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IDENTIFICATION OF ENVIRONMENTAL ELEMENTS IMPORTANT FOR SIMULATING VISUAL LOW-ALTITUDE FLIGHT

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This report has been reviewed and is approved for publication.

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Previous research has revealed that two properties of natural scenes dominate perception during low-altitude flight: (a) terrain shape and (b) object size. Experiments conducted in flight simulators reveal that these two properties can be rendered with sufficient perceptual fidelity in computer-generated scenes. In addition, a third property related to presence or absence of terrain texture becomes evident when using computer-generated scenes due to comparisons involving a control condition consisting of scenes with completely textureless terrain. Laboratory experiments reveal that information for perceiving self-motion can be traced to fairly specific stimulus properties. The purpose of the present experiment was to identify specific components of natural scene elements that mediate perception during low-altitude flight. The stimulus set consisted of computer-generated scenes exhibiting both natural scene elements revealed to be important in previous experiments plus geometrically regular shapes and surfaces intended to represent components of natural scene elements. These stimuli served in a multidimensional scaling analysis which revealed that perception of terrain surface relief is based upon elevation differences in the vertical depth axis whereas perception of flat terrain is based upon a horizontal perspective gradient. Perception of large objects is based upon discrete shape in the vertical plane whereas perception of a second type of object is based upon discrete shape in the horizontal plane. This information provides a basis for designing simulated scenes which highlight specific relevant information.

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PREFACE

This effort was conducted at the Armstrong Laboratory, Aircrew Training Research Division (AL/HRA), in Mesa, AZ in support of training research and development to maintain air combat readiness and visual scene and display requirements.

This work was performed by the University of Dayton Research Institute (UDRI) in support of Work Unit No. 1123-32-03, Tactical Scene Content Requirements, Principal Investigator, Dr. Elizabeth L. Martin, and 1123-03-85, Flying Training Research Support, Contract No. F33615-90-C-0005. Laboratory contract Monitor was Ms. Patricia A. Spears. 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.

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IDENTIFICATION OF ENVIRONMENTAL ELEMENTS IMPORTANT FOR SIMULATING VISUAL LOW-ALTITUDE FLIGHT

INTRODUCTION

The natural environment within which pilots fly poses a potentially complex visual stimulus consisting of objects, surfaces, and textured patterns on surfaces. Visual information obtained from the external environment plays an important role in maneuvering and navigating, particularly where there is a significant threat of contact with the terrain. Knowledge of the specific environmental elements to which pilots attend while flying would be useful in designing flight training programs to enhance learning of relevant information. Such knowledge would be particularly useful to designers of flight simulator visual scenes where elements of the simulated flight environment must be explicitly modeled. The purpose of the present experiment is to identify specific elements of the visual flight environment that mediate perception during low-altitude flight.

Previous research shows that both textured patterns on the terrain as well as vertical objects extending above the terrain surface are effective in facilitating perception and control of altitude in flight simulators (Buckland, Edwards, & Stevens, 1981; DeMaio, Rinalducci, Brooks, & Brunderman, 1983; Kleiss & Hubbard, 1993). Texture and objects have independent effects on performance, suggesting that each provides a different type of visual information (Kleiss & Hubbard, 1993). Data suggest that the importance of vertical objects derives from basic properties such as shape or orientation in the environment rather than realistic appearance (i.e., trees) (Kleiss & Hubbard, 1993).

Laboratory investigations of the influence of texture on visual perception of self motion have decomposed texture patterns into constituent components to isolate specific relevant stimulus information. Results also point to simple and specific stimulus properties as the basis for self motion perception. For example, elements of a grid pattern aligned parallel with the heading direction provide perspective information, change in which is an effective cue for perceiving change in altitude (Flach, Hagen, & Larish 1992; Wolpert, 1988; Wolpert, Owen & Warren, 1983). Perpendicular grid elements provide compression gradient information, change in which can also be an effective cue for perceiving change in altitude (Flach, et al., 1992; Johnson, Tsang, Bennett, & Phatak, 1989). Perpendicular grid elements and random dot arrays are sources of optical edge rate and flow rate information, change in which are cues for perceiving change in speed (Larish & Flach, 1990; Owen, Warren, Jensen, Mangold, & Hettinger, 1981).

Taken together, results discussed above suggest that the visual flight environment may be conceived as comprising fairly simple elements which define specific types of environmental structure. The apparent complexity of the natural flight environment stands somewhat in contrast to the view implied by these results. One possibility is that the natural flight environment does, in fact, contain considerably more information than has been considered thus far. Another possibility is that much of what contributes to the apparent complexity of the natural flight environment is irrelevant. Distinguishing between these two alternatives is crucial to designing an effective flight simulator visual scene as it will determine whether one attends primarily to technological advancements that allow ever higher levels of scene complexity or to the process of identifying the subset of environmental elements that are relevant. Kleiss (in press) began to address this question by examining the criterion environment, that is, the real world. The stimuli used in the investigation were videotape segments depicting low-altitude flight over a variety of real-world terrains. These were submitted to a multidimensional scaling (MDS) analysis which revealed that pilots perceived variation in two fundamental types of scene elements. Dimension 1 related to variation in terrain shape which ranged from flat to highly undulating terrain. Dimension 2 related to variation in object size and/or spacing which ranged from no discernible objects or vegetation in scenes to large objects (large buildings) or localized regions of dense vegetation. These results suggest that the apparent complexity of the natural flight environment can be reduced to two major classes of scene elements.

Several particulars are worth noting. First is that both dimensions were defined by scene elements with a significant vertical component suggesting that verticality dominates perception in the natural flight environment. The finding of a dimension related to objects (Dimension 2) is consistent with previous evidence that vertical objects are important for simulating flight (Buckland, et al., 1981; DeMaio, et al., 1983; Kleiss & Hubbard, 1993; Martin & Rinalducci, 1983). However, prototypical exemplars of objects in Dimension 2 were larger than individual tree-sized objects such as have been commonly used in flight simulators. Hence, there is a property of objects other than mere verticality that is important in the natural flight environment. A second consideration is that the importance of terrain vertical elements in Dimension 1 contrasts with the results of DeMaio, et al. (1983) who found that adding large mountains to a simulated environment so as to define a corridor within which to fly had no effect either on the accuracy with which altitude was estimated in scenes (Exp. 1) or on skill at controlling altitude (Exp. 2). An important difference between Kleiss' (in press) results and those of DeMaio, et al. (1983) is that hills and ridges in the real-world scenes did not extend into the flight path. Hence, they indicate vertical relief in the terrain surface rather than large vertical obstructions. The importance of terrain vertical relief is supported by the results of Barfield, Rosenberg and Kraft (1989) who found that accuracy at estimating impact point on final approach to a runway improved significantly when hills were added to the region surrounding the runway including the region beneath the glide slope.

In a subsequent experiment, Kleiss (1994) sought to determine the degree to which important elements of the real-world environment could be effectively rendered in a flight simulator using computer-generated imagery. Scenes were modeled so as to exhibit (to the degree possible) the range of elements in Kleiss' (in press) real-world scenes. An MDS analysis using those scenes as stimuli revealed three dimensions rather than just two. Two of the three dimensions were similar to dimensions obtained by Kleiss (in press) using real-world scenes. Dimension 2 related to objects, but in this experiment, a distinction was revealed between two types of objects, vertical objects exemplified by trees, and texture blotches on the terrain surface which appeared to reflect a horizontal component of objects. Unlike real-world scenes, there was no evidence that grouped trees were perceived differently than trees spaced evenly on the terrain. Hence, grouping does not appear to be the important property defining localized regions of dense vegetation in real-world scenes. Dimension 3 related to terrain shape and was exemplified by scenes containing highly undulating terrain. A notable feature of these scenes is that hills did not extend into the flight path, providing further support that the importance of hills is based upon vertical relief in the terrain surface rather than large vertical obstructions.

The additional dimension (Dimension 1) in Kleiss' (1994) experiment related to presence or absence of texture on the terrain. This dimension was defined by comparisons involving a control condition consisting of scenes with completely textureless terrain surfaces. Identification of terrain texture as a unique scene element in this experiment indicates that even the most austere real-world scenes used by Kleiss (in press) (e.g., a dry lake bed and a calm ocean) contained sufficient texture to conceal this distinction. It is of interest to note that the control scenes with textureless terrain served to define two relevant scene elements which were not evident with real-world scenes, terrain texture in Dimension 1 plus a distinction between two types of objects in Dimension 2.

A remaining question concerns the specific properties of natural scene elements such as objects and hills to which attention is directed during flight. Researchers have investigated texture variables useful for perceiving self motion by decomposing geometrically regular texture such as as a grid pattern into constituent components (Flach, et al., 1992; Johnson, et al., 1989; Wolpert, 1988; Wolpert, et al., 1983). Natural scene elements such as objects and hills lack the geometric regularity of grids which would allow them to be decomposed into constituent components. However, geometrically regular elements could be constructed from grids by adding vertical sides to square grid elements and enclosing them with a square top. Such elements would exhibit 3D shape or volume and would be similar in this way to large objects and hills. The vertical sides could be isolated to provide a specific type of vertical information related to discrete shape in the vertical plane. Sides could be oriented either parallel with or perpendicular to the heading direction to further isolate these two components found to be important in texture (Flach, et al., 1992; Johnson, et al., 1989; Wolpert, 1988; Wolpert, et al., 1983). Unlike grid lines which extend continuously across the visual field, discrete elements exhibit edges that are not present in grids. The horizontal surface defining the top could be isolated to provide vertical information related to depth differences in the vertical depth axis. The square horizontal base could be isolated to provide a discrete shape in the horizontal plane. Such shapes would exhibit many of the properties of grids. Smaller volumes would provide information pertaining to differences in size. Lastly, texture could be manipulated on the terrain as well as on discrete elements to investigate the role of texture on surfaces versus luminance edges in defining relevant scene elements. The present stimulus set will comprise scenes exhibiting geometrically regular elements and scenes exhibiting natural elements to isolate specific structure to which attention is directed in natural scenes.

METHOD

Subjects

The subjects were three females (mean age = 32.67 yr, R = 18-42) and eleven males (mean age = 28.27, R = 20-49) with normal or corrected to normal vision. Two male subjects (numbers 6 and 9 respectively) were licensed private pilots with 160 and 320 hr flying time respectively. One male subject (subject number 5) was a U.S. Air Force pilot not currently on flying status with approximately 1500 hr flying time, mostly in fighter-type aircraft.

Apparatus

Scenes were generated by the Advanced Visual Technology System (AVTS) (see Eibeck & Petrie, 1988 for specifications). Among its capabilities is cell texturing, a technique by which a complex digitized pattern is rendered on a surface by modulating the lightness and darkness of the surface. Subjects were seated in a jet-fighter simulator cockpit with no functioning instruments or controls. Imagery was back-projected onto three pentagonal screens using three Barco Graphics 500 CRT projectors. Maximum addressable resolution for each of the three channels was 1,000 lines by 1,000 elements/line. Each screen measured a maximum of 1.75 m horizontally by 1.32 m vertically. The screens were positioned within a dodecahedral frame, one to the front of the cockpit and one on each side. The maximum field of view with this arrangement was approximately 210 deg horizontally by 100 deg vertically measured from a viewing distance of 1 m.

Stimuli, Design and Materials

Stimuli were 5 s segments of straight-and-level flight through a variety of computer-generated scenes at a constant speed of 450 kn. Altitude was 150 ft above the highest point in the scene. When terrain was flat or contained small objects, altitude was relative to the terrain surface.

When hills or large vertical elements were present, altitude was relative to the tops of those elements. Because hills and large vertical elements were all approximately 75 ft in height, altitude in relation to flat terrain was 225 ft. The above speed and altitudes are typical of jet-fighter aircraft during combat missions.

The stimulus set comprised 17 scenes. Four were prototypical exemplars of dimensions in the experiment of Kleiss (1994). One was a control scene which comprised a completely flat and featureless terrain surface with a horizon line (this scene was coded ∅). The terrain was a uniform shade of green with a luminance of 1.939 Cd/m^2 measured with a Photo Research model PR703A spectral scanner. The second scene contained a flat terrain surface with a complex textured pattern on the surface (this scene was coded T for texture). Texture consisted of an irregular pattern of variously sized green blotches exhibiting three levels of luminance. Mean luminance of texture sampled across a range of texture luminance values was 2.001 Cd/m^2. The third scene contained flat terrain with texture plus cell-textured pine trees scattered evenly on the terrain (this scene was coded "Pines"). Pine trees were 35 ft tall with a mean luminance sampled across a range of texture luminance values of 0.637 Cd/m^2. The fourth scene contained a dense array of hills with terrain texture plus cell-textured pine trees clustered into groups (this scene was coded DG for dense hills with grouped trees). The sides of dense hills sloped upward about 13 deg from horizontal. Average center-to-center spacing of hills was about 800 ft. Adjacent hills were joined such that no flat terrain was visible between them.

Thirteen additional scenes contained geometrically regular polygons of various shapes and sizes. All scene elements were based upon large or small enclosed volumes (coded V). Large volumes were truncated pyramids 75 ft in height with 600-ft square bases and 450-ft square tops. The sides sloped inward at an angle of 45 deg. Small volumes were enclosed rectangular shapes 50 ft in height with 25-ft square bases and tops. Flat objects (coded F) were square bases lying coplanar with the terrain surface. Horizontal objects (coded H) were square bases and tops with three horizontal surfaces spaced equally in between. Parallel objects (coded Par) were a single vertical side of a volume aligned parallel with the heading direction. Perpendicular objects (coded Perp) were a single vertical side of a volume aligned perpendicular to the heading direction. Because polygons exhibited no thickness, parallel polygons exhibited essentially no surface area in the region close to the heading direction whereas perpendicular polygons exhibited no surface area along the axis perpendicular to the heading direction which passed through the eyepoint. Objects were positioned at points of intersection within an invisible grid. Grid spacing was 900 ft for large objects and 600 ft for small objects. Grid columns were parallel with the heading direction whereas rows were perpendicular to the heading direction. Objects occupied alternating positions within each row and column. Positions were alternated between columns such that each occupied position was flanked on either side by a vacant position. Center-to-center spacing within each row and column was 1,800 ft for large objects and 300-ft for small objects.

Texture was manipulated on the terrain and on polygons. The texture pattern used on the terrain and on large polygons was the same as that used in natural scenes described above. Large polygons with texture could, therefore, be taken to be extensions of the terrain surface. This texture pattern was reduced in scale for use on small polygons. Untextured objects were equal in luminance to the darkest texture blotches in the terrain texture pattern (1.555 Cd/m^2). AVTS also uses a shading algorithm which subtly varies the luminance of polygons according to their position in relation to the simulated sun.

The number of possible combinations of the factors described above was unmanageably large and a subset was selected for the experiment. Several combinations were deemed important because of the particular types of stimulus information they provided. One was large volumes with texture combined with textured terrain which was considered to be most similar to dense hills in natural scenes. Stevens (1995) has hypothesized that motion discontinuities mediate perception of depth during low-altitude flight. Several conditions were selected to isolate various possible sources of motion information. Large parallel polygons with texture combined with textured terrain allowed isolation of optic flow discontinuities (often termed "shear") off-axis from the heading direction. Large perpendicular polygons with texture combined with textured terrain allowed isolation of optic flow discontinuities arising from motion discontinuities in direction of heading, what Stevens (1995) calls "stretch" due to the increasing difference in angular velocity between upper edge of a vertical surface and the background terrain. Large horizontal surfaces with texture combined with textured terrain allowed isolation of motion discontinuities arising from depth separation in the vertical depth axis. Large untextured volumes combined with textured terrain allowed isolation of accretion/deletion background terrain. Several possible combinations of polygons and texture were excluded from consideration due to poor visibility. One such condition was large flat objects with texture combined with textured terrain which was identical to texture on flat terrain (coded T above). All small objects with texture combined with textured terrain were excluded because of poor contrast with background terrain. The rest of the stimulus set consisted of a random selection of the remaining combinations. Table 1 shows the thirteen new scenes used in this experiment. Figures 1 a-f show exemplars of various factors.

Table 1. Combinations of Factors Selected for Stimulus Scenes.

	Large					Small				
	Flat	Para	Perp	Horiz	Vol	Flat	Para	Perp	Horiz	Vol
Terrain texture										
Object texture	-	X	X	X	X	-	-	-	-	-
No object texture					X	-	-	-	-	-
No Terrain texture										
Object texture			X	X			X	X		
No object texture	X	X				X				X

Note: - = excluded due to poor visibility

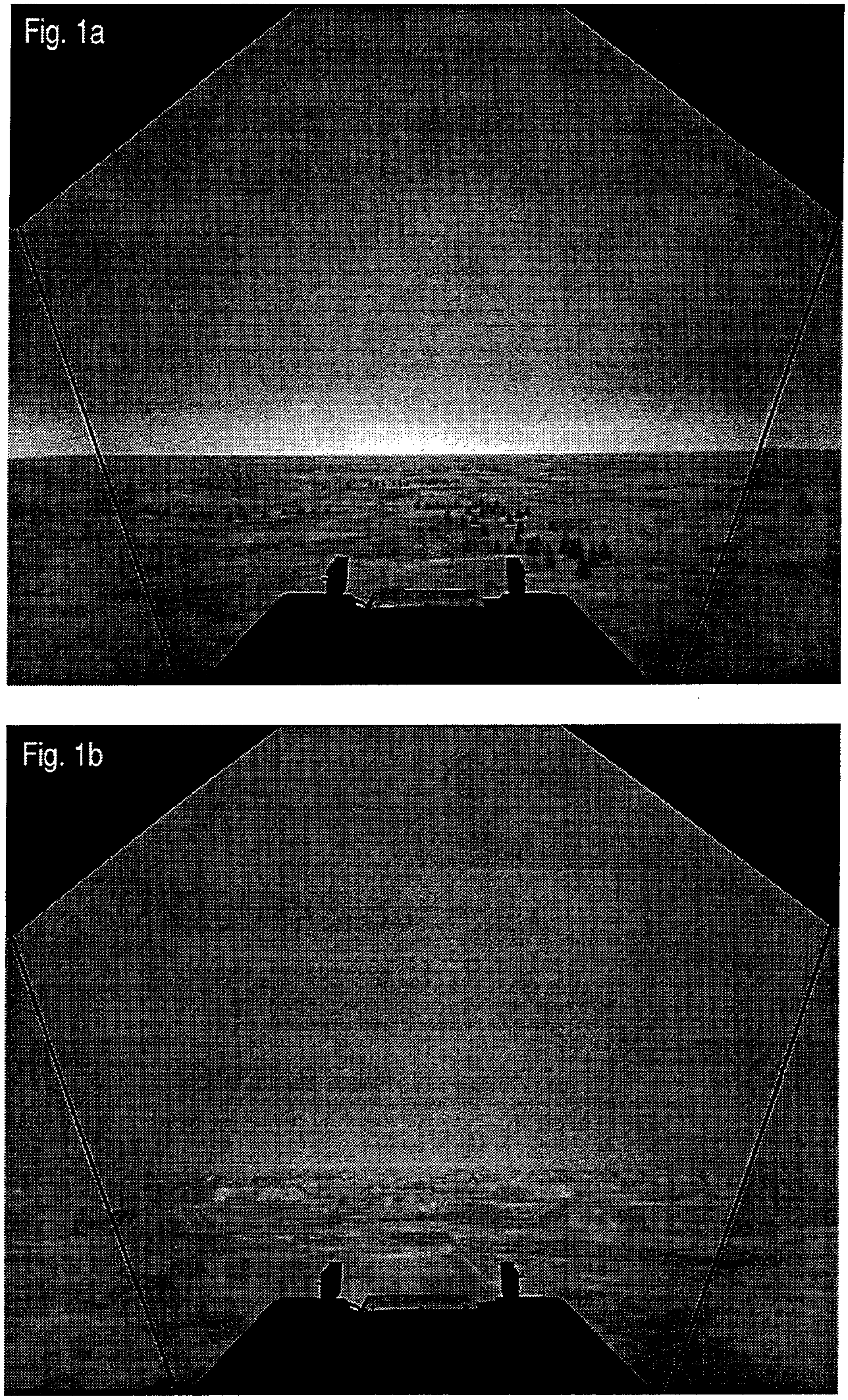
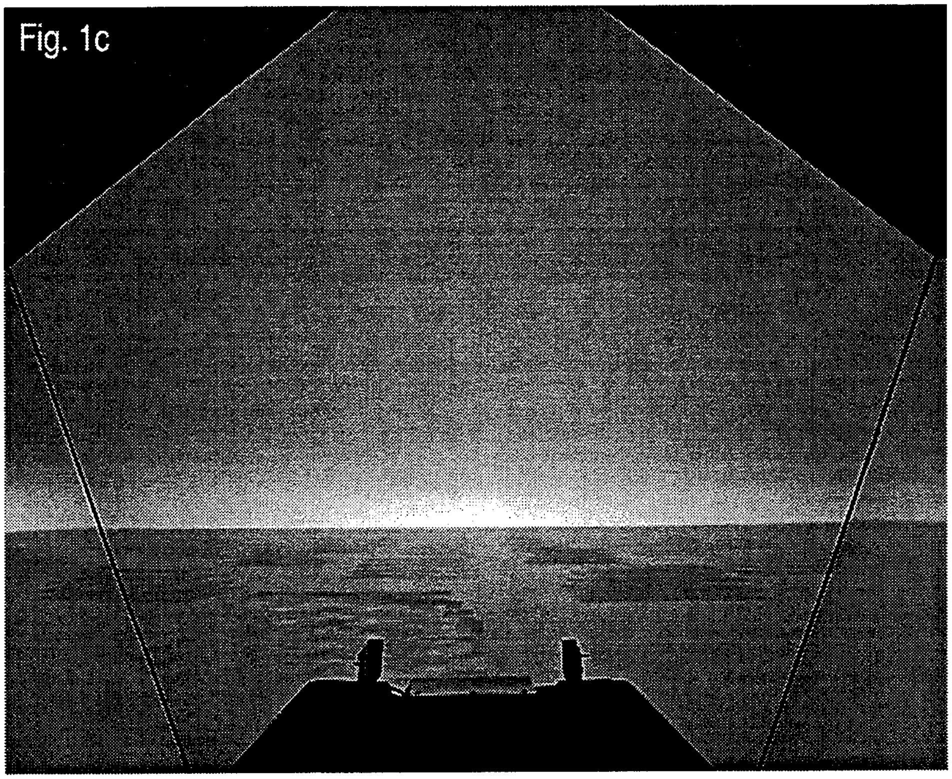


Figure 1 a, b.

Dense Hills w/Grouped Trees (a) and Large Volumes with Textured Terrain (b).



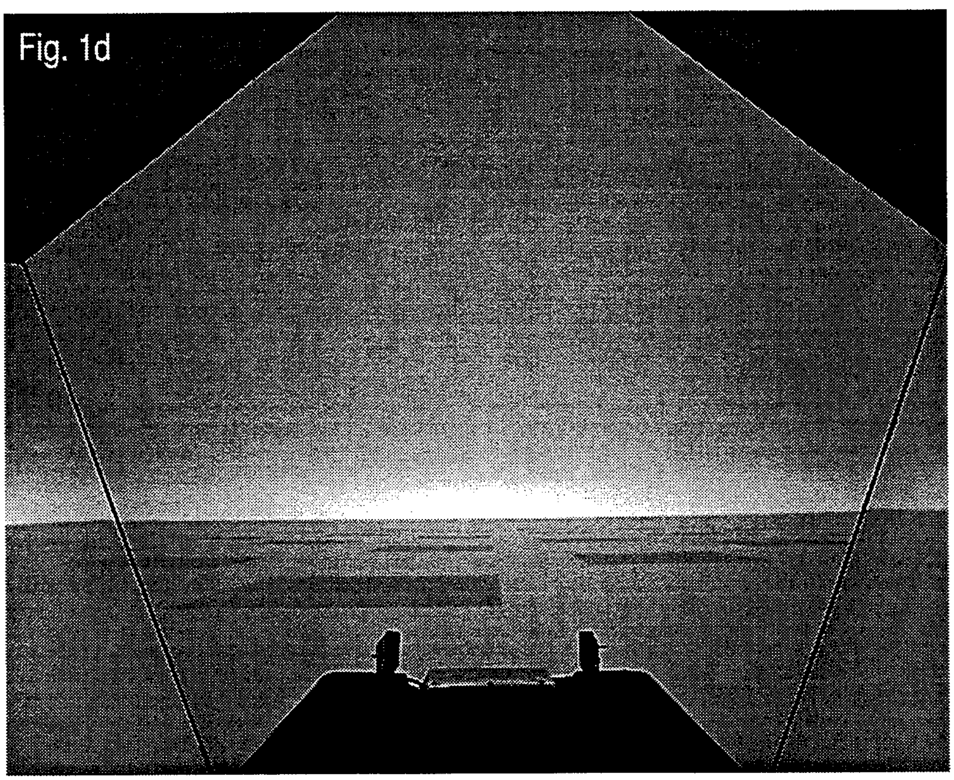


Figure 1 c, d.

Large Horizontal Polygons with Textured Terrain (a) and Large Squares (b).

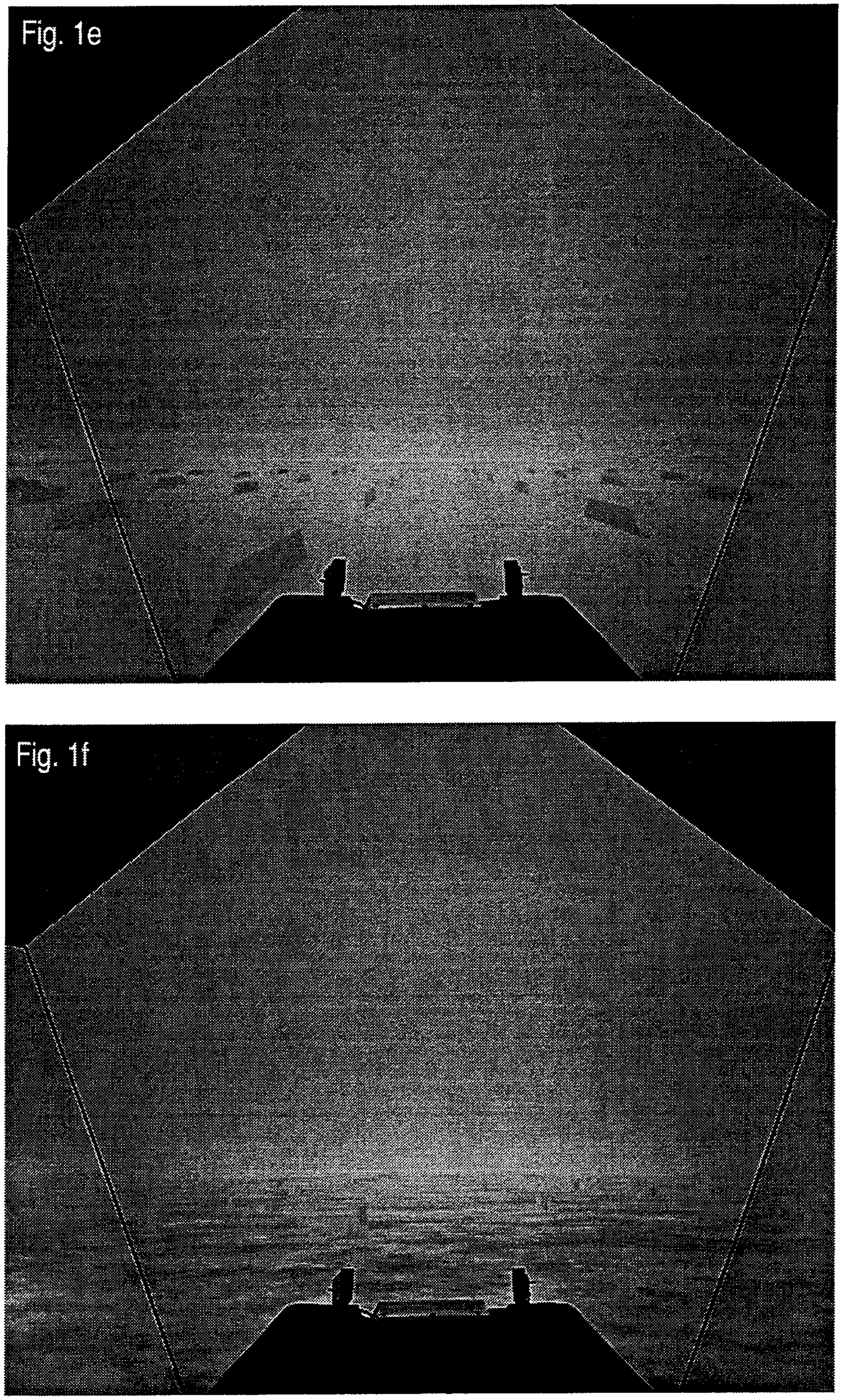


Figure 1 e & f.
Large Parallel Polygons without Texture (e) and with Texture (f).

The 17 stimuli yield a total of 136 unique stimulus pairings. Time constraints precluded presentation of all 136 stimulus pairs necessitating an incomplete data design in which each subject viewed only half (68) of the 136 possible stimulus pairs (see Schiffman, Reynolds & Young, 1981). MacCallum (1978) provides evidence that structure can be successfully recovered from data with as many as 60% missing observations so long as sample size is moderately large (greater than 10), random error is low, and different observations are missing across subjects. The 136 possible stimulus pairs were randomly divided into two subsets with the constraints (a) that individual scenes appeared about equally often in each subset, (b) that individual scenes appeared about equally often as the first and second elements of a pair, and (c) that no scene appeared in consecutive pairs. Two additional subsets were similarly created with the exception that the order of scenes within each pair was reversed.

Following Schiffman, et al. (1981), similarity judgments were recorded on 120-mm, ungraduated lines anchored at the left with "Same" and at the right with "Different." Rating scales were arranged in a booklet containing four scales per page, each numbered in sequence.

Procedure

Subjects were informed that the purpose of the experiment was to investigate scene elements useful for perceiving one's motion when flying in a simulator. They were told that they would be viewing short segments of flight through a variety of simulated scenes and would make judgments regarding how similar the scenes looked. The stimuli were to be presented sequentially in pairs, and subjects were asked to imagine that they were actually piloting the aircraft and had only their eyes (no instrumentation) to guide them. They were asked to rate the degree to which the second scene in each pair looked different from the first scene with respect to scene items they would attend to while flying. If the second scene looked the same as the first, they were to place a mark at the extreme left end of the rating scale. If the second scene looked different than the first, they were to place a mark somewhere along the scale indicating how different. It was explained that the two scenes in a given pair would never be exactly identical to one another, but that individual scenes would be repeated in different pairs. Subjects were encouraged to base their judgments on a general impression of similarity rather than an item-by-item analysis. They were also encouraged to use the entire range available on rating scales. To familiarize subjects with the range of scene elements available, scenes were shown individually before presentation of stimulus pairs. Subjects were also informed of the speed and altitude depicted in scenes. Approximately equal numbers of subjects viewed each of the four subsets of stimuli.

Each trial began with a uniform gray display field which remained visible until the subject pressed a button to initiate onset of the first scene in the stimulus pair. Scenes within each pair were separated by a uniform blue display field which remained visible for about 2-4 s depending on the time required to access the next scene. Following presentation of the second scene in a given pair, the gray display field reappeared and remained visible until the subject initiated the next trial.

RESULTS

Data were distances in millimeters measured from the left end of each scale to the point at which the subject marked the scale. The maximum range of values was 0 to 120 with larger values indicating greater dissimilarity. Rating data were submitted to a multidimensional scaling analysis using ALSCAL for PCs (Young, Takane & Lewyckyj, 1978). A weighted (individual differences) approach was used because: (a) it generally yields the most robust and reliable results, (b) spatial configurations are fixed in relation to dimensional axes and are directly interpretable without axis rotation, and (c) information is provided regarding possible individual differences among subjects with regard to the relative weighting of dimensions (Schiffman, et al., 1981). Ratings were assumed to be ordinal and continuous. Missing stimulus pairs were treated as missing values.

Three measures describe the discrepancy between dissimilarities derived from rating data and corresponding interstimulus distances in MDS spatial configurations: Stress (Kruskal & Wish, 1978), S-Stress (Takane, Young & de Leeuw, 1977), and 1-RSQ. Stress is based upon MDS distances, S-Stress is based upon squared MDS distances, and 1-RSQ is the proportion of variance in dissimilarities not accounted for by a regression of dissimilarities onto MDS distances. Smaller values indicate better fit for all three measures. Figure 2 shows S-Stress, 1-RSQ, and Stress as a function of increasing dimensionality. Note that ALSCAL does not compute a one-dimensional solution with the individual differences approach. A common criterion for identifying correct dimensionality is the occurrence of an "elbow" at a particular dimensionality indicating a point at which extracting higher dimensions produces a diminishing improvement in fit (Kruskal & Wish, 1978). Given prior evidence for three dimensions with natural scenes (Kleiss, 1994) we would anticipate at least three dimensions in the present experiment. Note that there is a large improvement in 1-RSQ between Dimensions 3 and 4 in Figure 2. This suggests consideration of the four-dimensional solution. The improvement in S-Stress and Stress also appears to taper off somewhat beyond dimensionality equal to four.

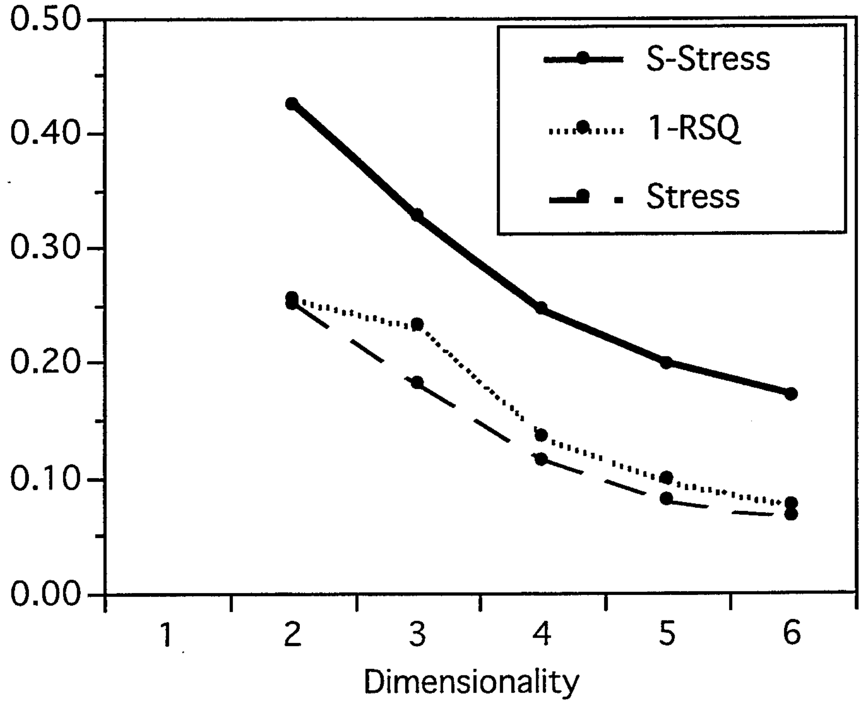


Figure 2.
S-Stress, 1-RSQ and Stress as a Function of Dimensionality.

A feature of ALSCAL output provided with the individual differences option is subject weights which reflect the relative importance of each dimension for individual subjects. The extent to which the weighting of dimensions for a given subject is proportional to the group is indexed by "weirdness." A weirdness value near one indicates one large weight and others small. A weirdness value near zero indicates that weights are exactly proportional to the group average. Squared subject weights sum to RSQ for individual subjects. When averaged across subjects, squared subject weights provide estimates of variance explained by each dimension for the group. These must be taken as estimates because the data are assumed to be ordinal in nature and do not satisfy the metric assumptions underlying usual interpretations of variance. Table 2 shows subject weights and weirdness values for individual subjects plus average squared subject weights for each dimension. Note first that subjects 5, 6 and 9 (indicated in bold type) were the licensed pilots and did not differ notably from other subjects with respect to weirdness values. Dimension 1 has the largest average squared subject weight indicating that stimulus differences reflected in this dimension had the largest impact on similarity ratings. Subjects 10 and 14, both females, weighted Dimension 1 particularly heavily (indicated in bold type) and this fact is supported by large weirdness values for these two subjects. Dimension 3 has the second largest average squared subject weight and three subjects (Subjects 2, 4, and 8, all males) weighted this dimension particularly heavily. These three subjects had the next largest weirdness values. Dimension 2 has the third largest average squared subject weight and Subject 11 weighted this dimension particularly heavily. However, the weirdness value for this subject is not particularly large indicating that the overall pattern of weights for this subjects does not deviate greatly from the group. Dimension 4 has the smallest average squared subject weight indicating that stimulus information reflected in this dimension had the least impact on similarity ratings.

Table 2. Subject Weights and Weirdness Values for Individual Subjects Plus Average Squared Subject Weights for Each Dimension.

Subject	Weirdness	Subject Weights			
		Dim. 1	Dim. 2	Dim. 3	Dim. 4
1	0.3613	0.4926	0.6399	0.1558	0.4697
2	**0.4968**	0.1532	0.3574	**0.7405**	0.2436
3	0.4694	0.2452	0.6082	0.2022	0.6331
4	**0.5973**	0.1241	0.3601	**0.7773**	0.1474
5	0.4252	0.3115	0.6573	0.1772	0.5488
6	0.4510	0.6659	0.3409	0.6017	0.0905
7	0.4373	0.3259	0.4708	0.2306	0.6654
8	**0.5952**	0.2034	0.3754	**0.7992**	0.0940
9	0.3815	0.4181	0.5002	0.2229	0.6314
10	**0.6418**	**0.8530**	0.1293	0.4366	0.0744
11	0.3915	0.3877	**0.7154**	0.1772	0.4778
12	0.3980	0.4551	0.2454	0.6839	0.2121
13	0.2776	0.6116	0.4966	0.2347	0.4628
14	**0.6701**	**0.8686**	0.1521	0.4144	0.0370
Average Squared Weights		0.2442	0.2183	0.2335	0.1683

Figure 3 shows two two-dimensional spatial configurations. The upper spatial configuration shows Dimensions 1 and 2 whereas the lower spatial configuration shows Dimensions 3 and 4. The null symbol (∅) indicates the control stimulus consisting of a completely flat and featureless terrain surface. Solid circles indicate scenes with texture on the terrain whereas outline circles indicate scenes with no texture on the terrain. Symbols for the four scenes used in previous experiments are circled. Labels indicate presence in scenes of volumes (V), squares (Sq), parallel polygons (Par), perpendicular polygons (Prp), or horizontal polygons (H). Polygons with texture have a "t" suffix added. Large polygons are indicated by large typeface.

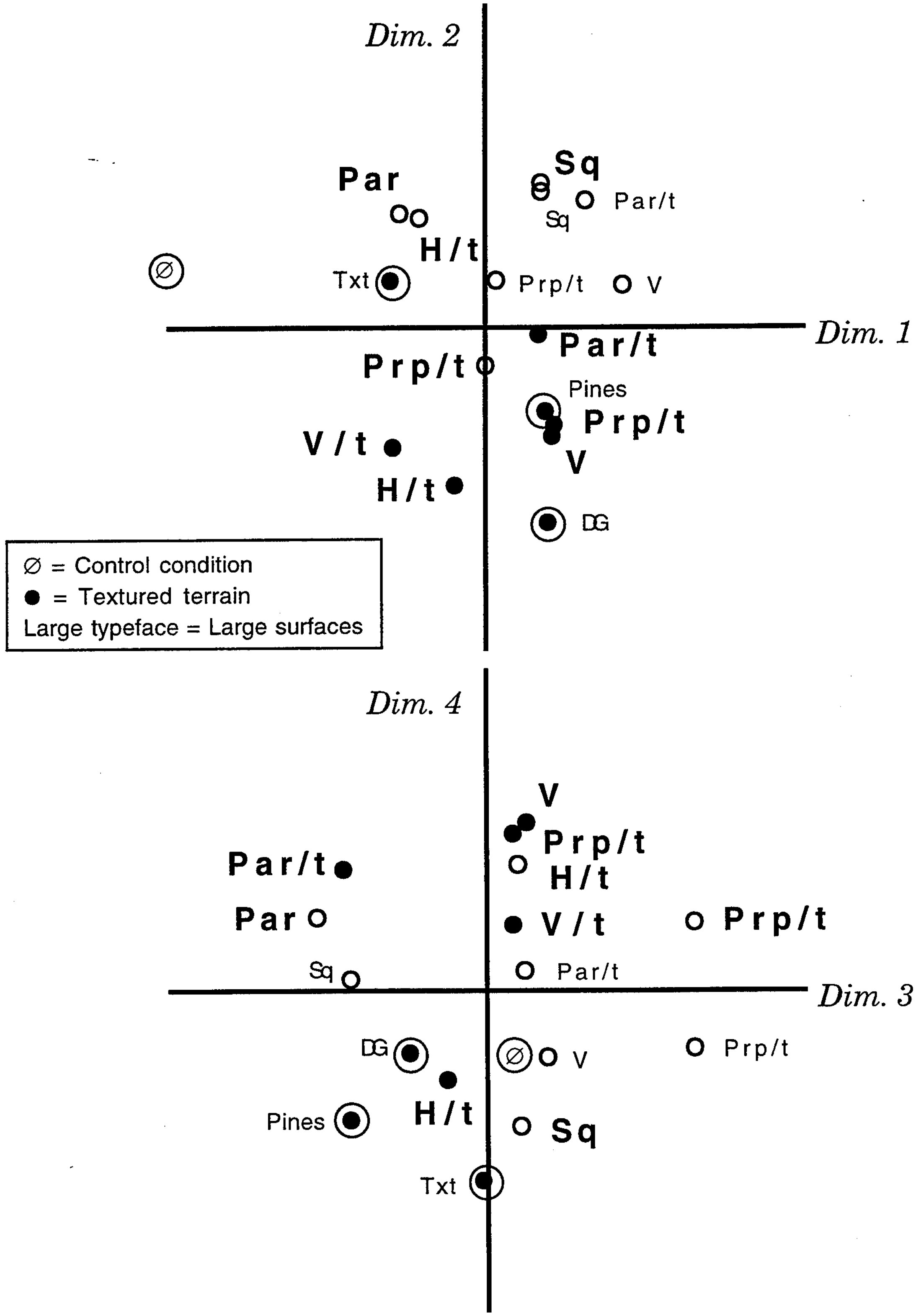


Figure 3.
Spatial Configurations Depicting the Four-Dimensional Solution.

Examination of the top spatial configuration in Figure 3 reveals that the control scene is isolated at the extreme left pole of the Dimension 1 axis whereas remaining scenes are clustered around the middle of the dimension. Dimension 1, therefore, reveals a nonspecific form of information related to the mere presence of elements in scenes. This dimension appears similar to Dimension 1 in the experiment of Kleiss (1994, Exp. 1) which revealed a distinction between textured versus untextured terrain. In the present experiment, however, many scenes clustered near the middle of the dimension lack texture on the terrain. There is no obvious pattern distinguishing among scenes within the cluster suggesting that Dimension 1 relates to a highly nonspecific type of scene structure provided by elements of a variety of shapes, sizes, and orientations.

At the bottom pole of the Dimension 2 axis is the scene with dense hills and grouped trees (DG) which exemplified the terrain shape dimension in the experiment of Kleiss (1994, Exp. 1, Dim. 3). This suggests that Dimension 2 relates to information specific to terrain shape in natural scenes. All scenes positioned near the bottom pole of Dimension 2 have texture on the terrain suggesting that terrain shape is defined, at least in part, by relationships between vertical elements and background terrain. The scene positioned nearest DG at the bottom of the Dimension 2 axis contains horizontal polygons with texture which has no surfaces with vertical slant. This suggests that the important property defining terrain shape is elevation differences in the vertical depth axis rather than surface slant. Note that scenes containing slanted surfaces (i.e., V/t, V, Prp/t, etc.) are positioned nearer the middle of the Dimension 2 axis suggesting that slanted surfaces may actually reduce perception of elevation differences. Note, also, that the two scenes containing large volumes are positioned about equally in relation to the Dimension 2 axis despite the fact that large volumes in one scene lack texture. This provides evidence that elevation differences in these scenes are mediated by accretion/deletion of background terrain rather than texture discontinuities between surfaces separated in depth.

Scenes positioned near the upper pole of the Dimension 2 axis contain geometrically regular elements combined with untextured terrain. All elements in scenes near the upper pole of Dimension 2 exhibit edges aligned parallel with the heading direction. The positioning of the control scene nearer the middle of the Dimension 2 axis suggests a point of demarcation distinguishing between scenes with elevation differences and scenes exhibiting parallel edges. The parallel component of geometrically regular texture provides perspective information, change in which is a powerful cue for perceiving change in altitude (Flach, et al., 1992; Wolpert, 1988; Wolpert, et al., 1983). It is possible that perspective information serves a more general function of defining a horizontal plane extending continuously in depth. Dimension 2, therefore, may be conceived as distinguishing between two types of terrain shape information, elevation differences in the vertical depth axis versus a continuous horizontal plane. It is of interest to note that the scene with complex texture on flat terrain, which bears closest resemblance to flat terrain in natural environments, is positioned near the control scene. This suggests that a continuous horizontal plane defined by perspective information may not be a dominant characteristic of natural environments.

The two scenes isolated at the extreme right pole of Dimension 3 (lower spatial configuration in Figure 3) contain untextured terrain with vertical elements aligned perpendicular to the heading direction. Because elements exhibit no thickness, they become essentially invisible as they pass through the plane perpendicular to the heading direction and centered on the eyepoint. Therefore, these two scenes define environments in which there are large differences in visibility of elements in different regions of the environment. Given this fact, we might anticipate the opposite pattern at the left pole of Dimension 3, that is, parallel elements. Indeed, two scenes with large parallel elements are positioned at the extreme left pole of Dimension 3. However, several other scenes which do not contain parallel elements are also positioned near the left pole of Dimension 3. These scenes do not appear to share any other obvious characteristics in common. Hence, it is not immediately obvious what specific information defines this dimension. The highly idiosyncratic nature of Dimension 3 and the fact that it is unrelated to any previously identified dimension suggests that it is of little practical importance for simulating flight.

Scenes positioned near the upper pole of Dimension 4 contain large elements oriented vertically in relation to the terrain surface. The one exception is the scene with horizontal polygons combined with untextured terrain. Horizontal polygons are spaced sufficiently close that, when viewed from altitude, they occlude untextured background terrain and subtend an area similar to that of large volumes. Apparent volume is not critical, however, because many scenes near the upper pole of Dimension 4 contain vertical polygons with no volume. The common property shared by all scenes near the upper pole of Dimension 4 is presence of elements with large (in the context of these scenes) subtended area in the vertical plane. The variety of combinations of texture on terrain and polygons exhibited by these scenes indicates that none are dominant. Hence, discrete area in the vertical plane is defined by both luminance contrast as well as texture differences. Texture differences are effective, however, only when vertical surfaces are present. Note that the scene with horizontal polygons combined with textured terrain is positioned nearer the bottom pole of Dimension 4. The fact that this scene exemplified elevation differences in Dimension 2 highlights the distinction between these two types of vertical information.

The control scene is positioned near the middle of the Dimension 4 axis suggesting a point of demarcation between large vertical elements at the top pole of the dimension and scenes at the bottom pole of the dimension. The scene nearest the bottom pole of Dimension 4 contains texture on flat terrain. This pattern in which vertical elements are positioned at one pole of the dimension and the scene with texture is positioned at the opposite pole with the control scene in between matches that reported by Kleiss (1994, Exp. 1, Dim. 2) for a dimension which distinguished between vertical objects and texture blotches. In the experiment of Kleiss (1994, Exp. 1, Dim. 2), vertical objects were trees which in this experiment are positioned near the middle of the Dimension 4 axis among other scenes with small objects. This indicates large vertical objects dominate perception and this is consistent with results of Kleiss (in press) using real-world scenes as stimuli. The positioning of the scene with large squares near the bottom pole of Dimension 4 supports the hypothesis that texture blotches are perceived as discrete elements in this dimension. However, texture remained the best exemplar of this property suggesting that large size of squares may be detrimental. The scene with small squares is positioned near the middle of the dimension indicating that small squares may be too small.

DISCUSSION AND CONCLUSIONS

The assumption underlying this research is that pilots attend to specific elements of the natural environment and that flight simulator visual scenes will be enhanced to the degree that those elements are represented. Three of the present four dimensions (Dimensions 1, 2 and 4) were similar to dimensions obtained previously using natural scenes as stimuli (Kleiss, 1994). Hence, these dimensions would appear to reflect information underlying perception of natural scene elements. Dimension 1 revealed a nonspecific form of scene structure that is satisfied by almost any type of scene element. For that reason, it probably deserves little further consideration. Because of its idiosyncratic nature, Dimension 3 is probably of little practical importance as well. However, Dimensions 2 and 4 revealed specific types of scene elements that can be related directly to elements of natural scenes and bear further examination.

Dimension 2 revealed two types of terrain shape information, elevation differences in the vertical depth axis versus a horizontal plane extending continuously in depth. The finding that perception of terrain vertical relief is mediated by elevation differences is consistent with Stevens' (1995) hypothesis that depth discontinuities revealed by visual motion cues are important for perceiving depth during low-altitude flight. Present results isolate the vertical depth axis as the most relevant. An important cue for perceiving elevation differences in present scenes was accretion/deletion of background terrain by higher-elevation terrain elements interposed along the line of sight. Terrain texture played an important role in perceiving elevation differences. However, elevation differences may be mediated by other types of information as well. For example, Kaiser and Proffitt (1992) reported that depth was conveyed in a moving map display by relative motion between contour lines depicting different levels of terrain elevation. The importance of elevation differences implied by present results suggests an alternative method for rendering terrain in flight simulators. Typically, terrain in flight simulators is rendered as a mosaic of polygonal surfaces such that elevation changes are mediated by slanted surfaces. Present results suggest that a more effective method of rendering terrain might be with horizontal surfaces corresponding to terrain cross sections layered in the vertical depth axis; in essence, a three-dimensional elevation map. Figure 4 shows three views of a cone-shaped object which has been cut into horizontal cross sections separated along the vertical depth axis. Each view corresponds to a different distance from the object at a constant altitude. Note that a distinct impression of verticality is apparent in the top view and the middle view despite the lack of vertically slanted surfaces. Note also that cross sections do not occlude one another in the middle view indicating that the vertical depth axis is implied by relative positions of cross sections. These relationships are not apparent when the object is viewed from directly overhead and the impression of depth is correspondingly reduced.

A second type of terrain shape information in Dimension 2 is related to a continuous horizontal plane defined by a perspective gradient. Change in perspective has been shown to be a powerful cue for perceiving change in altitude (Flach, et al., 1992; Wolpert, 1988; Wolpert, et al., 1983). If perspective defines a horizontal plane, change in perspective may be conceived as a case of perceiving change in one's position in relation to a plane viewed from an angle tangent to the plane. Despite the importance of perspective information for perceiving change in altitude, present results suggest that perspective may not be a prominent feature of the natural environment. The scene with texture on flat terrain, which bears closest resemblance to flat terrain in the natural environment, was not perceived to be a good exemplar of a continuous horizontal plane. The distinction between an array of texture elements and perspective information is supported by the results of Warren and Riccio (1985) who investigated skill at controlling altitude using different types of visual cues. One type of cue was defined by perspective lines, one was defined by a random array of dots, and one was defined by a combination of the two. The most effective stimulus for controlling altitude was the perspective lines. When perspective lines were combined with the random dots, perspective dominated perception to the degree that learning associated with the dots was reduced. Evidence of interference from perspective lines suggests that perspective information differs in type from that provided by random dots. One question raised by present results concerns the role of perspective information in natural environments which appear to be dominated by surfaces with a more random array of texture elements.

Dimension 4 revealed a distinction between two types of discrete scene elements, vertical versus horizontal. The importance of large vertical surfaces implied by present results is consistent with results of Kleiss (in press) who found that large objects dominated perception in real-world scenes. Present results isolate surface area in the vertical plane rather than apparent volume as the important property of defining large objects. Included among large objects in the real-world scenes of Kleiss (in press) were groves of trees. Present results suggest that such features can best be

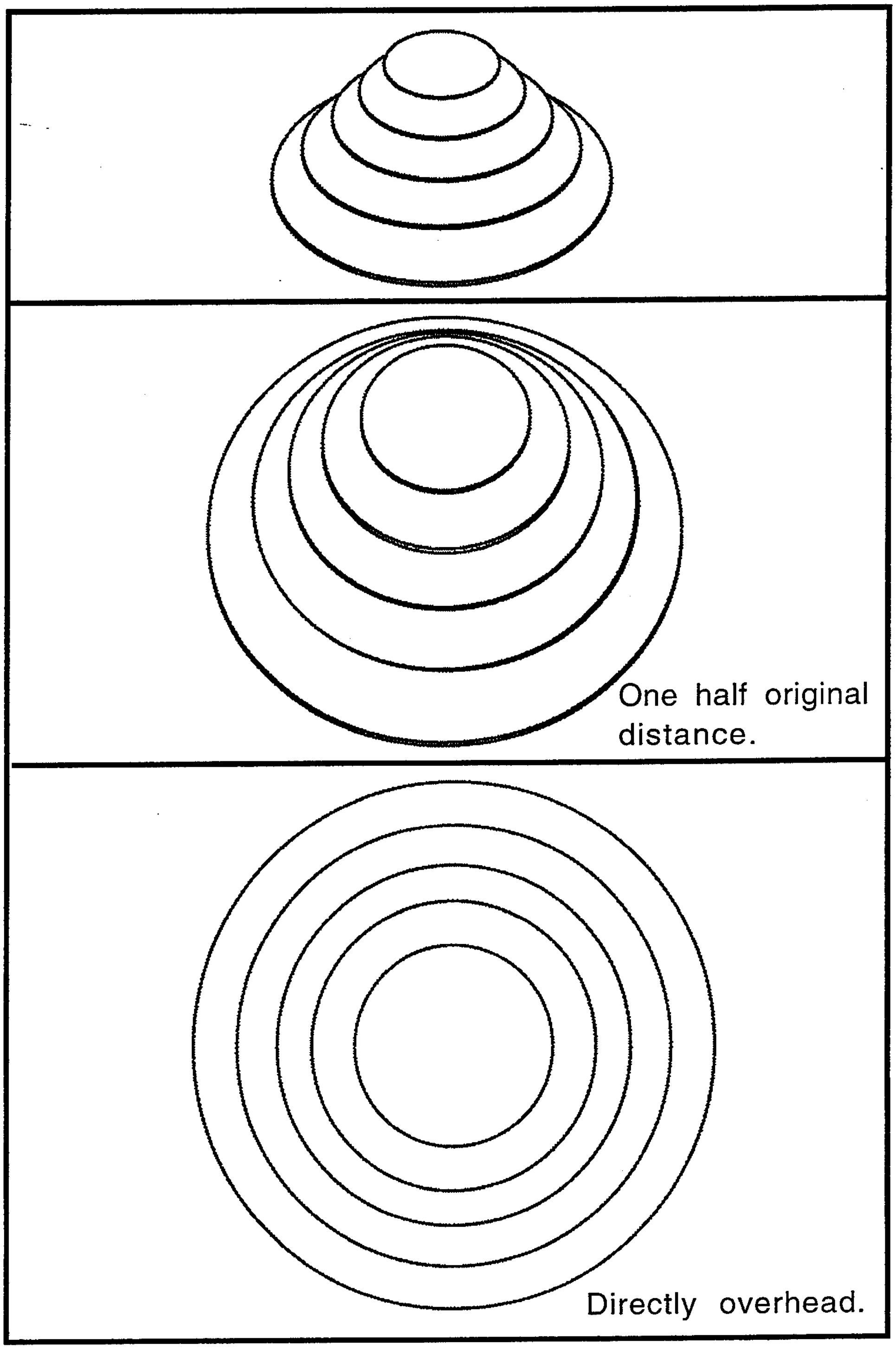


Figure 4.
Sections of a Cone Separated Along the Vertical Depth Axis Viewed from Different Distances at a Constant Altitude.

rendered in flight simulators as large vertical surfaces rather than groups of smaller objects or large volumes. The fact that volume is not important suggests that an array of large vertical surfaces corresponding to vertical cross sections may be advantageous.

A second type of discrete scene element was defined by texture blotches and squares lying coplanar with the horizontal terrain surface. The distinction in Dimension 4 between scene elements of different orientations in relation to the terrain surface suggests attention to geometric properties of shape specific to horizontal and vertical planes. Harker and Jones (1980) discuss one difference between horizontal and vertical scene elements which may be pertinent. Any large object subtends a finite area defined by its near and far edges. This area can be expressed as an angle (the subtense angle) along the line of sight between its near and far edges. An object also occupies a specific location in relation to the horizon and that location can also be expressed as an angle of depression below the horizon. A vertical object and a flat object may appear equal in both measurements when viewed from a stationery vantage point. However, as one approaches to fly over an object, the relationship between these two angles differs notably between the two cases. Specifically, the ratio of the angle of depression to the angle of subtense (the subtense ratio) grows smaller upon approach to a flat object whereas it remains fairly constant upon approach to a vertical object and then grows rapidly larger (Harker & Jones, 1980, p. 35). These relationships are illustrated in Figure 5 which shows three views of a pair of objects from three different distances at a constant altitude. The left object in each frame is a horizontal circle whereas the right object in each frame is a vertical oval. None of the views shows a horizon line. Note that both objects appear to be of approximately equal shape in the upper frame of Figure 5. At half the original distance the angular subtense of the horizontal circle has grown considerably in relation to the vertical oval. When viewed from directly overhead in the bottom frame, the circle reveals its true shape whereas only the edge of the oval can be seen. Present results are not diagnostic with regard to the specific geometric relations that underlie the difference between vertical and horizontal objects. However, these results do indicate that such relations are important and should be examined further.

To summarize, present results provide evidence that the natural flight environment can be conceived as comprising two specific types of visual structure: elevation differences mediated by depth relations between terrain elements separated in the vertical depth axis and large discrete elements, of which two orientations (vertical or horizontal) are distinguished. It is of interest to note both types of structure relate to properties of planar surfaces, either depth relations between planar surfaces or shape within a plane. Hence, 3D shape or volume does not appear to be a dominant characteristic of the natural flight environment.

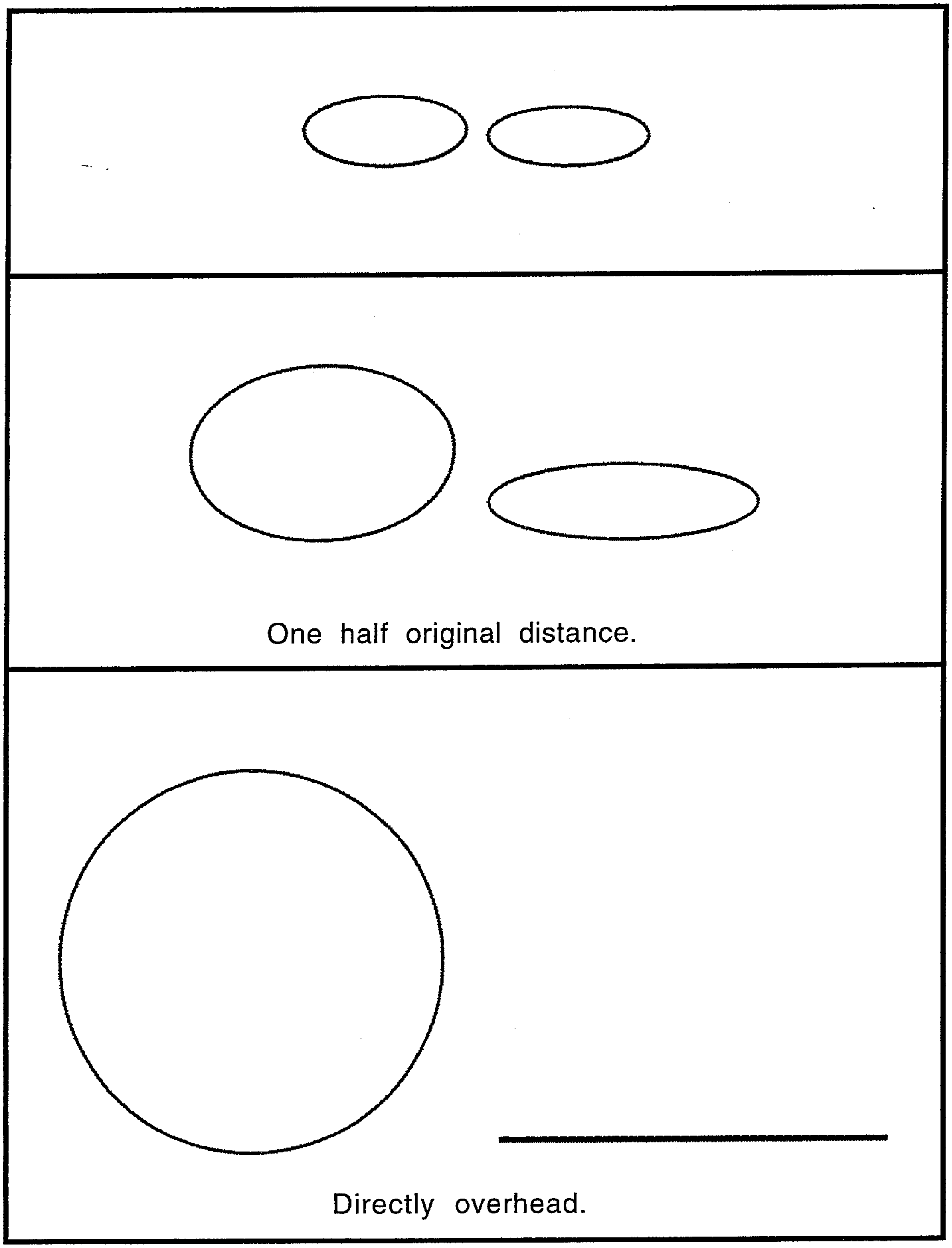


Figure 5.
A Horizontal Circle (Left) and a Vertical Oval (Right) Viewed From Different Distances at a Constant Altitude.

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