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TERRAIN VISUAL CUE ANALYSIS FOR SIMULATING LOW-LEVEL FLIGHT: A MULTIDIMENSIONAL SCALING APPROACH

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Mulidimensional scaling was used to analyze the features of real-world terrain that are salient to pilots during low-level flight. The stimuli were nine short (5-second duration) videotape segments depicting low-level, high-speed flight over a variety of terrain types. The segments were paired in all possible combinations, yielding a total of 36 stimulus pairs. Fifteen experienced pilots rated the visual similarity of each terrain pair on a 10-point scale anchored at 0 with Highly Dissimilar and at 9 with Highly Similar. The rating data were submitted to a nonmetric multidimensional scaling analysis using the procedure ALSCAL. A two-dimensional solution yielded dimensions corresponding to (a) terrain flatness/verticality, and (b) a composite of the size, density and spacing of scene elements. The only two A-10 pilots in the investigation weighted Dimension 2 much more heavily than did any other subjects. These results suggest that (a) efforts should be directed toward effectively modeling vertical features such as hills and ridge lines in simulator visual scenes; (b) a high density of small-scale and closely spaced scene elements (e.g., desert bushes) is less effective than larger-scale, more distinguishable scene elements (e.g., buildings); and (c) mission requirements for certain aircraft (e.g., the V-10) may place special emphasis on particular types of scene content.

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SUMMARY

Real-world terrain provides a rich array of visual cues for controlling altitude during low-level flight. To simulate low-level flight, relevant visual cues must also be modeled in flight simulator visual scenes. Multidimensional scaling was used in the present investigation to identify the features of real-world terrain that are salient to pilots in the low-level, high-speed flight arena. Nine short (5-second duration) videotape segments depicting low-level, high-speed flight over a variety of terrains were paired in all possible combinations. Fifteen pilots rated the similarity of each terrain pair relative to visual cues for low-level flight. A multidimensional scaling analysis of the rating data revealed one dimension that corresponded to terrain flatness/verticality and a second dimension that corresponded to a composite of the size, density and spacing of scene elements. The only two A-10 pilots in the investigation weighted this second dimension much more heavily than did F-5 and A-7 pilots.

These results suggest that techniques should be developed to effectively model visual cues arising from vertical features (e.g., masking and motion shear) in flight simulator visual scenes. Although high element density is important, small and closely spaced scene elements appear to be less effective than larger, more spatially distinct elements. Lastly, mission requirements for certain aircraft such as the A-10 may require special emphasis on particular terrain features.

PREFACE

This effort was conducted in support of the current Air Force Human Resources Laboratory (AFHRL) Research and TechnologyPlan, one objective of which is training research and development to maintain air combat readiness and, specifically, the Visual Scene and Display Requirements goal.

This work was performed in support of AFHRL Work Unit No. 1123-32-03, Tactical Scene Content Requirements, Principal Investigator, Dr. Elizabeth L. Martin, and 1123-03-83, Flying Training Research Support, Contract No. F33615-87-C-0012, Contract Monitor, Capt Claire A. Fitzpatrick. One of the objectives of these work units is to identify flight simulator visual scene content factors that contribute to training effectiveness for low-altitude flight.

The idea for this research arose out of conversations with Drs. Herbert H. Bell and Peter M. Crane, AFHRL Operations Training Division (AFHRL/OT), to whom the author is grateful. The author also wishes to thank Drs. Elizabeth L. Martin and Dee Andrews (AFHRL/OT) for helpful comments on an earlier draft of this report; Dr. David C. Hubbard, who assisted with data analysis; Mr. DeForest Joralmon, who edited the videotapes; and Ms. Marge Keslin, who oversaw final editing.

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I. INTRODUCTION

Real-world terrain provides a rich array of geographic and cultural features that are potentially useful to pilots as visual cues for controlling altitude during low-level, high-speed flight (Academic Text: Low Altitude Training, 1986). It follows that to simulate low-level flight, effective visual cues must also be represented in flight simulator visual scenes. An important question for designers of simulator scenes concerns which terrain features are most effective as cues.

Increases in simulator scene detail facilitate performance of a variety of tasks involving flight near the terrain surface. Example tasks include altitude control in low-level flight (Engel, 1980; Martin & Rinalducci, 1983), dive bombing (Lintern, Thomley-Yates, Nelson, & Roscoe, 1987), and estimation of impact point on final approach to a runway (Barfield, Rosenberg, & Kraft, 1989). However, some types of scene detail are more effective than others. For instance, altitude control is better with lines running parallel to the flight path rather than perpendicular to it (Wolpert, 1988); altitude control is better with three-dimensional objects than with two-dimensional surface texture (Buckland, Edwards, & Stephens, 1981; Martin & Rinalducci, 1983; McCormick, Smith, Lewandowski, Preskar, & Martin, 1983); perception of change in altitude is better with increases in three-dimensional object density than with increases in the realism of individual objects (Kleiss, Curry, & Hubbard, 1988; Kleiss & Hubbard, 1989); and estimation of impact point on final approach to a runway is better with a grid pattern than with dots on the runway (Reardon, 1988). The quest for greater detail in simulator scenes must, therefore, be tempered by the question of what types of detail are most relevant for simulating low-level flight.

It should be noted that all visual cues of interest are represented in the variety and complexity of real-world terrain. The problem, of course, is to identify the relevant cues given large amounts of irrelevant information. Fender (1982) commented that pilots certainly know a great deal about the visual environment in which they fly and that this knowledge would be of great value in designing flight simulator visual displays. Unfortunately, pilots are not necessarily consciously aware of all that they know and may not be able to reliably communicate that information verbally. Fender (1982) suggested that multidimensional scaling may be a useful technique for tapping this type of knowledge.

Multidimensional scaling is a statistical technique that maps the perceived structure of a set of stimulus objects by positioning stimuli within an n-dimensional spatial configuration. The mapping is typically derived from judgments of similarity between stimulus pairs such that similar stimuli are positioned close to one another in space whereas dissimilar stimuli are farther apart. To the extent that judgments are affected by two or more stimulus characteristics, multiple spatial dimensions are required to adequately fit the pattern of similarities. It is assumed that the ordering of stimuli along each spatial dimension in the configuration reflects ordinal position relative to a different stimulus characteristic. Subsequent examination of the properties of stimuli serves to identify the characteristic captured by each dimension.

The present investigation was an attempt to apply multidimensional scaling to the problem of identifying real-world terrain features that are salient to pilots in low-level flight. The stimuli were videotape segments depicting low-level, high-speed flight over a variety of terrains, and the subjects were pilots experienced in low-level flight. It was hypothesized that the obtained dimensional structure would reflect the terrain features that are most salient to pilots. To illustrate, one might find that terrains at one end of a given dimension are rich in trees and bushes whereas terrains at the opposite extreme are devoid of that feature. The presence or absence of trees and bushes would then be said to be a relevant terrain feature for low-level flight.

One concern was whether pilots could restrict their judgments to terrain features that are relevant only for low-level flight rather than, for example, navigational features or even aesthetics. Dupnick (1979) varied the context within which stimulus pairs were rated and found that different dimensional structures were obtained for the same subjects rating the same stimuli in different contexts. One of Dupnick's experiments (Chapter 6) is particularly relevant to the present investigation. Therein a subject skilled in photo interpretation rated photographs relative to two different stated task purposes: (a) identification of unspecified objects in general and (b) identification of objects of a particular class. Replicable changes in dimensional structure were obtained for the two task contexts, demonstrating that orienting instructions were effective in focusing subjects on specific types of information.

Orienting was to be accomplished in the present experiment by instructing pilots to imagine themselves flying over each terrain, and then to rate the similarity of each terrain pair relative to visual cues for low-level flight.

II. METHOD

Subjects

The subjects were ten F-5 instructor pilots (IPs) from the 425th Tactical Fighter Training Squadron, Williams Air Force Base, Arizona (mean hours total flying time = 1,880); three A-7 IPs from the 195th Tactical Fighter Training Squadron, Arizona Air National Guard, Tucson, Arizona (mean hours total flying time = 3,433); and two A-10 pilots from the 353rd Tactical Fighter Squadron, Myrtle Beach Air Force Base, South Carolina (mean hours total flying time = 1,800). Missions for each of these types of aircraft include air-to-ground attack involving low-level flight.

Stimuli and Materials

The stimuli were 12 videotape segments, each 5 seconds in duration, depicting low-level, high-speed flight over a variety of terrain types. The segments were selected from the video library at the Research Communications Center, Air Force Human Resources Laboratory/Operations Training Division (AFHRL/OT), Williams Air Force Base, Arizona. The segments were filmed primarily from helicopters, and the speed of the video was increased to produce the appearance of high-speed flight. Some variation in altitude and apparent speed was evident among the segments, and exaggerated motion sometimes resulted from the increased speed. Three segments were selected to be used for practice, resulting in a final stimulus set of nine segments. A representative frame from each of these nine segments is shown in the Appendix.

The nine stimulus segments were paired in all possible combinations and two randomly ordered sequences of the resulting 36 stimulus pairs were recorded on videotape. Each member of a pair appeared first in one sequence and second in the other, and the three practice pairs preceded the experimental pairs. There was a 1-second interval between each member of a pair and a 5-second interval between pairs.

Similarity ratings were recorded in a seven-page booklet that contained 10-point rating scales--3 scales for the practice pairs and 36 scales for the experimental pairs. Scale values ranged from 0 to 9 and were anchored at 0 with "Highly Dissimilar" and at 9 with "Highly Similar." There were no more than six scales per page. A cover sheet attached to the booklet outlined the purpose of the experiment, described a mission scenario requiring visual low-level flight in the range of 100 to 300 feet above ground level (AGL), and described the rating task.

Procedure

Small groups of two to four subjects viewed videotapes displayed on 14- and 19-inch color monitors that were available in squadron briefing rooms. Subjects began each session by reading the cover sheet of the booklet. Subjects were encouraged to imagine themselves flying over each terrain at 100 to 300 feet AGL, to rate the similarity of each terrain pair relative to visual cues for visual low-level flight, and to use the entire range of values on the rating scales. Subjects were asked to ignore, to the extent possible, variations in altitude and speed, as well as the exaggerated motion. Although pilots frequently commented on these factors upon first viewing the imagery, there were no reports of problems in performing the task.

To familiarize subjects with the range of terrains used in the investigation, the stimulus segments were first shown individually in sequence. The 3 practice pairs were then presented. After a pause for questions, the 36 experimental pairs were presented, with approximately one-half of the subjects seeing each of the two random sequences of video pairs. The entire experiment took approximately 40 minutes. No problems were reported concerning the rapid pace of the videotape presentations.

III. RESULTS

Similarity ratings were converted to dissimilarities by subtracting each value from 9. The dissimilarities were analyzed using the multidimensional scaling procedure ALSCAL (Young, Takane, & Lewyckyj, 1978) available with the $SPSS^X$ statistical package ($SPSS^X$ User's Guide, 1986). A weighted, nonmetric approach was used which assumes that the data are ordinal. Because it was also assumed that similarity ratings were continuously distributed, ALSCAL "untied" any tied ratings.

The measure of how well a given spatial configuration fits a set of similarity data is "stress." Smaller stress corresponds to "better fit." The correct dimensionality for a set of data (i.e., the dimensionality with maximum structure) is often taken as that at which stress becomes sufficiently small. Kruskal (1964) suggests that stress of .100 is fair, whereas values less than .025 are excellent. However, stress will inevitably decline (i.e., fit will improve) as dimensionality increases, even with purely random data. This is particularly true with small stimulus sets for which spurious solutions may easily be obtained in higher dimensionalities. To guard against this possibility, Kruskal and Wish (1978) recommend against extracting more than two dimensions with nine stimuli.

The two-dimensional solution yielded a stress value of .242, with 55.6% of the variance accounted for. High stress may result from either a lack of structure in the data at a given dimensionality, the presence of error or noise in the data, or both. Inspection of the derived two-dimensional spatial configuration shown in Figure 1 suggests that there is meaningful structure in the data. Terrains at the extreme left of Dimension 1 are flat, whereas terrains at the extreme right are rougher. Dimension 1, therefore, appears to capture the characteristic of terrain flatness versus terrain vertical development. Terrains at the extreme lower end of Dimension 2 have few or no scene elements (i.e., objects and/or texture), whereas the Suburb terrain at the upper extreme has a dense array of objects. Dimension 2, therefore, appears to capture some aspect of the presence/absence of scene elements. The ordering of terrains along this dimension does not reflect a simple quantitative increase in the number of scene elements present, however, as the Desert and Winter Forest terrains each have a high density of elements (bushes, trees and branches) but are located near the middle of the dimension. Dimension 2 may best be characterized as a composite of element size, density and spacing with a high density of small, closely spaced elements apparently less effective as visual cues than larger, more spatially distinct elements.

Given the evidence for meaningful structure in the data, the high stress may be attributed to error or noise. The precise ordinal positions of individual stimuli should, therefore, be accepted with caution.

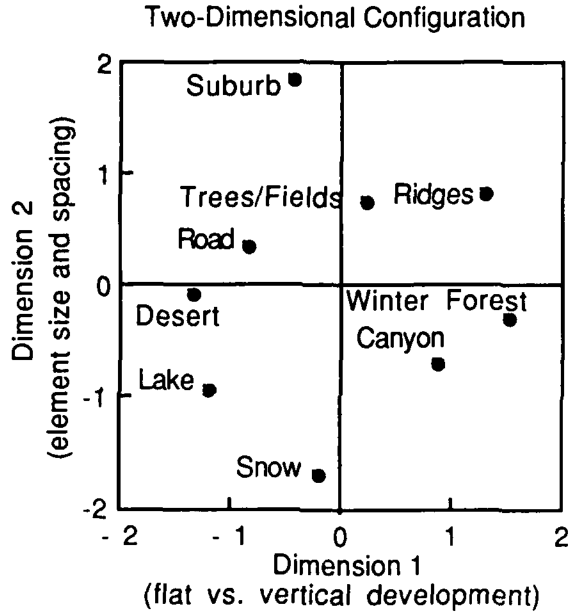

Figure 1. Two-Dimensional Spatial Configuration.

Subject Spaces

An important feature of ALSCAL output (and any weighted multidimensional scaling procedure) is subject weights which reflect the relative importance of each dimension to each individual subject. Subject weights and values for "weirdness," a measure of the extent to which a given subject's weights are proportional to the average, are shown for each subject in Table 1. A weirdness value of 0 indicates weights exactly proportional to the average. A weirdness value near 1 indicates one weight is very large and others very small. Inspection of Table 1 shows that four subjects have relatively large weirdness values: Subjects 8, 9, 14 and 15. Subjects 8 and 9 weighted Dimension 1 more heavily than Dimension 2, whereas the reverse was true for Subjects 14 and 15.

Table 1. Subject Weights

Subject	Aircraft type	Weirdness	Dimension 1 weight	Dimension 2 weight
1	F-5	.007	.602	.554
2	F-5	.306	.665	.376
3	F-5	.038	.378	.374
4	F-5	.145	.630	.467
5	F-5	.319	.384	.605
6	F-5	.217	.345	.228
7	F-5	.252	.446	.625
8	F-5	.630	.887	.248
9	F-5	.723	.802	.166
10	F-5	.236	.646	.412
11	A-7	.074	.494	.410
12	A-7	.456	.529	.225
13	A-7	.377	.329	.577
14	A-10	.922	.059	.906
15	A-10	.565	.320	.839

Given a subject's stimulus weights, a spatial configuration can be plotted which reflects the relative importance of each dimension for that subject. Configurations for Subjects 8, 9, 14, and 15 are shown in Figures 2 through 5, respectively. Note that although similar to the configuration in Figure 1, these are stretched or shrunken according to each subject's weights. For Subjects 8 and 9, there is more variability along Dimension 1, indicating an emphasis on that dimension. For Subjects 14 and 15, there is more variability along Dimension 2, indicating an emphasis on that dimension. This is especially evident for Subject 14.

IV. DISCUSSION

These results suggest that at low altitudes pilots attend mainly to terrain vertical features (Dimension 1) and to characteristics related to the size, density and spacing of objects and/or texture elements on the terrain surface (Dimension 2). The important question, therefore, is what cues pilots derive from these features.

Terrain verticality provides at least two cues for low-level flight (Academic Text: Low Altitude Training, 1986). The first, a static cue, is based on the fact that the extent to which foreground vertical features (e.g., hills and ridge lines) occlude or mask more distant background features increases systematically as altitude decreases. The second, a dynamic cue, results from the fact that motion through an environment produces an optical flow discontinuity, or shear, as foreground features move against the background of more distant features. Shear results from differences in the rate and direction of optical flow between foreground and background features and helps define terrain contour. In addition, the relative motion of the shear boundary, up or down, is also a cue for whether foreground features will be cleared by the aircraft or impacted. If the relative motion of the shear boundary is upward, then the point of impact is below the shear boundary; that is, on the surface of the foreground vertical feature.

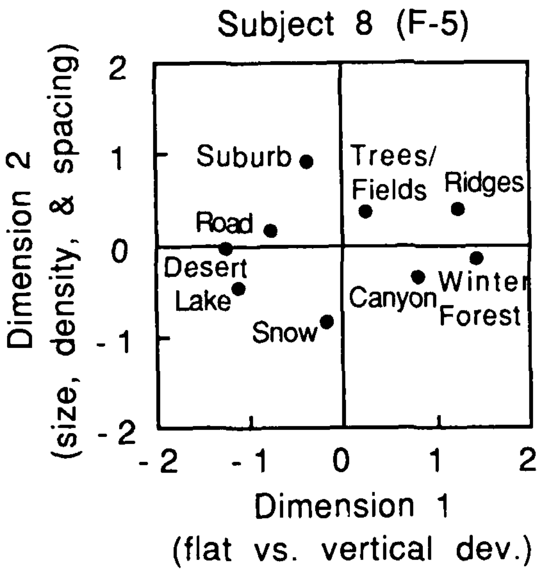

Figure 2. Subject Space for Subject 8, an F-5 Pilot.

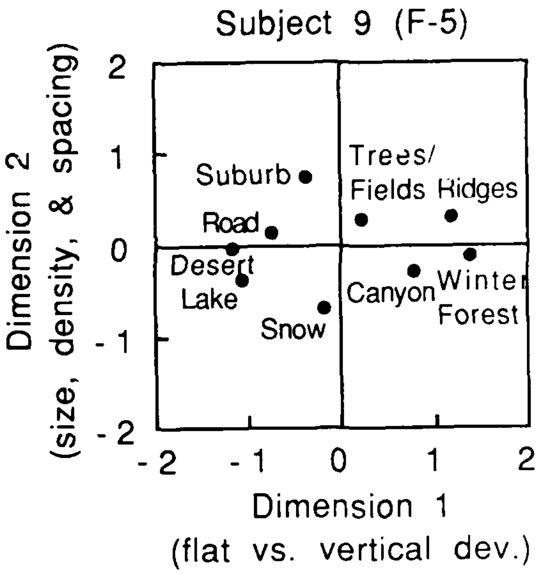

Figure 3. Subject Space for Subject 9, an F-5 Pilot.

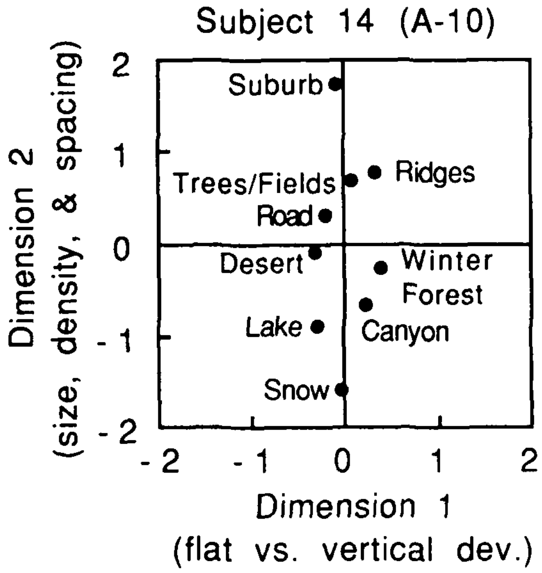

Figure 4. Subject Space for Subject 14, an A-10 Pilot.

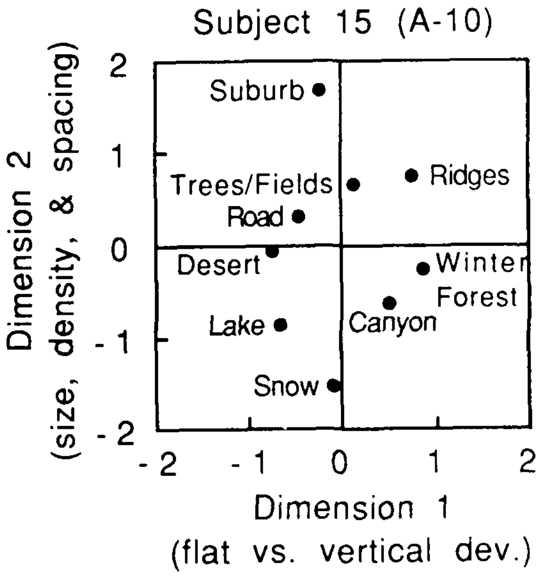

Figure 5. Subject Space for Subject 15, an A-10 Pilot.

Rather than simply modeling terrain elevation with a high degree of accuracy, the goal in simulators should be to emphasize factors related to perception of terrain masking, contour, and shear. For example, Previc (1989) found that shear was sufficient to detect a foreground plane in a dot pattern only when dot density, regularity and initial depth separation of the two planes were suitably high. This suggests that the size and/or spacing of vertical features, as well as the spatial distribution of objects and surface texture elements, are probably important factors. Future research should seek to define other factors that contribute to perception of cues arising from vertical features.

Optical discontinuities resulting from objects and/or texture elements on terrain surfaces are the basis for the optical flow field, without which there would be no information specifying self-motion. It is not surprising, therefore, that the presence of scene elements on terrain surfaces was found to be an important feature of real-world terrains in this investigation. The precise characteristic of scene elements that affected judgments is not immediately obvious, however. Many previous investigations have shown that performance improves with increases in the density of both two-dimensional surface texture (Hettinger, Owen, & Warren, 1985) and three-dimensional objects (Engel, 1980; Kleiss et al., 1988; Martin & Rinalducci, 1983). The ordering of terrains along Dimension 2 is generally consistent with increasing object density, although the Winter Forest and Desert terrains each have a high density of scene elements but are positioned near the middle of the dimension rather than at the extreme.

The scene elements in the Winter Forest and Desert terrains are small and closely spaced such that they form a more or less homogeneous blanket of texture. One possibility is that optimal cuing effectiveness requires larger or more spatially distinct elements. Warren, Morris, and Kalish (1988, p. 652), for example, comment that accurate heading judgments are typically made in response to distinguishable features of the terrain (i.e., features that in some sense stand out perceptually) rather than to undifferentiated, homogeneous surfaces. Although the density of elements in these two terrains would appear to provide a rich basis for optical flow information, individual elements are difficult or impossible to distinguish from one another. In contrast, the Suburb terrain also has a high density of scene elements (most notably houses), but these are relatively larger and are arranged in regularly spaced rows (recall that Previc, 1989, found regular spacing to be a factor affecting perception of shear). In addition to the quantity of objects or texture elements in scenes, therefore, an important consideration also appears to be the size and spatial arrangement of elements.

Many modern image generators allow terrains such as forests, deserts and plains to be created by replicating digitized texture patterns on large surfaces. These, also, can yield the appearance of a homogeneous pattern. It may be possible to enhance these textured surfaces by adding features with more clearly discernible boundaries such as clearings (similar to the Trees/Fields terrain), objects, or roads.

The location of the Suburb terrain at the extreme end of Dimension 2 suggests that, within the present context, this terrain reflects an optimal combination of visual cues. The larger size and regular spacing of objects, plus the clearly delineated boundaries provided by streets, may have been contributing factors. It is also possible that houses provide more effective known-size references which pilots use to judge altitude. Kleiss et al. (1988) found no advantage for familiar objects such as trees and bushes compared to simple inverted tetrahedrons. However, the sizes of objects such as houses may be easier to judge than those of trees and bushes.

Four subjects showed a pattern of large weights on one dimension and small weights on the other dimension. Subjects 8 and 9 were influenced more by Dimension 1, whereas Subjects 14 and 15 were influenced more by Dimension 2. This may simply reflect individual differences in how pilots approach the task of low-level flight. For instance, although Subjects 8 and 9 were influenced more by terrain verticality, the other eight F-5 pilots weighted the two dimensions more or less equally. Subjects 14 and 15, however, were the only two A-10 pilots in the investigation, and both weighted Dimension 2 more heavily than Dimension 1 in contrast to all other pilots. Pilots in the A-10 aircraft might, therefore, approach the task of low-level flight somewhat differently than pilots flying other types of aircraft. The A-10 is, in fact, notably different from both the F-5 and the A-7 in that it is slower and more maneuverable. These factors may predispose A-10 pilots to attend more to visual cues on the immediate terrain surface than to cues arising from more distant terrain vertical features.

V. CONCLUSIONS

These results suggest that terrain vertical development (Dimension 1) and the size, density and spacing of scene elements (Dimension 2) are the most salient features of real-world terrain to pilots flying at low altitudes. The emphasis in simulator visual scenes for training low-level flight should, therefore, be on enhancing the cue effectiveness of these features. This conclusion is mitigated somewhat by the fact that a relatively small number of stimuli were employed, thus limiting the number of possible dimensions that could be identified. Also, variation in the altitudes and speeds depicted in the video segments may have influenced the extent to which certain terrain features affected judgments. Replication of this investigation with a wider range of terrains photographed under more tightly controlled conditions of altitude and speed is therefore recommended.

The possibility that pilots of different types of aircraft attend to different types of visual cues suggests that visual scenes for simulator training should be designed for specific training applications. Replication of this investigation with pilots from a variety of aircraft types is, therefore, also warranted.

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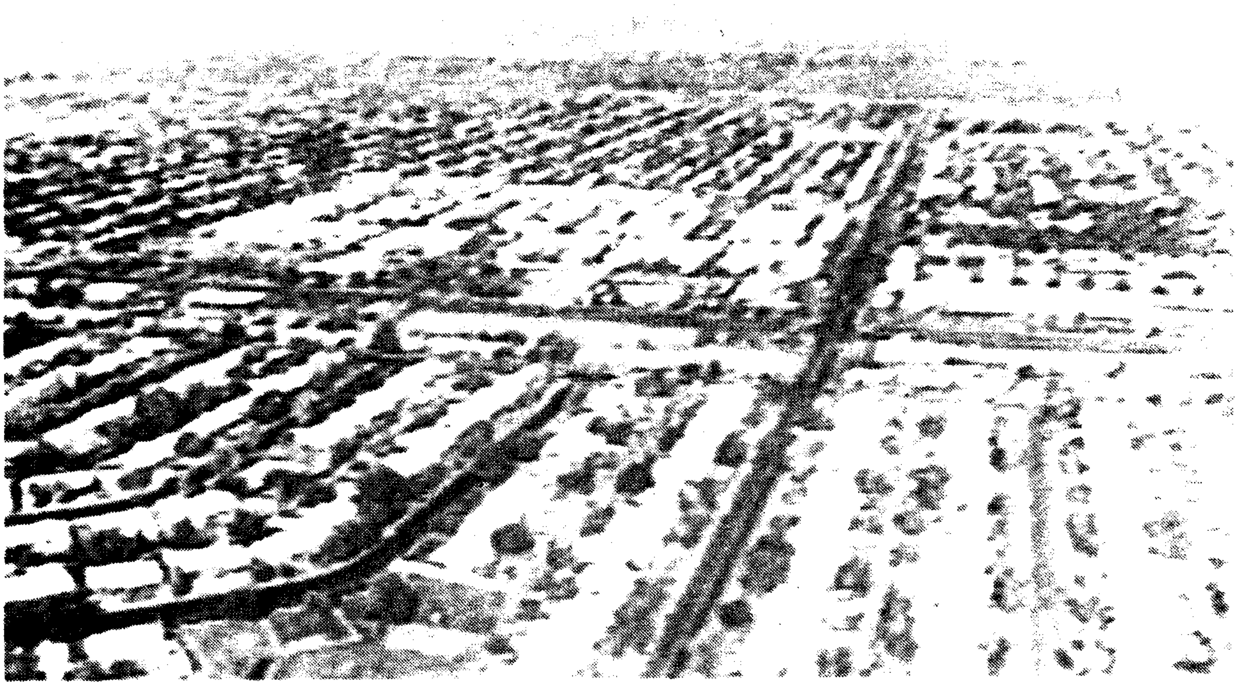
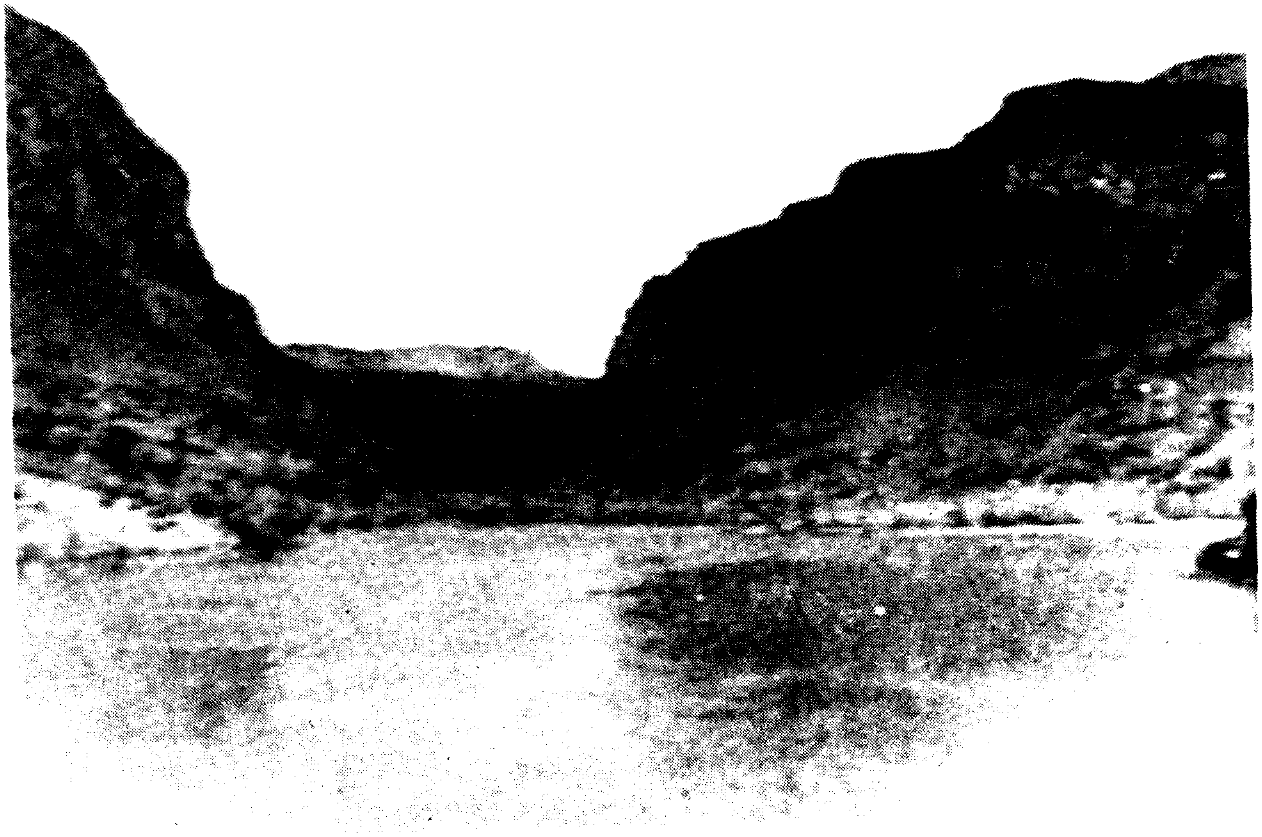
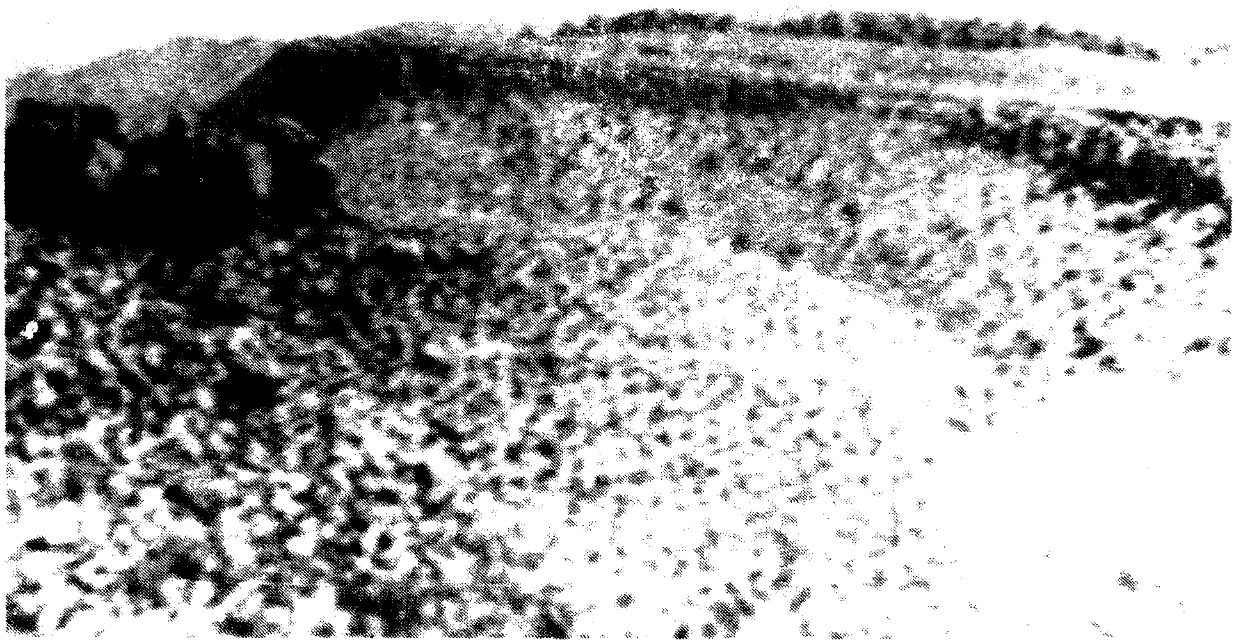
APPENDIX: REPRESENTATIVE FRAMES FROM THE NINE VIDEO SEGMENTS



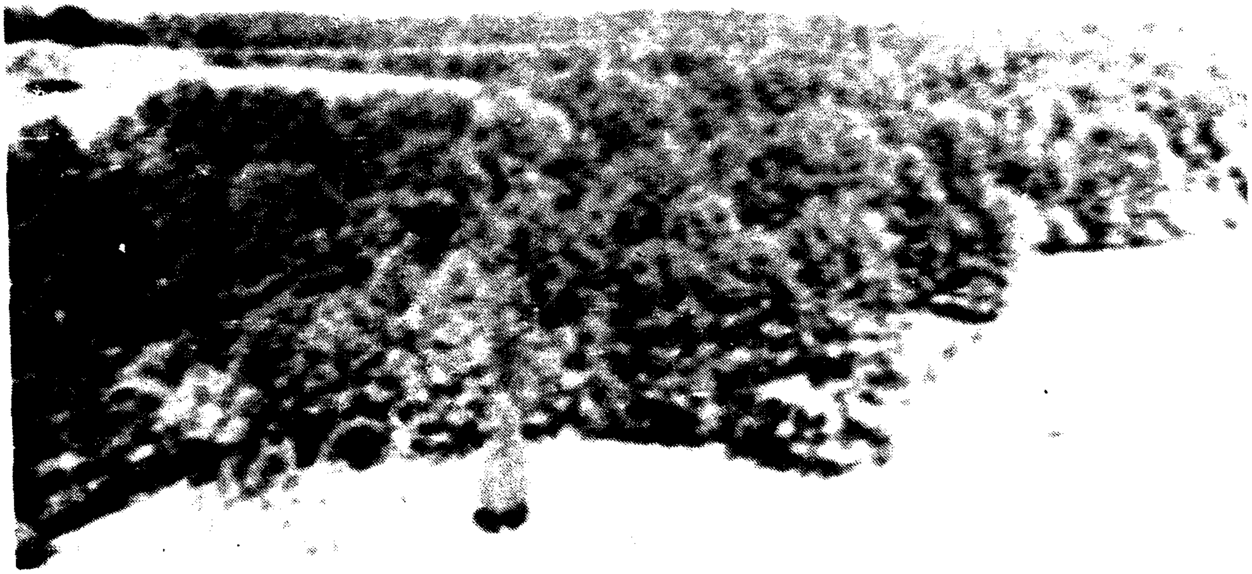
Terrain 1, Suburb.



Terrain 2, Canyon.



Terrain 3, Ridges.

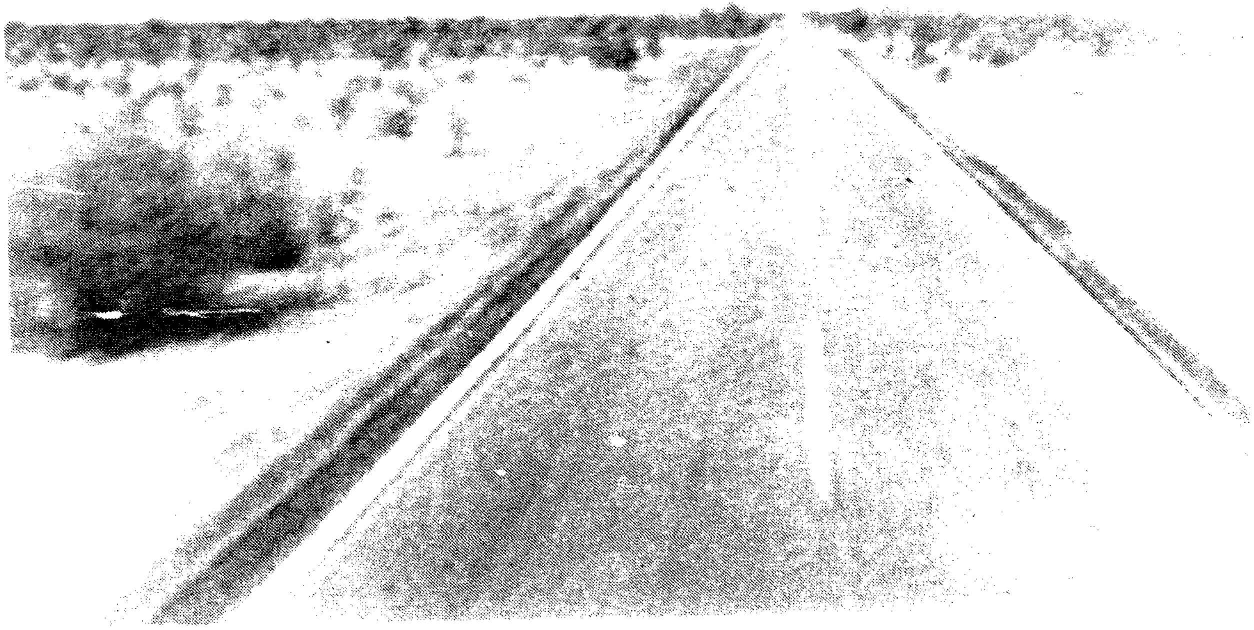


Terrain 4, Trees/Fields.

Terrain 5, Desert.

Terrain 6, Lake.

Terrain 7, Snow.



Terrain 8, Road.

Terrain 9, Winter Forest.

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