altitude the pilots maintained above the valley floor (i.e., altitude above flat earth only) for all conditions was 198 ft. The average altitude maintained for shallow-turn segments was 175 ft, and 221 ft for steep-turn segments. The average altitudes maintained for each condition of 2-D texture and 3-D objects are listed in Table 3.

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2-D TEXTURE		3-D OBJECTS	
NONE	199.76	NONE	201.05
150 ft	202.69	HOUSE	201.57
300 ft	193.26	W/HOUSE	197.3
450 ft	197.06	TREE	197.93
		MIXTURE	192.89

STEEP-TURNING FLIGHT = 221.49
SHALLOW-TURNING FLIGHT = 175.12

TABLE 3 - MEAN ALTITUDE (feet)

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The dependent variables of RMS error altitude, maximum altitude, and mean altitude above flat earth were included in a multivariate analysis (the SPSS MANOVA Procedure Release 9.0) to include univariate F-tests. An alpha level of 0.10 was chosen for the univariate tests. Scheffe's S-method was used to explicate the F-test results. The main effects of turn and object factors were significant on at least two of the three dependent measures. The F-tests on the interaction effects of Objects X Texture was significant. In addition, all subject effects were significant.

It should be noted at the outset that the data contain a high level of between- and within-subject variability, and that the variance is not always distributed heterogenously. The task structure allowed differences in individual flying technique, particularly in terms of lateral flight path (i.e., the pilot chose his path within the 3,000-ft wide corridor). For example, some pilots worked very hard to avoid going over the portions of elevated terrain, whereas other pilots attempted to fly the shortest distances regardless of terrain. In addition, many pilots attempted different strategies during the course. Much of this type of variability cannot be controlled with group-oriented statistical analyses. The nature of the variability may have concealed some effects that may be revealed in a more structured task. The data collection procedure used in this study did not lend itself to idiographic analysis techniques.

The steep-turn corridor section was clearly associated with poorer altitude control than the shallow-turn segment, presumably because of the difficulty of the greater bank angles required in the steep-turn section.

The main effect of texture was not reliable ($p = .069$). There were reliable effects of Object type on both RMS error ($p = .035$) and maximum altitude ($p = .05$). Post hoc tests (Scheffe's S-method) revealed that for RMS error, the Mixed Object condition was significantly better than either the No Object or Houses Only condition. On the maximum altitude variable, the Mixed Object condition was reliably better than the No Object, Houses, and Warehouse conditions. Additionally, the Trees were associated with significantly lower maximum values than Houses, Warehouses, or No Object. Warehouses were reliably better than No Objects.

There was a significant Objects X Texture interaction. The post hoc tests revealed that the condition of 300-ft square texture and Mixed Objects was associated with significantly lower mean altitudes than no texture with Houses or Mixed Objects, 150-ft square texture wih either No Objects or Houses, 300-ft square texture and No Objects, or 450-ft square texture with Trees.

In summary, altitude control was significantly worse in the steep-turn sections; the Mixed Object condition was the best, with Trees second-best and No Objects worst. There was no reliable main effect of texture on altitude control, but there was a reliable interaction between objects and texture such that the combination of 300-ft square pattern with Mixed Objects was the best condition.

Pilot Reports

The pilots' subjective comments concerning the effectiveness of the various combinations of scene content indicated that most of the test conditions were able to support low-altitude 480-kt flight. The comments contained no consistent preference for either texture size or object type. Many pilots commented that they had no idea of how high or low they were in the No Object or No Texture condition. The pilots' levels of comfort and confidence with the scenes increased as features were added to the corridor segments. The ranking from low to high resulting from additional corridor content was 3-D objects, 2-D surface texture, and both 3-D and 2-D features.

Experienced pilots felt they could follow the terrain at low altitudes in the LADDER database. After completing the experiment, which lasted over an hour, many pilots requested more simulator time to test their flight control capabilities beyond the task of maintaining an altitude of 100 ft. During these unrecorded sessions, pilots consistently flew at altitudes as low as 30 ft without crashing.

DISCUSSION

Considering the results of the terrain crash and altitude data along with pilot opinion, it is clear that a combination of 3-D objects and 2-D terrain surface texture best supports controlled low-altitude flight. The distribution of terrain crashes most clearly reflects the importance of both types of cues. The results of previous research had led us to expect a more systematic relationship of performance with respect to the size of surface texture squares. The present study did not reveal a reliable main effect of surface texture. The ordinal rankings suggest that the 300-ft square condition was the most effective and the No Texture condition the least effective. It is curious that the clear inferiority of the No Texture condition as reported by the pilots and reflected in the distribution of terrain crashes was not reflected in at least the RMS error measure. However, note that the visual database included modeling the effects of sun angle so that shading cues were almost always present to signal variations in terrain, and that the bordering mountains provided strong peripheral cues to changes in altitude. This suggests that even the most impoverished cue conditions contained sufficient information about surface orientation for some altitude control.

Another somewhat surprising finding is the effectiveness of the Mixed Object condition. The results of previous research had indicated the potential for abstract geometric shapes (pyramids and cones) to aid in altitude control and terrain avoidance. However, the Mixed Object condition did not differ significantly from the Tree condition on the Maximum altitude variable, and both were superior to the two building types and to no objects at all. On the RMS error measure only, the Mixed Object condition was found to be reliably superior to the Houses or No Object condition. It is possible that the differences in size and/or shape of the objects when found together in a section provided a significant enhancement of information that the pilot could use.

A much greater difference in performance attributable to objects and texture was desired. Even the results found to be statistically reliable were not large in terms of absolute magnitude (with the exception of the differences between steep and shallow turn). As noted earlier, problems with performance variability due to the task structure and differences in individual technique may have concealed some perceptual relationships. However, it is equally plausible that since the pilots did not have to simultaneously attend to navigation or tactical tasks, the visual environment provided sufficient information in even the No Object or No Texture condition to maintain relatively good low-level performance. The minimum scene content condition of a corridor with mountains, ridges, and hills (and sun shading) may have been nearly adequate for the pilots to maintain low-altitude flight. The relatively large number of crashes in the two segments without the bordering mountains suggests this might be true. The corridor without texture or objects in the valley is still more complex than most training simulator databases available today. The perceptual problem facing the pilots was also somewhat easy, since the valley floor was always flat and level, except for the obvious ridges and hills. This allowed pilots to make the valid perceptual assumptions that reduced their need for additional visual information to resolve ambiguities.

The pilots who participated in the experiment demonstrated that CIG scenes can support low-altitude, high-speed flight control. During the experiment, the pilots maintained an overall average altitude of 198 ft, which is higher than the 100 ft above the valley floor that the pilots were instructed to maintain. This result should be expected, since the 200-ft ridges within the corridor occasionally forced the pilots to fly higher than 100 ft. In addition, most of the pilots controlled their altitude to fly no lower than 100 ft instead of maintaining an average altitude of 100 ft. These two factors would cause the average altitude to be greater than 100 ft.

The LADDER experiment required the pilots to fly the corridor at low altitude for approximately one hour. Since pilots in the past have often expressed a distaste for flying simulators, it was surprising that many pilots requested more time to exercise both man and simulator to the limits of performance. Their requests and the extremely low flight maneuvers they accomplished during these periods attest to the effectivenes of the scene content in most of the LADDER database corridor sections.

The issue of scene content is far from being resolved. However, the LADDER database has demonstrated that it is possible to produce a CIG database that supports low-altitude, high-speed flight. In this sense, the results of the experiment are very encouraging. Clearly, more basic and applied research is needed to better understand the relationship between pilot performance and visual system database content.

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