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Visual Perception in High-Speed Low-Altitude Flight

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An ongoing exploratory development program on visual perception and control in high-speed low-altitude flight is being conducted by the Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory. This paper begins with a discussion of the necessity of vision for low-altitude flight; proceeds to an analysis of objectives, strategies, and issues in designing a comprehensive research program; presents an overview of several experiments in support of the effort; and ends with a discussion of perceptual information. One of the simulator experiments involves the use of a non-mimetic task, flying at a zero altitude in the presence of strong gusts, in an effort to maximize adaptation to the low-altitude environment. Implications for simulator use are discussed.

AN ONGOING EXPLORATORY development program on visual perception and control in high-speed, low-altitude flight is being conducted by the Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory (AAMRL). This paper begins with a discussion of the necessity of vision for low-altitude flight; proceeds to an analysis of objectives, strategies, and issues in designing a comprehensive research program; presents an overview of several experiments in support of the effort; and ends with a discussion of perceptual information.

Necessity of Vision in Low-Altitude Flight

High-speed, low-altitude flight is a supremely visual and demanding task. That the task is demanding is obvious: at high speeds and low altitudes, there is almost no margin for error either above or below the chosen altitude. Altitude and heading control must be precise on the down side to avoid impact with the ground or a fast approaching hill crest. Control must be precise on the up side to avoid detection. As a further demand, control must be continuous for long periods with no lapses in attention.

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That the task is visual is not so obvious. It would seem that such a dangerous task should benefit from advanced sensors and instruments. One problem is that no head-down displays contain the richness of information needed for high-speed, terrain-following, terrain-avoidance flight. If an exclusively instrument-guided flight is not plausible, a second approach is to fly by alternately looking head-down at the instrument displays and looking outside the cockpit. There are two problems with this alternative: the first is that it takes time to examine an instrument display and often several displays are consulted. Even if the examination time is less than 0.5 second (s), significant and possibly deadly terrain avoidance problems can occur because of the high speeds and proximity to the Earth. Another problem is that even after the eyes return to outside viewing, they are momentarily near-sighted. When the eyes focus and accommodate a near distance such as that of an instrument panel, they cannot instantly refocus to accommodate far objects (near-field myopia). Again, because of the high speeds and close proximities involved, unfocused hill crests may not be seen; therefore, they may not be avoided.

One solution to the problem of alternating head-down viewing is to use head-up displays (HUDs). Critical information can then be displayed at the same accommodative distance as the environment (which need not be at optical infinity) (17), thus avoiding the problem of near-field myopia. And further, since the HUD "symbology" is optically superimposed on the outside scene, the eyes need not "wander" far from external items of interest, and the chance of missing critical features of a fast changing scene should be reduced. This technique is used today for high-speed, low altitude flying.

However, HUDs are not a complete solution (11,13). Head-up displays have a limited field-of-view, centered straight ahead. The problem is that many items of interest may lie well above the pilot's head or off to the side and down. When a pilot looks off to the side, he is deprived of his instruments, whether head-up or head-down, and has all the attendant problems of alternating views. A possible solution is to use a helmet-mounted display (HMD) so that the information that is optically superimposed on the outside scene moves with and remains in front of the pilot's head. These displays are still in the developmental stage, but do show great promise. One such display is used in the Visually Coupled Airborne Systems Simulator at the Armstrong Aerospace Medical Research Laboratory (11).

Even if we had fully operational, helmet-mounted displays, the problem of understanding visually-controlled high-speed, low-altitude flight would remain. The problem of visually-controlled self-motion has a long history (5,6,15) and is still not fully understood. For example, accidents do occur today in both ground and air transportation because a vehicle operator did not see an obstacle or another vehicle. Further, although low-altitude flight requires vision, vision is susceptible to illusions of size, speed, distance, and orientation. If we understood the nature of these illusions and their causes, we might be able to predict them, forewarn pilots, and develop safe procedure for dealing with them. To achieve this understanding, we at AAMRL have created and are continuing to refine our low-altitude research program.

Toward A Low-Altitude Program

Objectives: The laboratory research program has three objectives. The ultimate objective is to enhance real terrain-following, terrain-avoidance flight. A more immediate objective is to understand visual perception and its relation to pilot control actions in high-speed, low-altitude flight. Another immediate and practical objective is directly related to the design and use of flight simulators. Design in this context refers to the contents of the visual displays. A key question concerns the degree of richness of the imagery and the level of detail that should be used for maximally effective displays. A closely related concern is the establishment of fidelity requirements.

Scope: This paper describes the visual, perceptual aspects of the AAMRL program. However, the program has two other aspects which are noted here to give a broader perspective of our purpose, scope, and approach. The second important aspect of the overall program is concerned with the temporal integration of visual and whole-body motion cues (2). Temporal asynchronies are not really a problem in actual flight, but can be a major obstacle in pilot acceptance and effectiveness of flight simulators. The problem may be readily appreciated by analogy with the familiar case of viewing a motion picture in which the sound track and the visual frames are out of "sync." Even if we had a perfect understanding of the visual-perceptual aspects of flight simulation, the value would be limited without a concomitant understanding of the contributions and interactions of other perceptual systems. With this caveat, we turn to a description of the visual program.

General approach

We take an integrated multistage approach to studying the perception and control of high-speed, low-altitude flight. The first stage consists of analyses of the pilot's tasks and needs. The second stage involves ascertaining and mathematically describing the perceptual cues available to the pilot. The third stage comprises empirical, psychophysical studies of the relative perceptual and control efficacy of the various cues including their interaction, dominance relations, criticalness, and role in illusion. The fourth stage attempts to mathematically model the empirical results and presumed functional subprocesses.

These four stages characterize our research program. Before we describe some of our experiments, it would be useful to further comment on some of these stages.

The initial stage of front-end analyses is critical: it sets the tone for the subsequent stages. Here we try to define or delimit what there is to be perceived. Some perceivables such as normal events, critical events, and day/night contrasts are straightforward—but not trivial—to define. Others such as illusory, impoverished, and visually risky environments are more difficult to define because, by their nature, they are often unexpected abnormalities to both pilots and perceptual researchers.

The second stage, that of ascertaining the cues or optical information variables specific to particular perceivables, is most difficult. The difficulties are not particular to aviation, but rather to the field of perception as a whole. For example, although we know that speed and altitude are perceived (albeit not always veridically), we do not really know what the actual cues are. There are, to be sure, some candidates, but the exact mathematical characterization is not yet available.

The third stage uses experiments to evaluate the value of the cues to pilots. It is possible for two cues to specify the same referent equally in a geometric sense, but not be equally useful to a pilot. That is, optical information may be redundant and some cues may be deleted in a simulator without adversely affecting the usefulness of the simulator. In fact, deleting unused cues may enhance simulator usage by permitting pilots to concentrate on the cues they will actually use in real flight. Whatever the implications of the existence of redundant information, we cannot make intelligent decisions about display design until we have the experimental data to guide the decisions. The next section of this paper will report several laboratory studies on cue use for altitude control.

The fourth stage involves the development of mathematical models of the empirical data. The mathematical models serve three functions: they form convenient summaries of the data; they guide future research; and they force theoretical assumptions to be made explicit. An example of the modeling of flight cues is found in Zacharias, Caglayan, and Sinacori (18).

The various stages of the effort are proceeding in parallel. Before discussing the optical information for the perception of speed and altitude it is useful to review some experiments.

Experiments

The experiments reviewed here were initially designed to answer two questions: how well can people fly a simulator at low altitudes in the presence of strong gusts, and how valuable are various types of simple scenes and their combination for altitude control? The three experiments reviewed begin with the task of holding an assigned but low altitude, progress logically to the task of flying as low as possible without crashing, and descend still further with the apparently illogical task of "flying" at zero altitude. Since the experiments share a common methodology, that is presented first.

General Method

The common methodology is relatively simple—displays are limited to 53.1°, scenes are schematic, and flight dynamics are limited to pitch and altitude changes. This simplicity is a strength, in that it permits scientific rigor; but is also a weakness, in that generalization to the operational world must be very careful and tentative. The program is one of exploratory development by design and that should be kept in mind. Enough details of the method are presented to reasonably evaluate the design and findings, but for more detail see Warren and Riccio (16).

Subjects: The paid subjects were college students with normal or corrected-to-normal vision. None were pilots.

Apparatus: The visual flight simulator was fairly rudimentary. A DEC PDP 11/60 was used to collect data. An EAI 2000 analog computer simulated the pitch-related dynamics of an F-16. An AP 400 array processor augmented the PDP 11/60 for display generation, and a DEC GT40 served as the display processor. Observers directly viewed the displays on a high-speed Hewlett-Packard monitor and controlled the simulated aircraft using a side-mounted force stick. Fig. 1 shows the equipment configuration.

Displays: Displays were of three types consisting either of a schematic roadway scene, a perspective view of a field of random dots, or the superimposition of the dots and roadway. Fig. 2 shows the combined display.

Display changes: Displays changed as a function of aircraft pitch state and altitude. Pitch changes resulted in changes in the vertical position of the horizon line on the CRT screen where pitching up caused the horizon line to move down the screen. For the roadway, increasing altitude resulted in the perspective central angle diminishing. For the dots, increasing altitude resulted in the global optical density increasing and the global optical speed decreasing.

Gust disturbance: Aircraft and display state changed as a function of both subject commands and buffeting by very strong (7.7 ft·s^{-1} RMS) vertical wind gusts. These gusts were formed by a sum of 13 sinusoids to approximate the power spectrum of a strong vertical gust using the Dryden model (9).

Speed: Both the ground and airspeeds were 400 knots.

Experimental trials: Although the number of trials per day, the task, and the scene content during a trial varied with each experiment and condition, the general within-trial procedure was always the same. Each trial begun with a short passive viewing period followed by a 120-s interactive phase. Data was collected during the last 102.4 s of a trial at 40 Hz. At the end of each trial, subjects were given feedback as to various performance measures such as their mean or RMS altitude or flight path error.

Experiment: Assigned Altitude Holding

The main purpose of the assigned-altitude holding series was to assess the effect of different display parameters on this ability.

Task: On a given trial, a subject's task was simply to maintain an assigned altitude in the presence of strong vertical gusts.

Altitude assignment and holding: Altitude assignment was made visually at the start of a trial. The scene which corresponded to the assigned or target altitude appeared in "perfect" nonperturbed form for 15 s for inspection and "memorization" by the subject. For example, a roadway kept the central angle, and the flowing dots kept the characteristic optical speed and optical density that corresponded to the target altitude. Since gusts and pitch commands would perturb the display, altitude holding with our displays meant keeping the display as close as possible to its initial appearance.

Procedure: All subjects were first trained with a single intermediate altitude of 90 ft. Since the subjects were not pilots, this training was necessary to build basic competency before any real manipulations were

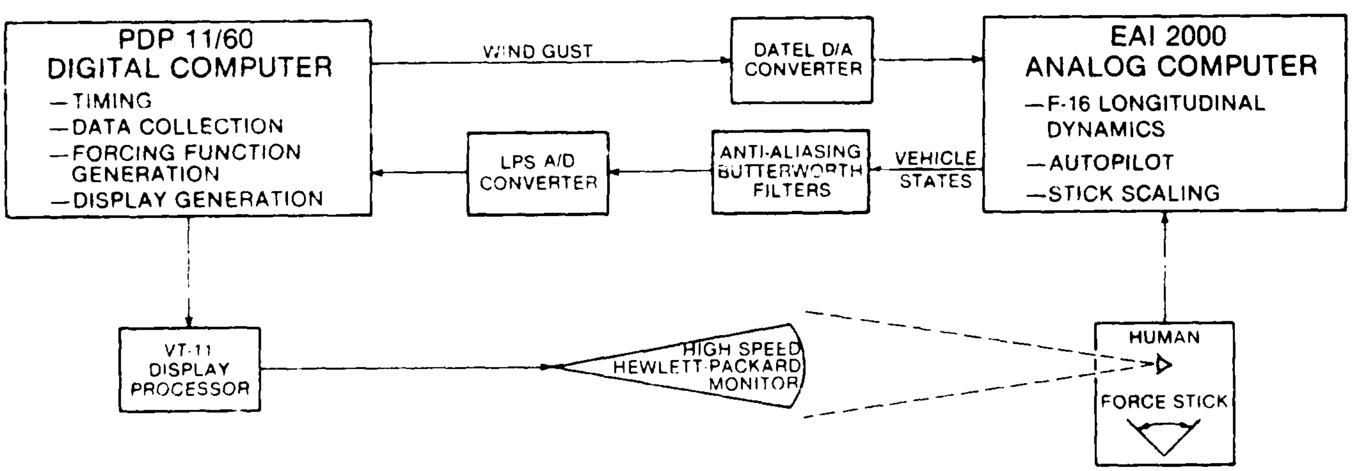

Fig. 1. Simulator configuration.

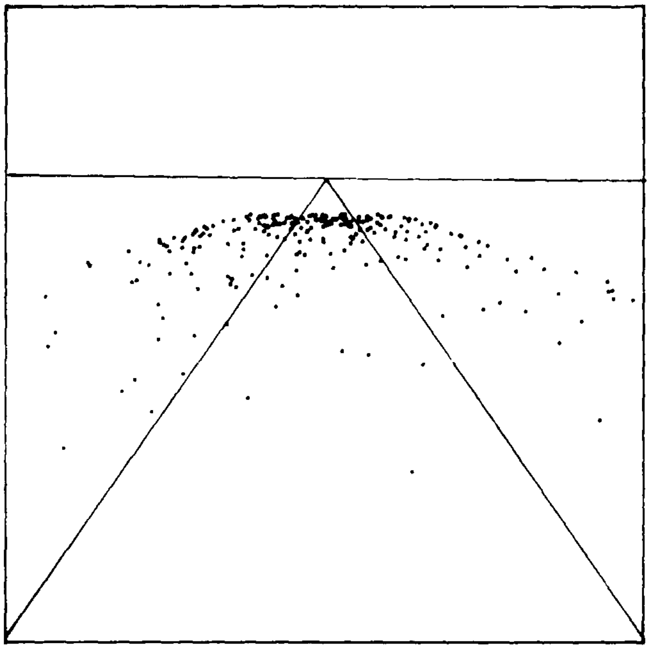

Fig. 2. Sample frame from the combined cue display during low-altitude level flight.

attempted. Subjects were then extensively trained on the four target altitudes. During advanced training, subjects received two sessions (of four trials) each day. Each of the four trials in a session was assigned a different altitude, but the assignment was not known prior to the start of a trial. Subjects were then tested for eight sessions which yielded eight test trials on each of the four assigned altitudes. From the subjects' point of view, testing trials were indistinguishable from the advanced training trials.

Design and displays: A total of 18 subjects participated. The type of display (roadway only, dots only, or roadway plus dots) used during the training phase of the experiment defined a between-groups factor with six subjects per group. Assigned altitude was studied as a within-groups factor having four levels. The displays containing a roadway can be further described by the size of the roadway central angle and its spatial rate of change with respect to altitude. Table I presents the assigned altitudes used for all three display types. In addition, Table I presents the road widths that were paired with the altitudes and the resulting size of the perspective central angle of the road and its spatial rate of change with respect to altitude at the assigned altitude. The rates of change are negative because central angle decreases with increasing altitude. Note that assigned altitude and road width are environmental variables, whereas perspective road angle and its spatial rate of change are optical (i.e., projective) variables.

Results: The main data collected during each trial were the deviations from the assigned altitude. Each trial was summarized by the mean and standard deviation of the 4,096 samples of height error per trial. Tables II and III present the midmeans of these statistics as functions of the display type and assigned altitude. Each midmean is based on 48 values: the 8 test trials per subject times 6 subjects per display type.

Table II indicates that, on average, subjects were able to fly at their assigned altitude even when it was 47.7 ft, although generally with a small positive error. The roadway-only display, however, proved slightly better than the roadway-plus-dots display. These displays, in turn, were markedly better than the dots-only display for the task. This pattern is even more evident when the standard deviation is the index of performance (Table III).

Discussion: On the assumption that the more information (or the higher the fidelity of a display) the better, the superiority of the roadway-only display over the combined cue display was surprising. The actual information content of the displays might account for the results: roadway-only displays contain no information for forward motion; they only afford information for change in altitude, which, in this experiment, is task-relevant. The dots-only display contains both information for change of altitude (by change in dot density) and for forward travel (by the flow of the dots). The information for altitude change here is task-relevant, but the information for forward travel is task-irrelevant. The combined cue display contains *two* sources of relevant information for altitude change (changes in dot density and size of the central road angle) and one source of irrelevant information (dot flow rate).

The concepts of quantity, relevancy, and irrelevancy of information may be used to explain our results and also raise questions about theories of fidelity and cue dominance hierarchies (16). When there are two different cues for the same referent, it is not unreasonable to expect one to be more psychologically effective than the other. In particular, it may be that the "target" roadway angle is easier to "keep in mind" than a target value of dot density. The poorer performance with the dots-only displays may also be due to the presence of the task-irrelevant information. The presence of an irrelevant cue may indeed be very deleterious. This is suggested by the intermediate performance under the combined display which had two relevant cues being offset or masked by one irrelevant cue.

The notion of relevancy/irrelevancy is very task-specific. For the purpose of inducing compelling feel-

TABLE I. DISPLAY PARAMETERS.

Height (ft)	Road Width (ft)	Road Angle (°)	Angle Rate (°·ft⁻¹)
47.7	25.0	30	−0.6
83.0	95.0	60	−0.6
95.5	51.2	30	−0.3
165.0	191.0	60	−0.3

TABLE II. MEAN HEIGHT ERROR (ft) AS A FUNCTION OF DISPLAY TYPE AND ASSIGNED ALTITUDE.

	Assigned Altitude			
	47.7	83.0	95.5	165.0
Both	6.3	−0.6	5.0	−3.2
Road	2.3	3.1	0.9	1.1
Dots	3.9	1.5	0.2	13.0

TABLE III. STANDARD DEVIATION HEIGHT ERROR (ft) AS A FUNCTION OF DISPLAY TYPE AND ASSIGNED ALTITUDE.

	Assigned Altitude			
	47.7	83.0	95.5	165.0
Both	13.0	11.1	14.3	14.4
Road	8.5	8.5	10.6	12.0
Dots	17.0	19.5	22.0	30.6

Each value is a midmean based on 48 standard deviations.

ings of self-motion, dots were definitely preferred over roadway. It seems that what is best for promoting scene realism (which is best for pilot preference and acceptance) may not necessarily be best for promoting good performance. In this experiment, the greater realism or fidelity of the combined cue displays did not lead to better performance over the single cue roadway displays. The issue of simulator fidelity is complex (16).

Another factor possibly influencing our results is the altitude holding task itself. This task may be construed as a pursuit tracking task, but with the target altitude never explicitly present during data collection. In effect, we have a "memorial" tracking task since the subjects had no way of knowing if they were "on target" except by "comparing" the current state of a scene (e.g., high optical density) with their memory of what the scene should look like at the assigned altitude. Even though we can argue that, by the testing phase, subjects had considerable exposure to the four assigned altitudes, and thus fairly well "knew" what the scenes should look like, the memorial aspect of the task might be interacting with the purely perceptual and control aspects.

As an example of a memorial interference on purely perceptual or control performance, consider a predicament several subjects reported: on occasion, a subject would be tracking a particular roadway angle and be pleased with how "tightly" they were tracking when they would realize that their concept of what the scene should look like had "drifted." Quandary: if they jerked the scene to the correct state, mean height error would be helped but standard deviation error would suffer, whereas if they continued a tight tracking of the current scene state, standard deviation error would be kept low but mean height error would be inflated. Thus, a subject would unavoidably incur some error which was, in fact, inflated over their perceptual and control ability from the time they realized their mistake.

Although the ability to maintain an assigned altitude is important, the ability to perceive the lower limit for safety is more important. The next series of experiments was designed to directly determine this limit and also to avoid the possible complications of the memorial tracking task.

Experiment: How Low Can You Go?

The main purpose of this experiment was to directly determine the lowest altitude that could be "flown" without crashing using our simulator and displays. This follows naturally from the assigned altitude-holding studies. A further purpose was to eliminate the possible effects of the memorial nature of the assigned altitude task.

Task: A subject's task was simply to fly as low as possible without crashing in the presence of strong vertical gusts.

Crashing: A crash was defined as going below ground level. This is very striking visually since the display inverts—the ground plane becomes a ceiling.

Procedure: The procedure was very similar to that of the assigned altitude study. Trials started at 200 ft and subjects determined their own lowest altitude. If a subject crashed, the trial continued so there were always 120 s of flying per trial. This was done to ensure equivalent flying experience across subjects. Feedback was given at the end of each trial. If the trial was successful, mean altitude and standard deviation were given. If the trial was unsuccessful, the words "fatal crash" appeared as well as the total time flown before the first crash and the number of crashes. In addition, subjects were continually admonished as to the importance of not crashing.

Design: Twelve inexperienced subjects participated. The same displays were used as in the previous study (with a single road width of 50 ft), and display type was again a between-groups factor. Training lasted 3 days with 12 trials per day. Testing consisted of an additional day of 12 trials. Again testing and training were the same from the subject's point of view.

Results: The most striking aspect of the data was the large number of crash trials. The right side of Table IV presents the mean percentage of test trials that resulted in a crash as a function of display type. Each percent is based on 144 trials (12 test trials times 12 subjects). Dots-only displays led to the most crashes and roadway-only displays led to the least crashes.

The main data for crashless trials was the mean altitude. For test phase data, we report the mean of the best 6 crashless trials out of 12 during testing (Table Va, right). For training data, we report the equivalent results for the last training day (Table Va, left). Dots-only displays are the hardest and combined cue displays the easiest to fly as indexed by the lowest non-crash altitude attained.

Discussion: The large number of crash trials was unexpected especially since subjects were repeatedly instructed not to crash. One possible explanation is that the obvious safety factor may induce a certain degree of "simulator complacency" (4). In a related area, simulator complacency may be a factor in the hard landings observed for actual pilots in simulators. Since our subjects were not pilots, we may have had cases of "simulator bravado" as subjects pursued absolute minimums.

TABLE IV. PERCENT CRASH TRIALS DURING TESTING AS A FUNCTION OF DISPLAY TYPE AND TRAINING TASK.

	Training task	
	Zero Altitude	Lowest Altitude
Both	37.5	35.4
Road	45.8	22.9
Dots	50.0	45.8

TABLE Va. MEAN ALTITUDE FLOWN (ft) AS A FUNCTION OF DISPLAY TYPE WHEN TEST TASK WAS "FLY AS LOW AS POSSIBLE": LAST TRAINING DAY VS. FIRST TESTING DAY FOR TRAINING TASK "FLY AS LOW AS POSSIBLE."

Display	Day	
	Last Training Day	First Testing Day
Both	30.1	31.6
Road	45.8	39.5
Dots	56.7	51.1

TABLE Vb. MEAN ALTITUDE FLOWN (ft) AS A FUNCTION OF DISPLAY TYPE WHEN TEST TASK WAS "FLY AS LOW AS POSSIBLE": FIRST TESTING DAY FOR SUBJECTS TRAINED TO "FLY AT ZERO ALTITUDE" VS. SUBJECTS TRAINED TO "FLY AS LOW AS POSSIBLE."

Display	Training Task	
	Fly at Zero	Fly Low
Both	42.3	31.6
Road	35.5	39.5
Dots	114.9	51.1

The general pattern of results for display efficacy is similar to that of the altitude holding study. The dots alone were least effective (using either altitude or crashes as performance indices), and the roadway alone was most effective (using crashes as the index of performance).

Experiment: Flying at Zero Altitude

The very term "simulator" implies imitation. However, the flexibility of computers for cue generation and the safety inherent in ground-based systems permits us to explore novel and nonmimetic uses of these powerful machines. One such use is to "fly" at a zero altitude.

Task and displays: A subject's task was to fly as close as possible to a zero altitude in the presence of strong vertical wind gusts. This altitude task was assigned as in the first set of experiments but it did not have a memorial aspect as in the second set. There was no memorial aspect because the display takes on a unique look at altitude—all ground texture vanishes and all that is left is a horizon line separating the "above ground" from the "below ground." As in the lowest altitude studies, it was possible to cross the ground plane with a resulting inversion of the display.

Procedure: Since flying exactly at zero was impossible due to the gusts, subjects were expected to have many ground crossings and display inversions. Otherwise, the procedure was the same as in the "lowest" altitude experiments. Subjects were given feedback as to the percent time spent in subterranean flight with 50% as ideal.

Results: Inexperienced subjects could, on average, fly close to zero using all display types (mean altitude of 0.8, 1.7 and −4.0 ft, respectively, for the both cue, roadway-only cue, and dots-only cue displays). Variability about the mean was unavoidable due to the effects of the gusts. The dots-only displays were the most difficult to control, as evidenced by the variability measure.

Discussion: The generally good performance at the zero-altitude task as measured either by mean or standard deviation altitude is remarkable, since it is the optical equivalent of riding a bucking bronco. The ability to fly at a very low altitude entails the ability to control a display with a very high rate of change for a given altitude command. This "sensitivity" of the display varies inversely with altitude: the lower the altitude, the more change in visual effect for equivalent altitude change commands. At very low altitudes this optical sensitivity is dramatic and even "optically violent."

Change of Task: Heavy Bat Training

The motivation for the zero altitude study stemmed from an analysis of the learning process in the lowest altitude study. Our subjects followed a classical learning curve. They started flying with a high mean altitude and gradually flew at lower mean altitudes as training progressed. Similarly, the minimum non-crash altitudes were relatively high at first and gradually lowered. There is nothing remarkable about these facts, when we realize that mastering a situation entails gaining experience with that situation. But because of the learning curve, the proportion of time spent below 50 ft, for example, only gradually increased with training. Hence, in the early phase of training, our subjects did not gain much experience controlling optically violent displays because they were flying in a generally optically gentle regime!

One consequence of operating in an optically gentle environment is that an encounter with an optically violent episode (possible due to a poor control command or a particularly strong gust) is disorienting. A subject panics, overreacts with a too-strong climb command, in turn overreacts to the rapid climb, and crashes. This type of pilot-induced oscillation might account for the large number of crashes in the early trials.

The zero-altitude task was designed to ensure that subjects received considerable experience flying, literally, as close to the ground as possible. It was hoped that the experience controlling the most optically violent displays would lead to skill and confidence in controlling less violent displays. We set up a transfer-of-training situation which is also a change-of-task paradigm. We refer to this approach as "heavy bat training" by analogy to the practice of some athletes of training with a more demanding procedure than they encounter in actual competition.

Procedure: After zero-altitude training, subjects were tested under the identical instructions as the lowest-altitude subjects. Both groups had the same amount of training with the same displays. Only the training tasks differed.

Results and discussion: The results did not support the heavy bat training hypothesis. The mean altitude of the best 6 of 12 test trials for the 6 subjects is presented in Table Vb, left. Performance for the combined cue display and the dots-only display was worse than that of subjects trained an equivalent amount of time using the lowest altitude task (in Table Vb, right). Even the number of crashes was greater at all display types (Table IV). The lack of a training benefit for the zero altitude training is perhaps being offset by the difficulty of transitioning to a new task. Research is now being conducted to check this possibility. Even if heavy bat training should prove valueless for simulator training, the idea of using simulators in novel ways has merit.

Change of Display

A less drastic transfer procedure than a change of task is a change of display. Subjects from all three task groups (assigned, lowest, or zero altitude) who were trained and tested with the combined cue display were also tested on the roadway-only and dots-only displays. The purpose was to assess the impact of encountering an impoverished cue situation after extensive training in rich cue environments. The motivation for this is that pilots experienced with rich urban or well farmed environments can have difficulty over desert, water or night scenes if they must rely only on vision.

The predictions are straightforward. Based on our previous findings, the roadway-only scenes should lead to better performance than the dots-only scenes. If extensive experience with the new scenes were permitted, the asymptotic values should equal those of the single-cue trained subjects. But, we are interested here in the first or early encounters with the reduced scenes. Hence, we expect a moderate drop in performance for both single-cue scenes, as is common in transfer of training paradigms.

Results: Tables VI and VII present the average mean and standard deviations of height errors for the assigned altitude task. The top row presents the results of the combined-cue trained group before and after they were transitioned to the single-cue displays. The other rows present the means for single-cue trained and single-cue tested groups for comparison. (A cell value is the mean over six subjects, four assigned altitudes, and eight test trials.) Similarly, Table VIII presents the transfer-of-display mean altitudes for the lowest-altitude task. Table IX presents the comparable data for the zero-altitude trained subjects *after* their transition to the lowest-altitude task.

The main diagonals are the results prior to the display transition and form a basis for post-transition comparisons. In particular, the main diagonals of Tables VI, VII, and IX conform to the pattern we keep finding: roadway-only is slightly better than combined cues, and both in turn are better than dots-only for performance. The transition results in both Tables VIII and IX were comparable to those found with the assigned altitude task, so all display transition results are discussed together.

Discussion: For the assigned altitude task (Tables VI and VII), the transition to roadway-only displays is surprisingly better than predicted. The values are better than for the combined cue display and compare favorably with those of the asymptotic values of roadway-only trained subjects. It is as if subjects had fully utilized the roadway cues all during combined cue training and were being hindered by the presence of irrelevant information afforded by the dots. This is the same explanation offered earlier for the performance of the dots-only trained group. The argument about the deleterious effects of irrelevant information is further supported by the poorer than expected performance of the group transitioned to dots-only. It is as if subjects were trying to ignore the dots information (in favor of the roadway information) and hence, exhibited little direct or incidental learning to the dots information.

For the lowest and zero-altitude trained groups, transition to the roadway-only display led to much better performance than that originally obtained with the combined-cue display. This was much better than expected and, the same arguments presented in the discussion of the assigned altitude findings apply here. The transitioned-to-roadway groups are also much better than the roadway-only trained groups (Tables VIII and IX). However, the large differences in performance may be somewhat artifactual. The data for the main diagonal cells were collected first in the testing phase, whereas the data for the combined-cue trained, single-cue tested trials were collected second. Hence, the display transition data may reflect the benefits of extra experience. This might be especially true for the zero-altitude

TABLE VII. STANDARD DEVIATION HEIGHT ERROR (ft) AS A FUNCTION OF DISPLAY TYPE USED IN THE TESTING PHASE VS THE DISPLAY TYPE USED IN THE TRAINING PHASE FOR THE ASSIGNED ALTITUDE TASK.

		Test Phase Displays		
		Both	Road	Dot
Training	Both	13.2	12.3	35.7
Phase	Road	—	9.9	—
Display	Dots	—	—	22.3

TABLE VI. MEAN HEIGHT ERROR (ft) AS A FUNCTION OF DISPLAY TYPE USED IN THE TESTING PHASE VS. THE DISPLAY TYPE USED IN THE TRAINING PHASE FOR THE ASSIGNED ALTITUDE TASK.

		Test Phase Displays		
		Both	Road	Dots
Training	Both	2.0	1.5	16.4
Phase	Road	—	1.8	—
Display	Dots	—	—	4.7

TABLE VIII. MEAN ALTITUDE FLOW (ft) AS A FUNCTION OF DISPLAY TYPE USED IN THE TESTING PHASE VS. THE DISPLAY TYPE USED IN THE TRAINING PHASE: LOW TASK TRAINED—LOW TASK TESTED SUBJECTS.

		Test Phase Displays		
		Both	Road	Dots
Training	Both	31.6	24.3	76.9
Phase	Road	—	39.5	—
Display	Dots	—	—	51.1

TABLE IX. MEAN ALTITUDE FLOW (ft) AS A FUNCTION OF DISPLAY TYPE USED IN THE TESTING PHASE VS. THE DISPLAY TYPE USED IN THE TRAINING PHASE: ZERO TASK TRAINED—LOW TASK TESTED SUBJECTS.

		Test Phase Displays		
		Both	Road	Dots
Training	Both	42.3	24.1	70.2
Phase	Road	—	35.5	—
Display	Dots	—	—	114.9

trained subjects because they were transitioned to a new task as well as to new displays. The latter argument might also account for the superior performance of the transitioned-to-dots group over the trained-with-dots group in Table IX.

General Discussion

Obtaining basic facts about visual perception and control in high-speed, low-altitude flight is a good first step. But it is important also to seek to explain those facts. In addition to being physically fast and dangerous, the low-altitude environment is perceptually unique and demanding. Thus, there is no guarantee that laboratory-derived, perceptual theories and putative mechanisms will apply wholesale. We need a theory of cue availability and cue use specific to the low-altitude environment.

The cues for the perception of speed and altitude may be placed in two large classes: flow field and non-flow field cues. A review of the empirical research into the usefulness of these cues and their implications for visual simulation is found in Owen and Warren (14).

Optical flow field cues: The optical flow field is the concomitant of self-motion through the environment. Its characteristics depend only on the velocity vector of the observer, the distance to the ground, and the general topographical shape of the environment. In particular, it is independent of the patterning (dots, roads, fields, trees, and their spacing) of the surfaces of the environment. The flow field ceases to exist when the observer stops moving. Its importance for aviation was identified by Gibson (5), and its analysis remains a lively area of research (15).

A key optical concomitant of speed over a level terrain is the speed to altitude ratio (v/h) which is simply speed rescaled in terms of unit "eyeheight." It indexes the global optical speed of the apparent "flow" or streaming of the environment when one moves. As a baseline, a brisk walk (5.5 $ft \cdot s^{-1}$ at 5.5 ft altitude) is optically indexed as one "eyeheight per second." A car speeding on an expressway travels optically at about 23 eyeheights per second. Interestingly, a jet at Mach 1 at 50 ft altitude also optically travels about 23 eyeheights per second. This combination of speed and altitude is absurd, but the lesson is that aircraft do not produce optical streaming that is faster than speeding cars. What makes flying a plane optically difficult is the optical change due to changes of altitude.

Optical change due to change in altitude varies as the ratio of sink rate to altitude. This inverse relationship with altitude is nonlinear and accounts for the optically explosive or even optically violent effects at very low altitudes. For example, the perspective width of a 50 ft wide road is 14.25° at 200 ft altitude and 53.13° at 50 ft altitude. A sink rate of 600 $ft \cdot min^{-1}$ means a loss of 10 ft in 1 s. This results in a 0.74° change in 1 s at the higher altitude and a 10.88° change in 1 s at the lower altitude. These dramatic changes were exploited in the research reported here. Another approach to the study of perceptual factors in altitude control is to null the explosive quality of the change (but not the change itself) by reducing the sink rate as altitude is reduced (7).

Nonoptical flow field cues: The cues the optical flow field ignores are covered by the static field, its characteristics, and its dynamical interactions with the flow field. Here the patternings and spacings of the features of the environment take on primary importance. For example, the influence of visual pattern on perceived speed was studied by Denton (1). By placing progressively more closely spaced stripes on highways, he was able to achieve a 22.6% drop in driver speed which resulted in a two-thirds reduction in traffic accidents.

Progressive changes in the spacing of texture elements does occur naturally, for example, around water sources. A pilot flying in the direction of sparser and sparser vegetation might, in a manner inverse to Denton's drivers, get an impression of reduced optical speed. In an aircraft, a perceived drop in optical speed generally indicated an increase in altitude. Hence, a pilot might be misled into thinking he is climbing and erroneously give a sink command. Such "visually risky environments" can be identified and pilots forewarned.

General Conclusions

The most general conclusion is that we do not currently have a complete set of facts or a theory for understanding visual perception in high-speed, low-altitude flight. The studies reported in this paper do offer some interesting leads and suggest further studies. Some general findings include the following:

1. Simulator schematic displays can be useful in developing basic perceptual and control skills for low-altitude flight.
2. Rich cue, high-fidelity scenes may not be best for specific training on specific tasks. The presence of irrelevant cues can interfere with performance.
3. Different cues for the same referent are not all equally effective. The cue dominance hierarchy must be determined empirically.
4. Although the zero-altitude training was not beneficial in our experiments, it is worth investigating the potential value of non-imitative scenes and nonstandard tasks in simulator usage.

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