VISUAL CUEING EFFECTIVENESS: COMPARISON OF PERCEPTION AND FLYING PERFORMANCE

Joe De Maio
Air Force Human Resources Laboratory/Operations Training Division

Edward J. Rinalducci
Georgia Institute of Technology

Rebecca Brooks and John Brunderman
Air Force Human Resources Laboratory/Operations Training Division

ABSTRACT

Growing emphasis on simulation of low altitude and air-to-air tactical scenarios has greatly increased the requirement for simulator visual systems capable of providing the pilot high-fidelity out-of-the-cockpit cues. Evaluation of visual system performance through simulator flying studies has been the primary measure of system quality. Such studies can be costly and time consuming, and often they provide equivocal results. The present set of experiments was conducted to investigate the use of psychophysical measurement methodology to provide a quick, low-cost evaluation of the altitude cueing effectiveness of simulator visual displays. Experiment I examined altitude perception in several visual environments. Experiment II was a validation effort, in which flying performance was evaluated in selected visual environments. In Experiment I pilots made altitude estimates based on static and dynamic presentations of visual displays containing texture and varying sizes of 3-dimensional objects. Best-fitting power functions were used to relate perceived altitude to actual altitude. In Experiment II Air force pilots flew the Advanced Simulator for Pilot Training F-16 through five selected visual environments at 600 kt and 150 ft AGL. Reliable difference were found as a function of display variables. In environments which provided strong altitude cues, pilots were able to fly very close to the designated altitude. In environments which provided poorer cues, pilots flew substantially above designated altitude.

INTRODUCTION

As a result of the current trend in flight simulation toward tactical flight and combat scenarios, a need exists for methodologies to evaluate the effectiveness of visual system displays in providing out-of-the-cockpit flight cues. The simulator visual system presents the pilot with a variety of cues needed to perform the task. These range from airspeed, altitude, and navigation cues to cues relating to the presence, range, and behavior of threats and targets. Simulator flying studies have been performed to determine the effectiveness of texture (1), color (2), and three-dimensional objects (3) in providing low-altitude flight cues. While such studies provide the ultimate measure of the effectiveness of a visual system display in providing cues needed to perform simulated flight tasks, they can have severe methodological limitations. The requirements of such studies for simulator time, subject time, and development time are great. Simply to study the effectiveness of one type of visual cue can require as much as 50 hours of simulator time, even if only a small number of subjects is run. Therefore, only a limited number of visual environment displays may be investigated.

In order to perform the parametric studies required for the design of effective simulator visual environments, techniques are needed for assessing the cueing effectiveness of visual displays quickly and at low cost. Such techniques might be used to screen candidate displays so that only the most effective need be examined in more comprehensive simulator flight studies.

De Maio and Brooks (4) have used a free modulus altitude estimation task to evaluate the altitude cueing effectiveness of flight simulator visual environments. Five environments were investigated, which varied in the density of 3-dimensional objects and in the level of detail of individual objects. Object density was found to have a potent effect on altitude perception. The present set of experiments extends the findings of De Maio and Brooks to more detailed visual environments and investigates the relationship between altitude perception and flying performance.

EXPERIMENT I

The purpose of Experiment I was threefold. The primary purpose was to extend the findings of De Maio and Brooks to a very high object density environment. A second question of interest was the relative effectiveness of other types of environmental features than those used by De Maio and Brooks in providing altitude cues. The third question was a methodological one concerning the procedures used to evaluate cueing effectiveness.

Since the altitude judgements normally made by pilots are made at speed, there was some question regarding the appropriateness of the assumption underlying the static altitude estimation procedure for evaluating environmental cues which would be used in a dynamic context. De Maio and Brooks made the assumption that the distribution of objects in the static display provides essentially the same altitude cue information as does the flow of objects in the dynamic display. In Experiment I this assumption was tested by using both static and dynamic presentation modes.

METHOD

Subjects

Subjects were 21 A-10 pilots. None had had any previous experience with the Advanced

Simulator for Pilot Training (ASPT).

Apparatus

Three ASPT visual environments were used. These were created by varying the level of scene complexity in an extant ASPT environment design to support low altitude flight. The most complex environment (Cond 1) consisted of a valley floor approximately 1/2 mile wide and covered with a hand-modeled texture pattern. On each side of the valley floor were mountains approximately 4000 ft in height. Inverted tetrahedrons ("trees") with white bases were randomly placed on the floor and mountain walls at a density of about 700 per square mile. These trees had three heights: 35, 50, and 75 feet.

The intermediate complexity condition (Cond 2) consisted of the same mountains and textured valley floor without the trees. The minimal complexity condition (Cond 3) consisted of only the textured valley floor.

Three presentation modes were used: a static slide presentation (SL), a dynamic video tape (straight and level flight, A/S = 450 kt) presentation (DT), and a static video tape presentation (ST). The ST condition was used because the image quality was substantially poorer in the video tape than in the slides. This condition permitted determination any decrement which might have been caused by the image quality difference.

Eight altitudes were presented. Altitude varied between 50 ft and 400 ft in equal log intervals. This distribution was used to provide a uniform distribution of data points for the log-log linear fitting procedure.

Procedure

Two groups of subjects were run in a briefing room at Davis-Monthan AFB. Image size was seven ft X seven ft. One group (N=12) viewed the presentations in the order SL-DT-ST. The second group saw DT-SL-ST. Condition ST was always presented last because it was not of interest in itself but was merely a control condition to be used in the event that performance in condition DT was substantially poorer than expected.

Stimulus and interstimulus intervals for condition SL were determined by the cycle time of a carousel projector set for eight sec display. The video tape was edited to provide 6- to 8- sec stimulus intervals and 3- to 4- sec interstimulus intervals. Subjects were instructed to estimate the altitude (AGL) in the first stimulus presentation. Subsequent estimations were to be made relative to the first. Three runs of 24 trials (three environments X eight altitudes) were made through each display condition without feedback.

RESULTS

Data were analyzed by first converting actual and perceived altitudes to logarithms. A least-squares, linear function was then determined for each subject's data (Kling and Riggs, 1971). The slope (b) of this log-log, linear function was taken as a measure of the altitude cueing effectiveness of each environment. The first run in each display conditon was not analyzed. A repeated measures analysis of variance (display condition X environmental complexity) was performed on the slope data. The results of this ANOVA are shown in Table 1. Seven post-hoc comparisons were made by means of a Dunn test at the .01 level of confidence.

Table 1
Results of repeated measures ANOVA on slopes of the altitude estimation functions for five visual display conditions

SOURCE	MEAN SQUARE	D. F.	F-RATIO	P
TOTAL	.113	149	-	-
DISPLAY CONDITION	1.684	4	39.6	.001
ERROR	.043	116	-	-

Slopes for the nine display X complexity conditions are shown in Table 2. There was no significant effect of image quality in the static presentation modes (CR = .211, DIFF = .09). Dynamic presentation lead to better altitude perception in environmental condition 3 (CR = .177, DIFF = .352) but not in Cond 2 (DIFF = .077) nor in Cond 1 (DIFF = .064).

The question of the effect of environmental complexity on altitude perception was addressed by three comparisons: 1/SL V 2/SL, 2/DT V 3/DT 1/DT V 5/DT. None of these differences was significant (CR = .271, DIFF = .243, .104 and .125 respectively).

Table 2
Mean altitude estimation slopes in experiment I

ENVIRONMENT	DISPLAY CONDITION SLIDE	DYNAMIC TAPE	STATIC TAPE
1	.78	.84	.55
2	.54	.61	.58
3	.37	.72	.29

DISCUSSION

Experiment I was conducted to answer three questions. Two of these questions (static v dynamic presentation and cue equivalence) can be answered by examining the results of Experiment I alone. In order to make a parametric evaluaton of the effect of object density on altitude perception the results of De Maio and Brooks and of Experiment I need be examined.

With regard to the necessity of dynamic presentation, evaluation of the cueing effectiveness of two-dimensional texture does seem to require this presentation mode, but the cueing effectiveness of three-dimensional objects can be evaluated using static presentation. Apparently observers are able to perceive the distribution of discrete objects in the environment and to use this information as they do optic flow information. When environmental details are not discrete but instead form a continuous, two-dimensional mosiac, the density gradient information is not accessible to the observer, and optic flow information is necessary for the perception of altitude. Since the static presentation mode is both simpler and less expensive, this should be the preferred mode whenever possible.

A limited answer to the cue equivalence question can be obtained from the results of Experiment I. Two-dimensional texture (at least the pattern used in the present work) can provide an effective altitude cue, which is enhanced neither by the addition of large three-dimensional objects (Cond 2) nor by the addition of small three-dimensional objects (Cond 1). A caution is appropriate at this point, however. Since the texture pattern used in the present work was hand modeled, it is by no means representative of texture patterns in general. We cannot conclude from the present data that any texture pattern can provide an effective altitude cueing, nor do we know what attributes of a texture pattern lead to effective altitude cueing. A number of texture patterns needs to be evaluated in order to ensure that the factors contributing to altitude cueing effectiveness are understood.

To begin to address the question of what level of object density is adequate for accurate perception of altitude, the results obtained by De Maio and Brooks for very low density environments are examined along with the present data. Figure 1 shows the slope of the altitude estimation function versus object density in the two experiments. Also shown is a best-fitting exponential function. This function is not intended to model the process of altitude perception but only to serve as a tool for equating the cueing effectiveness of different environments. This function becomes asymptotic at roughly $\underline{b}$=.8. It is generally safe to assume that gains in performance are trivial past the point where the functon is 90% complete. The 90% point occurs at $\underline{b}$=.7 or the equivalent of about 12 to 15 objects per square mile. In order to address the question of how much is enough, it is necessary to determine the relationship between altitude perception and flying performance. A second experiment was performed to address this question.

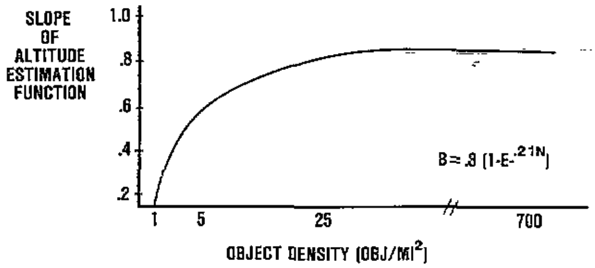

Figure 1. Altitude estimation slope vs object density

EXPERIMENT II

The purpose of Experiment II was to determine the ability of pilots to maintain altitude based on out-of-the-cockpit cues in selected environments, whose altitude cueing effectiveness was determined above. In this regard Experiment II can be viewed as a validation of the use of altitude perceptibility as a metric for the ability of a visual environment to support low altitude flight. This in-simulator validation can also be of use in determining what level of altitude cueing effectiveness is adequate to support low level flight.

METHOD

Subjects

Twelve Air Training Command instructor pilots at Williams AFB volunteered to serve as subjects. Of these, three were eliminated from the analysis due to unreadable data tapes. None of the remaining subjects had had any previous experience with ASPT.

Apparatus

Flying was performed in the ASPT F-16 simulator. Neither instruments nor Head-up displays (HUD) providing altitude, pitch, bank, vertical velocity or flight path angle information were available to the pilot. Five visual environments were used. Three were from De Maio and Brooks (Conds D-1, D-2, and D-5), and two were from Experiment I (Conds 1 and Cond 3). These five conditions spanned the range of cueing effectiveness levels obtained in the two experiments.

Procedure

Subjects were given a 15-minute practice period to get accustomed to the F-16 simulator. During this period they flew in two of the test environments (Conds D-1 and 1) with full instrumentation but only airspeed on the HUD.

Subjects flew two experimental runs through each environment with the cockpit instruments occluded. On each run the pilot was to fly the length of the course at 600 kt and 150 ft AGL. At a specified point the pilot performed a Whifferdill and then flew back to the start point at the same airspeed and altitude. The order in which subjects flew the five environments was counterbalanced to control for first order effects. Altitude AGL was recorded at 30 Hz.

RESULTS AND DISCUSSION

Data from the Wifferdill portion of the task were omitted from the present analysis. Only the level flight portions were considered. A target altitude was determined for each run by averaging the local altitude minima and maxima on that run. Mean target altitudes for each level of altitude cueing effectiveness are shown in Figure 2. When the dynamic altitude estimation slope is used for Cond 3, the correlation between mean slope and mean target altitude is -.98 ($P < .01$). This result demonstrates the validity of the altitude perception metric for evaluation of the ability of visual displays to provide the pilot information needed to maintain altitude. The superior prediction of flying performance obtained with the dynamic presentation evaluation of texture demonstrates the need for dynamic evaluation of altitude cueing effectiveness of this display feature.

Results of an analysis of variance on the target altitude data are shown in Table 3. Post-hoc analysis by a Dunn test showed that Cond D-2 was significantly worse than the average of Cond D-1 and Cond 1 (CR = 17.7, DIFF = 77.2, $P < .01$). Slopes associated with this comparison were .5 and .8, respectively. The difference between Cond D-2 and Cond D-5 was non-significant

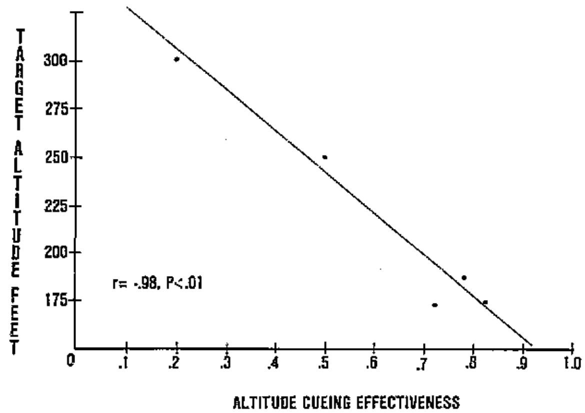

Figure 2. Target altitude vs altitude estimation slope

(DIFF = 51.8). Associated slopes were .5 and .2. Differences between Conds 1 and D-1 and between Conds 1 and 3 were also non-significant (DIFF = 12.5 and 7.7, respectively). These results support the previous conclusion that an environment giving an altitude estimaton slope of about .7 is necessary and sufficient to support maintenance of altitude in low altitude flight.

Table 3
Results of one-way ANOVA performed on target altitudes in five visual display environments

SOURCE	MEAN SQUARE	D. F.	F-RATIO	p
TOTAL	5100.49	44	-	-
ENVIRONMENT	29194.05	4	13.65	.001
ERROR	2138.35	32	-	-

There is one difficulty with the conclusions presented above. That is pilots report Cond 1 to be much easier to fly in than Cond D-1 even though they maintain altitude no better. The reason for this seeming discrepancy can be seen in Figure 3. Figure 3 shows examples of subjects' ground track in the two environments. It can be seen that ground track variability is much higher in Cond D-1 than in Cond 1. This difference results from the lack of distinctive features in Cond D-1. It is likely that the difference in subjective evaluation stems not from a difference in altitude cueing effectiveness but from differences in ground track cueing effectiveness. In order to specify completely the effectiveness of simulator visual environments in providing information needed for low altitude flight, research is needed to determine what aspects of the visual environment are relevant to ground track cueing and how they relate to flying performance.

CONCLUSIONS

1. Altitude perceptibility (slope of the altitude estimation function) is a valid metric of the ability of a simulator visual display environment to provide a pilot information needed to maintain altitude in low level flight. When an environment containing three-dimensional objects is evaluated, static presentation may be employed. Evaluation of the cueing effectiveness of two-dimensional texture requires a dynamic presentation mode.

2. A potent cue for altitude perception comes from the distribution, or flow, of environmental features.

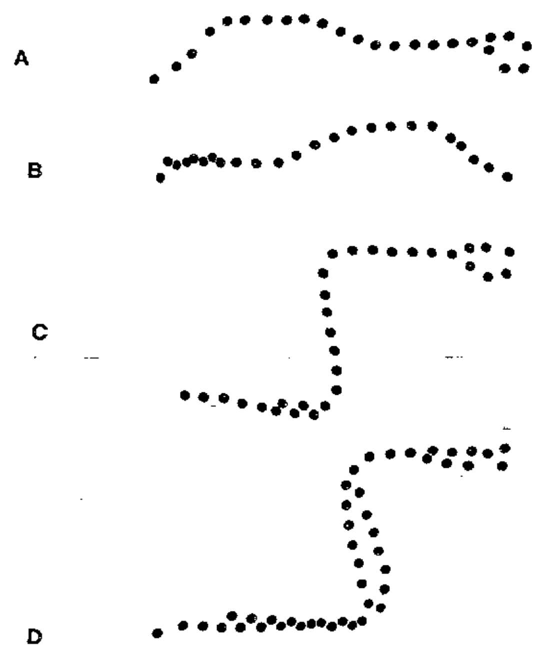

Figure 3. Examples of ground tracks, Cond 1 is shown in 3a and 3b, Cond D-1 is shown in 3c and 3d

Perception of this information improves as the density of features in the visual environment increases. For three-dimensional objects a density of about 12 to 15 objects per square mile is necessary and sufficient for maintaining of altitude. Equivalent cueing effectiveness ($\underline{b}$ = .7) can be provided by a two-dimensional texture pattern. A weak altitude cue is also provided by information about the aspect of individual objects, but the effectiveness of this cue is poor compared to that of gradient/flow cues.

3. A second aspect of visual cueing effectiveness was identified having to do with *ground track control*. This aspect of aircraft control involves initiation and control of turns. Visual cues required for ground track control are those which permit identification of roll-in and roll-out points. Unlike altitude cues, which must be uniformly distributed throughout the environment, ground track cues must be placed around particular decision points. A complete evaluation of the ability of a visual environment to support low level flight requires measurement of its ability to provide both altitude related information and ground-track related information.

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ABOUT THE AUTHORS

Dr De Maio and Ms Brooks are Research Psychologists at the Air Force Human Resources Laboratory/Operations Training Division, Williams AFB, AZ. Dr Rinalducci is a Professor of Psychology at the Georgia Institute of Technology, Atlanta, GA. First Lieutenant Brunderman is a T-38 Instructor Pilot with the 82 FTW, Williams AFB, AZ.