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Explicit and Implicit Horizons for Simulated Landing Approaches

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In a flight simulator experienced pilots flew landing approaches to a representation of an airport scene in which various sources of information had been distorted or removed. Reasonably accurate approaches could be made to a scene that contained only an aimpoint and a horizon. The addition of a runway outline did not enhance accuracy or stability, which lent credence to the hypothesis that the invariant angle between horizon and aimpoint can support glide slope control. Explicit distortion of this angle by simulation of up-sloping or down-sloping terrain beyond the runway had predictable effects on glide slope control. Implicit specification of a veridical horizon with texture lines parallel to the runway centerline weakened the effect of distortions in the explicit horizon. Thus both explicit and implicit specifications of the horizon contribute to perception of the glide slope angle. Implications of these results for the design of visual scenes for flight simulation are discussed.

INTRODUCTION

One critical issue in the design of modern flight-training simulators relates to representation of out-of-cockpit visual information. Essentially what elements or relationships must be presented in the visual scene to support the acquisition of flight control skills? The dominant design strategy is to provide the highest level of detail at the highest fidelity that can be achieved within appropriate cost constraints. However, an alternative strategy—presenting only the information that provides crucial support for acquisition of the target flight skills—promises more effective training at lower cost (Lintern, Sheppard, Parker, Yates, and Nolan, 1989).

As a step toward establishing how training scenes could be designed more economically, it would be useful to itemize the sources of visual information that support flight control. Few empirical data bear on this issue, however, and it is not even known whether the emphasis should be on explicit features or on abstract relationships. For example, is it important to represent the specific features of a landscape, such as trees, rocks, roads, and fences, or is it better to represent abstract relationships such as compression and perspective gradients, perhaps with generic features such as circles or grids?

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Information for Glide Slope Control

The aircraft landing task was selected as the focus for this research because it appears to be one of the more visually dependent flight control tasks (Lintern, Roscoe, and Sivier, 1990). The specific issue for this research is how pilots ascertain whether or not they are on the desired glide slope. The underlying assumption is that an approach to landing is a visually coupled task, in which case the visual scene must contain properties that can be used to support glide slope control. In Gibson's (1979) terms, those informational properties will remain invariant within the limits of human perceptual thresholds for correct control but will vary for incorrect control.

One possibility, advanced by Langewiesche (1944), is that glide slope control is maintained by reference to the distance between the runway aimpoint and the true horizon projected to a plane perpendicular to the pilot's line of sight. In basic perceptual research, this plane (referred to as *Alberti's window;* see Cutting, 1986) is imaginary, but for real or simulated landings it may be the windscreen of the aircraft or the computer display screen.

The projected horizon-aimpoint distance, also known as the *H-distance* (Berry, 1970), remains invariant for a constant angle of approach but varies for changes in angle of approach (Figure 1). This is the fundamental requirement of a perceptual invariant that might be used for the control of behavior (Gibson, 1979). If the H-distance is found to influence a pilot's accuracy of control on a landing approach, this would suggest that it

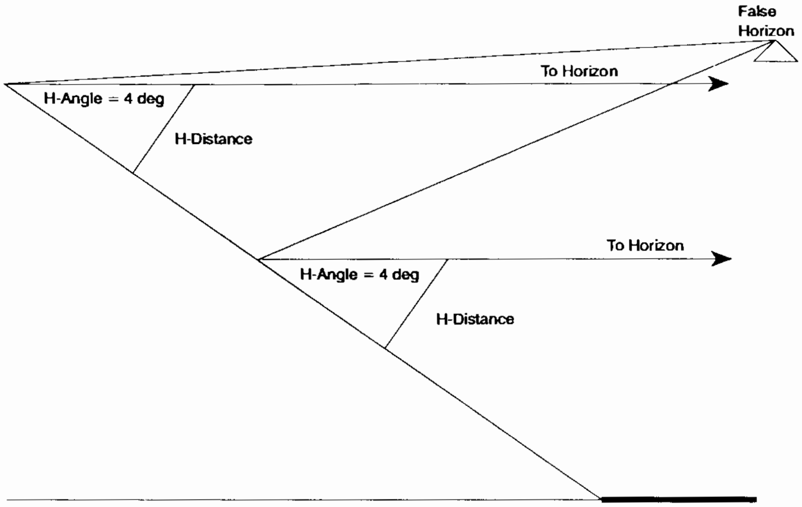

Figure 1. *The horizon-aimpoint distance, which is projected onto a plane perpendicular to the pilot's line of sight and is a constant distance in front of the pilot, remains constant for a constant angle of approach because the horizon is always at eye height (Gibson, 1979). The two triangles that contain H as one side are congruent. Note that the H-angle is also invariant; it is debatable whether the pilot would perceive the H-angle or the H-distance. Also shown is a nonveridical horizon such as might be found with rising terrain behind the runway. The angle between horizon and aimpoint is no longer invariant for a constant angle of approach, and a pilot who sought to keep the apparent H-angle constant would make a low approach.*

should be represented accurately in a simulated visual scene and that representation of other features and relationships may be unnecessary.

It is also apparent that the depression angle from horizon to aimpoint remains constant for a constant angle of approach. The H-distance is, in fact, the projection of the H-angle (the angle between the line of sight to the aimpoint and the line of sight to the horizon) onto a picture plane at some specific distance from the eye. Whether angles or distances projected onto an imaginary (or actual) plane are perceived is problematic. It is, however, more consistent with recent perceptual research (Mark, 1987; Warren and Whang, 1987) to recast the notion of an invariant H-distance into one of an invariant H-angle.

Formal analysis is only the first requirement for establishing the adequacy of an invariant; its functional significance must also be verified (Cutting, 1986; Warren and Owen, 1982). It is possible that changes in the invariant that correspond to changes in performance are so small in relation to the relevant perceptual threshold that they could not be responsible for the accuracy of control normally demonstrated (Cutting, 1986). Furthermore, it is possible that some perceptual invariants satisfy formal and threshold requirements but are not used. In such cases an invariant would be potentially usable but not functional. The functionality of a perceptual invariant is an empirical issue.

Despite considerable speculation (Berry, 1970; Hasbrook, 1975; Langewiesche, 1944), only Kraft (1978) has tested the functionality of the H-angle. He changed the location of the horizon by simulating a rising terrain behind the runway. An important distinction to be made here is between the true horizon, which is always at eye height except at high altitude (Gibson, 1979; Sedgwick, 1983), and the visible horizon, which may be above eye height because of rising terrain beyond the runway. The visible horizon can also be lower than eye level where the terrain falls beyond the runway. A high visible horizon will increase the explicit H-angle, and a low visible horizon will decrease it. A pilot who relies on the explicit H-angle will compensate for a high horizon by flying a lower approach (as is consistent with Kraft's results) and will compensate for a low horizon by flying a higher approach.

There are, however, reasons to question the H-angle hypothesis. Pilots do land successfully in a wide range of conditions, and accidents are relatively rare even where the visible horizon is high or low. It is possible to land with no visible horizon, and occasionally little more than a runway outline may be available, though the accuracy and stability of approaches made in these impoverished conditions have not been established. Accident rates remain the main source of data about the adequacy of landings, but some bias and instability do not inevitably (and, in fact, will not often) precipitate an accident.

Even if landing performance is not degraded by a horizon that is either displaced from the true horizon or invisible, the H-angle hypothesis might be salvaged by assuming an implicit horizon (Gibson, 1979; Sedgwick, 1983; Warren and Whang, 1987). In most natural or cultural environments, perspective and compression gradients provide sufficient information to specify formally the location of the true horizon. If that information can provide a functional specification of horizon location, it could be said that the horizon is specified implicitly by compression or perspective gradients, and the H-angle might be judged in relation to that implicit horizon. Only when that information is absent, as in Kraft's simulation or in night approaches over water, would there be no effective specification of an implicit horizon. However, there has been no empirical investigation of the functionality of terrain gradients in specifying an implicit horizon.

Overview

The effects of removing or distorting information that specified either an implicit or explicit horizon were contrasted in three experiments. The first two laid essential groundwork for the third by verifying that special procedures used in the experiment did not distort the nature of the task to an unacceptable degree and by establishing the interpretability of the performance measures. In addition, the first two experiments tested the basic assumptions that the simulated landing task is visually supported, that performance is not limited by the resolution of the action system or nonvisual perceptual systems, and that accuracy of glide slope control is not completely determined by optic outflow or by size or shape scaling of the runway.

EXPERIMENT 1

During planning and pretesting for this experiment, two concerns emerged relative to establishing a viable experimental method for assessing effects of changes in visual information. The first was that pilots would, as they neared the runway, almost certainly become aware of the glide slope control biases induced by changes in visual information because it would become evident that they were undershooting or overshooting the approach aimpoint. As a result, they might adjust their control strategies in later trials in a manner that is atypical of control strategies used in real flight. To prevent this, approaches in Experiments 2 and 3 were stopped several hundred meters short of the runway aimpoint.

It was anticipated, however, that this procedure might create other control problems. For example, a pilot may continually calibrate glide slope control with reference to the success of the final phase of the landing, and a large number of approaches terminated short of touchdown might cause this perceptual calibration to drift so that the approach angle would vary considerably across trials. Approaches in Experiment 1 were flown through touchdown and rollout to serve as a standard against which performances in the shortened trials of Experiments 2 and 3 could be compared to verify that the procedure of terminating trials short of the aimpoint would not introduce unacceptable distortions into the data.

The second concern was that, as demonstrated during informal testing, experienced simulator pilots (in this case, members of our research team) could fly almost perfect approaches without any assistance from the visual display or the flight instruments if given sufficient opportunity to set power and elevator trim and to calibrate the control pressures needed for the approach. To the extent that our pilot subjects would employ a nonvisual strategy, the viability of our procedures for assessing effects of visual manipulations would be weakened. The use of variable headwinds could, however, disrupt any nonvisual control strategy. The second purpose of Experiment 1 was to assess the effects of variable headwinds on glide slope tracking performance.

Method

Subjects. Eight male pilots, 18 to 30 years old, with 6/6 vision (corrected if necessary) and at least 100 hours of flight experience were paid $10.00 per hour to participate in the experiment.

Apparatus. The ILLIMAC flight trainer is a fixed-base, digital, light-aircraft simulator.

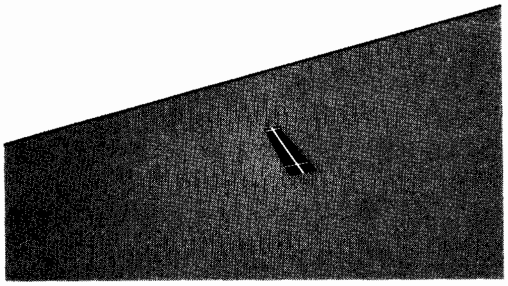

Figure 2. *Black-and-white representation of the pictorial landing display.*

The heading and attitude indicators were disabled for this experiment. A Silicon Graphics IRIS 2400 visual system provided a computer-animated, real-time, interactive pictorial landing display at an update rate of 12 Hz (Figure 2).

Runway size was 1500 m (4921 ft) × 27.85 m (91.2 ft). The simulated runway had the same proportions of length and breadth as Runway 32 at the University of Illinois Airport, a runway frequently used by all of our pilot subjects. Although the simulated runway is smaller than Runway 32, the work of Mertens and Lewis (1982) indicates that proportional equivalence is more important than size equivalence in eliminating glide slope biases attributable to an unfamiliar runway (see also Lintern and Walker, 1991). The smaller size was selected for consistency with another experiment (not reported here) in which runway proportions were varied. A runway length of 1500 m is more than adequate for landing a light aircraft.

Runway markings were as shown in Figure 2. There were no ground features. With a simulated pitch attitude of 0 deg, the horizon appeared halfway up the screen and at the point of convergence of the extended runway edges to give a veridical H-angle, assuming a locally flat earth. The screen, which was approximately 85 cm from the cockpit reference eyepoint, subtended angles of 19.5 deg vertically and 26.3 deg horizontally.

Task. In the criterion landing task, pilots were to make simulated approaches on a 4-deg glide slope starting 3078 m (10 000 ft) from the runway threshold, at 194 m (635 ft) altitude (i.e., 0.5 deg below the desired glide slope) and lined up with the runway centerline in straight and level flight. Pilots were instructed to fly straight and level until they intercepted the 4-deg glide slope, where they were to start their descent. They were advised that a power setting of 12.5 in. Hg was optimal for a 4-deg descent with no wind. During the descent they were to maintain an airspeed of 70 knots. They were permitted to adjust power and elevator trim but were required to return the power to 12.5 in. Hg at the start of every trial.

Trials were started with no image on the IRIS computer screen. The pictorial landing display appeared when the pilot pressed a push button to start the trial. Trials required approximately 90 s each and were flown through the roundout, flare , touchdown, and rollout. They were stopped automatically 644 m beyond the runway aimpoint.

Procedure. Each pilot flew 40 trials in five eight-trial blocks. The first eight trials were familiarization trials in which adaptively augmented guidance was used to assist pilots in their calibration of the 4-deg glide slope. The augmented guidance presents a visual corridor along the 4-deg glide slope (Figure 3). An adaptive algorithm was used to switch the guidance symbology on only when the pilot deviated from the desired flight path by 1.0 deg laterally and/or ±0.5 deg vertically, and to switch it off again when flight path errors were reduced to within ±0.5 deg laterally and ±0.2 deg vertically. Lintern et al. (1990) have demonstrated that this augmented guidance can help flight students cal-

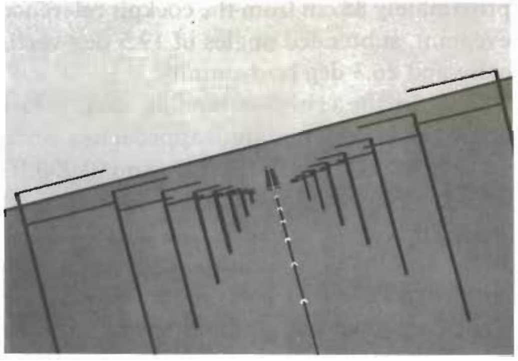

Figure 3. *Black-and-white representation of the pictorial landing display including augmented guidance F-poles.*

ibrate the approach glide slope, and it was used here under the assumption that it could also stabilize the performance of experienced pilots.

During the final four eight-trial blocks, headwinds of 0, 5, 10, or 15 knots, constant within trials but randomized between trials, were used either in Blocks 2 and 4 or 3 and 5, counterbalanced across pilots. In the absence of compensatory corrections, the mean value of headwind (7.5 knots) would increase the angle of descent (by effectively reducing forward speed relative to the ground) and would reduce the angle to aimpoint from 4 deg to 2.8 deg by the time a pilot reached 700 m from aimpoint. No headwinds were used in a given pilot's other two eight-trial blocks. Pilots were advised whether headwinds would be present in an eight-trial block but were not advised of the specific headwind value for any trial.

Data analysis. Altitudes recorded at 17 points every 152.4 m between 2525.6 m and 87.2 m from the runway aimpoint were converted to angles to aimpoint with relation to the ground plane. For consistency with later experiments in which trials were not flown to touchdown, data from the last four points were not included in the statistical analyses. Data from the first seven points were also excluded from the analyses because earlier experimentation (Lintern and Koonce, 1991; Lintern and Walker, 1991) had shown that the biasing effects of manipulated factors did not become apparent until later in the approach. The angles derived for the six distances from threshold in the range 1458.8 m through 696.8 m were analyzed with an analysis of variance (ANOVA) in which wind (present vs. absent) was treated as a repeated-measures factor.

Given that some of the experimental manipulations were predicted to affect stability rather than bias, a measure of stability was desirable. It is normal, in the analysis of tracking behavior, to assess within-trial stability. However, the landing task has considerable inertia, and within-trial variation is small. Lintern and Walker (1991) have shown that a measure of between-trials stability offers useful information for this task. Thus between-trials standard deviations were also analyzed with a repeated-measures ANOVA.

Results

Approaches flown with headwinds were, on the average, significantly lower than those flown without headwinds, $F(1,7) = 58.5, p < 0.001$ (Figure 4), which indicates that pilots

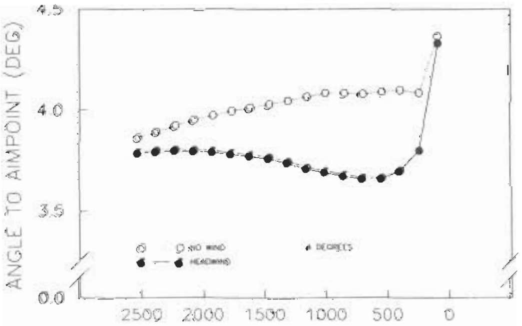

Figure 4. *Approach performances with and without headwind for Experiment 1.*

did not compensate fully for the headwinds. However, the mean angle to aimpoint did not approach the 2.8 deg at 700 m to be expected under the assumption that pilots made no compensatory corrections. In addition, the trial-to-trial stability of approach paths, as assessed by between-trials standard deviations, was not affected significantly by headwinds, $F(1,7) = 3.26, p > 0.10$.

Discussion

A fundamental assumption for this series of experiments is that of a coupling between visual information and control action in the simulated landing task. In the absence of such a coupling, flight path bias would have been more variable with varying headwinds than without headwinds. In addition, mean error was much lower at 700 m than the mean angle to aimpoint of 1.2 deg below the reference angle that would have been expected for an average headwind velocity of 7.5 knots. The data demonstrate the visually coupled nature of the task. However, the fact that pilots did not compensate entirely for the headwinds suggests either that the visual coupling was not as tight as it might have been or that the resolution of the action system (i.e., the overall dynamics of the pilot/simulated aircraft system) was exceeded by the headwind demands.

EXPERIMENT 2

Experiment 2 was designed (1) to ascertain whether the failure observed in Experiment 1 to fully compensate for headwinds was attributable to loose coupling between perception and action or to the limited resolution of the action system and (2) to assess the viability of the H-angle hypothesis in relation to several other possibilities. Four display conditions were tested: the first was the normal runway display used in Experiment 1, the second was the augmented runway display used for calibration trials in Experiment 1, and the third was a display that contained only a landing aimpoint and a horizon; in the fourth condition, no glide slope information was provided on the IRIS screen.

The use of visual guidance was intended to permit tighter coupling between perception and action in the simulated landing task. More accurate approaches under this condition—and lack of any difference between wind and no-wind conditions—would indicate that the sluggish control observed in Experiment 1 was not caused by limitations in resolution of the action system.

The comparison of performance on the horizon-aimpoint display with performance on the normal landing display and with the condition without glide slope information provided a test of the optic outflow hypothesis and of hypotheses relating to size and shape scaling. Gibson, Olum, and Rosenblatt (1955) have argued that a pilot guides an aircraft toward the landing aimpoint by controlling the point of optic outflow so that it coincides with the aiming point. When there are only two elements in a scene, there is no possibility of locating a center of optic outflow, and if that information is essential, performance should be as poor as if there were no information at all from an out-of-cockpit visual scene.

Discussions of visual guidance for landing approaches address the effects of runway size (Roscoe, 1980), runway proportions (Mertens and Lewis, 1982), and runway shape (Wulfeck and Queen, 1975). Although empirical work has shown that runway dimensions can affect glide slope control (Lintern and Walker, 1991; Mertens and Lewis, 1982), the evidence indicates that they may be minor factors. Better performance in a condition with an aimpoint but no runway outline in comparison with one in which all glide slope information was removed would indicate that factors other than optic flow and runway size or shape scaling were operative.

Method

All pilots who participated in Experiment 1 also participated in Experiment 2.

Visual scenes. Approaches were flown to four different visual displays. One was the standard runway-horizon combination used in Experiment 1 (Figure 2). Runway size was the same as in Experiment 1. For a second visual display the runway was replaced with a disk 6.1 m (20 ft) in diameter located at the landing aimpoint (Figure 5). This was judged to be too small to offer size cues or to permit identification of the center as the point of optic outflow, but it was large enough to be visible throughout the approach. In a third display the augmented guidance symbols used in Experiment 1 (Figure 3) were added to the normal runway. This guidance was present throughout the guidance trials (i.e., the adaptive algorithm used for calibration trials was deactivated). The fourth display contained symbolic elements that gave the pilot information about heading and bank but no information about pitch or descent path in relation to any runway representation. In the following text and figures these four displays are referred to, respectively, as *runway*, *aimpoint*, *guidance*, and *no-scene*.

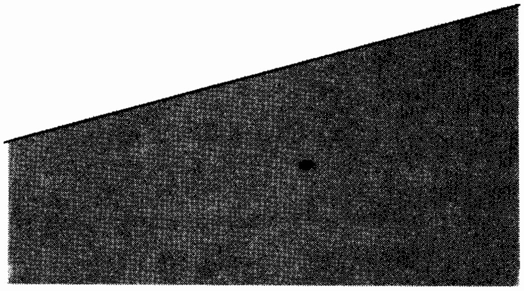

Figure 5. *Black-and-white representation of the aimpoint landing display.*

Procedure. Pilots were required to perform the same task as in Experiment 1 except that the approach was stopped automatically 697 m short of the landing aimpoint. These trials required approximately 60 s each.

Each pilot flew 10 calibration and 32 experimental trials in each of two sessions. For the calibration trials, adaptive augmented guidance was presented as in Experiment 1. Experimental trials in one of the sessions were flown under the headwind conditions described for Experiment 1. No headwind was present in the other session. The session order for headwind/no headwind was counterbalanced across pilots.

Each session started with eight calibration trials in which adaptive augmented guidance was used. Four blocks of eight trials followed in which each of the visual scenes described earlier was presented for one block. Two additional calibration trials were flown immediately prior to the eight-trial block in which the no-scene display was used. Prior to these two additional calibration trials, pilots were advised of the nature of the no-scene display and of the strategy of paying attention to control pressures and descent rate. They were also reminded that this strategy would be relatively ineffective in the presence of unspecified headwinds. The order of displays was reversed across sessions within subjects and counterbalanced across subjects.

Data analysis. Data were collected as described for Experiment 1. The data used for analyses and for figures were means of angles to aimpoint taken at the six distances from threshold in the range 1458.8 m through 696.8 m. These performance measures were analyzed with 2 (wind present or absent) × 4 (displays) × 8 (subjects) ANOVAs (Gentile, Roden, and Klein, 1972). Where significant interactions were found in the main analyses between pilots and another main factor, single-subject analyses were undertaken with 2 (wind) × 4 (displays) ANOVAs.

Results

Mean angle to aimpoint was not affected significantly by headwind or scene (Figure 6a), and there were no significant interactions of these factors with pilots. Trial-to-trial stability (Figure 6b) was affected by both winds, $F(1,21) = 40.9$, $p < 0.001$, and scenes, $F(3,21) = 16.6$, $p < 0.001$. The interaction of winds with scenes was also significant, $F(3,21) = 4.76$, $p = 0.011$. Inspection of Figure 6b indicates relatively stable performance for trials with guidance, whether with or without headwind, and for the runway and aimpoint displays in the absence of headwind. Performances were less stable with the runway and the aimpoint displays in the presence of headwind and for the no-scene display with or without headwind.

A significant interaction of pilots with headwind, $F(7,21) = 4.14$, $p = 0.005$, and a near-significant interaction of pilots with scenes, $F(21,21) = 1.84$, $p = 0.086$, in trial-to-trial variability prompted closer examination of individual patterns of behavior. A consistent pattern of low variability with the guidance display, high variability with the no-scene display, and moderate variability with the runway and aimpoint displays emerged for six pilots in headwind conditions. Two pilots had much less variability with the no-scene display, but this was accompanied by very low approaches. In the presence of headwinds these two pilots flew the no-scene display by quickly descending to a low altitude and then maintaining a relatively constant altitude (presumably by reference to the altimeter) throughout the remainder of the trial.

Supplementary analyses of mean angle-to-aimpoint and trial-to-trial variability, in which data from the runway display in both Experiments 1 and 2 were compared, failed to reveal any significant main effect for experiment (mean approach angle), $F(1,7) = 0.61$, $p > 0.10$; trial-to-trial variability, $F(1,7) = 2.47$, $p > 0.10$. There was, however, a significant Experiment × Wind interaction for mean angle to aimpoint, $F(1,7) = 13.04$, $p = 0.009$. Comparison of Figures 4 and 6 suggests that this resulted because of adjustments toward the optimal approach angle in Experiment 2. Rather than evidence of instability, the trend is toward better calibration of the descent path. This most likely indicates that

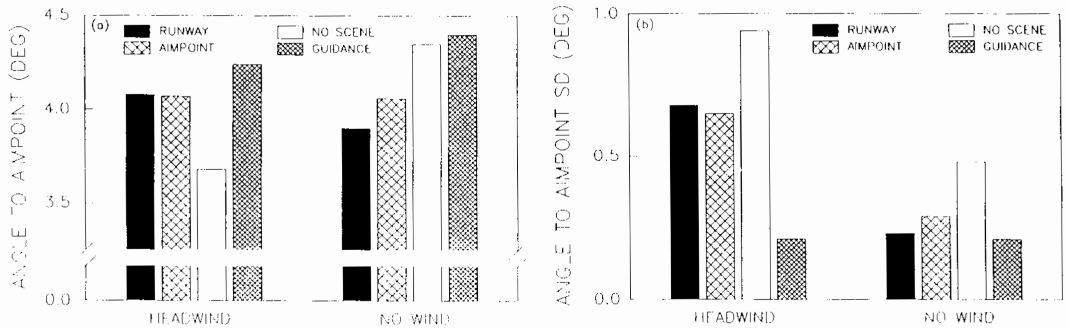

Figure 6. *Approach performances across headwind and display conditions for Experiment 2: (a) angle-to-aimpoint means; (b) between-trials angle-to-aimpoint standard deviations.*

our pilot subjects had learned to cope more effectively with the headwind conditions. There is no evidence here that the procedure of terminating approaches prior to touchdown introduced unacceptable distortions into the data.

Discussion

Performance deteriorates in the presence of headwinds even when normal runway information is available. That this deterioration is not attributable to a limited capability of the action system is indicated by performance with augmented guidance in which there was no loss in stability with the addition of headwind. We conclude that although the approach to a normal runway is a visually coupled task, the coupling is relatively loose, so changes in visual information will lead to gradual rather than immediate and complete compensatory adjustments. This conclusion is also consistent with observations on actual flight trials (Lintern and Koonce, 1991).

The fact that performance with a small aiming point is as good as with a normal runway suggests that runway size and shape are not essential sources of information for glide slope control. Hypotheses relating to optic outflow and runway size or shape also are not supported by these data, though optic outflow and runway size or shape cannot be dismissed as possible alternative or supplementary sources of information. The data of Lintern and Walker (1991) and Lintern and Koonce (1991) indicate that something about a more detailed scene can enhance glide slope control, and the data from our augmented guidance condition in this experiment reveal that more stable control is possible. Nevertheless, the data from Experiment 2 suggest that the H-angle hypothesis merits serious consideration.

EXPERIMENT 3

Because a horizon may be explicit (visible) or implicit (specified by terrain gradients), the H-angle may also be explicit or implicit. The location of the explicit horizon can be changed by either raising or lowering it in relation to the veridical location. This would simulate the real-world conditions in which runways have rising or falling terrain behind them. Pilots who control glide slope by seeking to converge on a previously calibrated value of the explicit H-angle will make a low approach to a high horizon and a high approach to a low horizon (Figure 1).

One hypothesis not examined in Experiment 2 is that pilots control the angle of depression to the aimpoint from a reference that is perceived independently of the horizon. In the simulator, relationships to boundaries of the visual display screen or the depression angle to the runway aimpoint perceived in relation to the physical structure of the simulator cockpit may provide a functional reference. One method of changing the horizon location in the simulator is to bias the scene within the display in a manner that would be analogous to flying an approach with a higher or lower aircraft pitch attitude. If angle to a pitch-related reference is controlled during the approach, implementation of a low horizon by a screen bias should make the runway appear lower, causing the pilot to compensate by flying a lower approach. A high horizon implemented by this procedure should induce a high approach. These predictions are the opposites of those for similar distortions of the H-angle.

In a natural airport scene the location of the implicit horizon may be specified by the point of convergence of the runway edges extended to the horizon and of terrain features that run parallel to each other (Sedgwick, 1983). Except for some special instances, such as rail lines or straight roads, parallel lines do not usually extend to the horizon. Thus if such lines effectively specify an implicit horizon, they must be able to do so even though the actual point of convergence is not visible. In a simulated visual scene the representation of normally parallel lines (e.g., runway edges) by lines that are not parallel should distort the perception of the implicit horizon, whereas the addition of parallel lines to an otherwise impoverished scene should strengthen veridical perception of horizon location. Implicit specification of a veridical horizon might eliminate (or at least weaken) the effects of distorting the explicit H-angle. Implicit specification of a false horizon may generate biases similar to those induced by an explicit specification of a false horizon.

Method

The same pilots used in Experiments 1 and 2 were also used in Experiment 3. Except as outlined as follows, the task and procedures were identical to those of Experiment 2.

Visual scenes. Four variations of the normal runway scene (Figure 2) were tested.

- *H-angle:* The explicit horizon was raised or lowered 1.2 deg of visual angle by simulating rising or falling terrain beyond the runway. Except for the change in H-angle, there was no information available in the scene to indicate that the simulated terrain was not flat.
- *Pitch angle:* The explicit horizon was moved up or down 1.2 deg of visual angle by biasing the displayed scene in the monitor screen. (Note that adjustment of the H-angle changed only the position of the horizon, whereas adjustment of pitch angle changed the location of all elements in the scene but did not change their locations relative to one another.)
- *Runway convergence/divergence:* The location of the implicit horizon as specified by the runway edges was changed by simulating runways with converging or diverging edges. Runway end lengths were 30.57 m (100.3 ft) and 25.27 m (82.9 ft), which are 1.1 and the reciprocal of 1.1 times the length of the standard runway ends of 27.85 m (91.2 ft) used in Experiments 1 and 2 and also for the calibration trials in this experiment. The converging runway (near end, 30.57 m and far end, 25.27 m) specified an implicit horizon 1.2 deg below veridical, and the diverging runway (near end, 25.27 m and far end, 30.57 m) specified an implicit horizon 1.2 deg above veridical.
- *Perspective gradient:* Texture lines parallel to the runway centerline running from some distance before the runway threshold to some distance past the far end of the runway were added to the normal runway scene (Figure 7). These parallel lines specified a veridical implicit horizon.

Procedure. The four factors were fully crossed in a factorial design: 2 (rising vs. falling terrain: H-angle) × 2 (scene biased up or down: P-angle) × 2 (converging or diverging runway: runway C/D) × 2 (presence or absence of parallel lines: perspective gradient or P-gradient). The data were collected over four sessions of 40 trials (approximately 1 hr) each. There were four eight-trial blocks of experimental trials in each session, with each eight-trial block being preceded by two calibration trials identical to the calibration trials of Experiment 2 (i.e., normal runway, normal horizon, adaptively augmented guidance, no screen bias, and no perspective gradient).

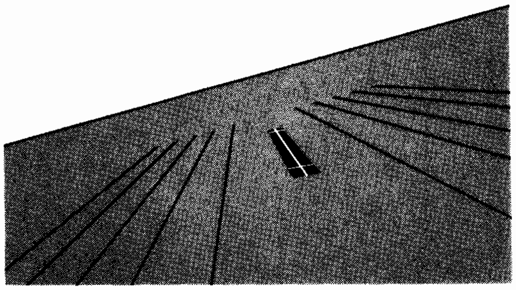

Figure 7. *Black-and-white representation of the pictorial landing display with the addition of perspective gradient lines that implicitly specify a veridical horizon.*

Four pilots flew with the P-gradient in their first two sessions, and the remaining four flew with it in their final two sessions. Runway C/D was manipulated over sessions, counterbalanced across pilots, and within order of P-gradient. Each of the four explicit horizon conditions was tested in each session with order counterbalanced across pilots and sessions.

Data analysis. The data were analyzed with 2 (H-angle) × 2 (P-angle) × 2 (runway C/D) × 2 (P-gradient) × 8 (subjects) ANOVAs. Single-subject analyses were undertaken with 2 × 2 × 2 × 2 ANOVAs.

Results

Both manipulations of the explicit horizon (H-angle and P-angle) produced significant effects for mean angle to aimpoint in the hypothesized directions, $F(1,79) = 51.4$, $p < 0.001$; $F(1,79) = 87.9$, $p < 0.001$ (Figure 8). The main effects of the other two factors were not significant.

There was a significant interaction between P-gradient and H-angle, $F(1,79) = 3.96$, $p = 0.05$. Figure 9 indicates that the effect of changes in H-angle were smaller in the presence of the P-gradient, which is as predicted.

A significant interaction between pilots and P-gradient, $F(1,79) = 3.93$, $p = 0.001$, prompted further single-subject analyses. The results of those analyses showed that five pilots flew higher approaches with P-gradient present (three significantly) and that the other three flew lower (one significantly).

Analysis of trial-to-trial stability revealed that approaches with P-gradient present were more stable, $F(1,79) = 4.83$, $p = 0.031$ (Figure 10a). A significant H-angle effect, $F(1,79) = 4.02$, $p = 0.048$ (Figure 10b), was the result of lower variability with the low horizon.

Discussion

These data show that distortions of the explicit H-angle affect performance in predictable ways and that implicit specification of a veridical horizon can serve to modify this effect. It should be noted, however, that specification of the implicit horizon by manipulation of runway edges did not have a consistent effect between pilots or a significant effect across pilots. A global specification of an implicit horizon, as provided by more numerous parallel lines of greater length, may be necessary. Nevertheless, it appears that the H-angle, whether explicitly or implicitly specified, can affect glide slope control.

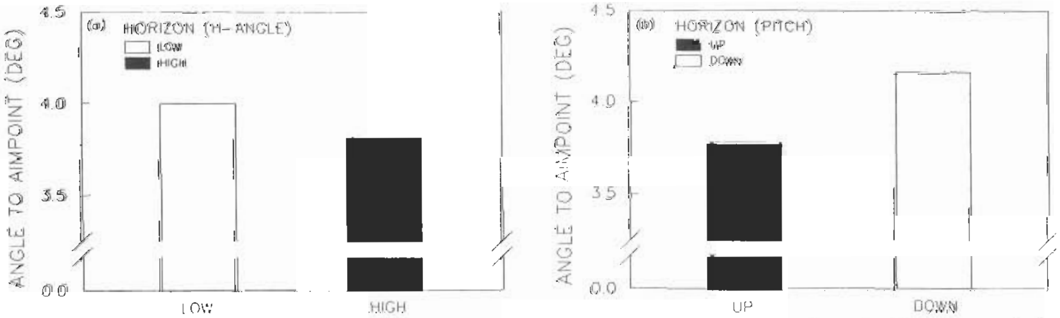

Figure 8. *Angle-to-aimpoint means across changes in the height of the explicit horizon for Experiment 3: (a) H-angle, (b) P-angle.*

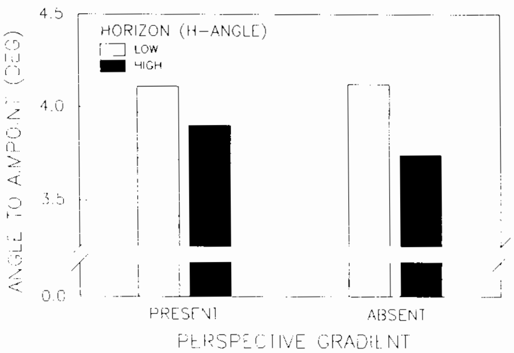

Figure 9. *Interaction of perspective gradient display with H-angle for Experiment 3.*

The P-angle manipulation was included as a control condition because it had seemed possible that a horizon specified by features other than those of the visual display could serve as a reference. Our data indicate that this is the case. Within a simulator there are many possibilities for a functional specification of the horizon, and almost any feature within the simulator cockpit—or even a sense of body orientation—may serve that purpose. This raises the possibility that glide slope control (and presumably other forms of human action) can be guided by direct judgments of critical visual angles (see also Mark, 1987, and Warren and Whang, 1987), a possibility that has not been recognized in aviation and which has been less favored in perceptual theory than other seemingly less parsimonious accounts, such as the size-distance invariance hypothesis. Taken together, these data from manipulations of H-angle, perspective gradient, and pitch angle underscore the importance of the horizon for glide slope control and further show that each method of specifying the horizon contributes to its perceived location.

The addition of perspective lines was shown to stabilize performance. Approaches tended to be less variable in the presence of perspective lines, an effect that we suspect is related to that found by Lintern and Walker (1991) and Lintern and Koonce (1991), in which the addition of nonspecific texture and detail to the runway surround also stabilized approaches. There is, however, no explicit rationale for this effect. A possibility we plan to test is that the addition of detail strengthens perception of the implicit horizon and stabilizes judgments of the H-angle. Whether or not better stability with the smaller H-angle is a manifestation of the same effect is also something we plan to test.

The addition of the perspective gradient appeared to bias control behavior, but the effects were not consistent across subjects. It

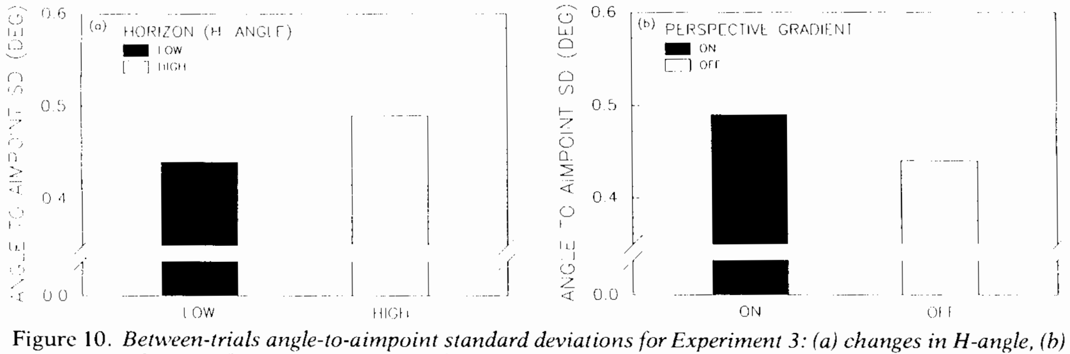

Figure 10. *Between-trials angle-to-aimpoint standard deviations for Experiment 3: (a) changes in H-angle, (b) presence or absence of perspective gradient display.*

remains a puzzle how a bias might be induced by the addition of lines to the scene, but this trend was also found by Lintern and Walker (1991) when nonspecific ground clutter and detail were added to the runway surround. One possibility is that the addition of detail affects visual accommodation, as Roscoe (1980) has proposed. Because the predicted direction of bias would differ according to whether an individual's dark focus was in front of or behind the display screen, this might account for the Pilot × P-gradient interaction. A precise test of this proposal requires on-line measurement of visual accommodation. We plan to acquire a capability for that measurement prior to further investigation of this effect.

GENERAL DISCUSSION

In this series of experiments we sought to identify sources of visual information that are used for glide slope control of an approach to landing. The hypothesis of Langewiesche (1944) that glide slope is controlled by reference to an invariant distance between aimpoint and horizon, projected onto a plane in front of the pilot, is supported by our data. We have recast the H-distance hypothesis into terms of visual angle for consistency with other recent work on human perceptual judgments (Mark, 1987; Warren and Whang, 1987). The H-angle is a property of the optic array that conforms to Gibson's (1979) notion of an invariant. It remains constant under transformation of the optic array if the pilot maintains a constant angle of approach to the runway aimpoint, and it changes if that angle of approach changes. Formally, it satisfies the requirements that permit it to serve as a basis for glide slope control, and our data show that it is functional in that respect.

In an extension of Langewiesche's hypothesis, we have shown that the horizon need not be visible or explicit and that an implicit horizon specified by a perspective gradient can influence glide slope control. Others have speculated on the role of an implicit horizon (Gibson, 1979; Mark, 1987; Sedgwick, 1983; Warren and Whang, 1987), but this is the first demonstration that it has predictable effects on behavior. Although not tested here, other specifications of an implicit horizon, such as a compression gradient, might also be effective. In particular it should be noted that regular features such as those provided by our parallel lines are not required for the specifications of perspective and compression gradients. Distributions of irregular features can also specify those gradients, the only essential constraints being that those distributions are stochastically regular and of adequate density (Sedgwick, 1983).

Static versus Kinematic Information

Notions of information derived from systematic transformations in optic flow have pervaded discussions of the control of locomotion (Gibson, 1966, 1979). Following Pattee (1982), such information is viewed here as kinematic or rate dependent because its availability and strength depend on rates of observer motion. In the context of landing, the analysis of Gibson et al. (1955) identified the center of optic outflow as an invariant that might be used to guide the direction of locomotion. Nevertheless, our research has provided evidence for the sufficiency of nonkinematic (rate-independent) or static information, which raises the question, Is there a role for kinematic invariants, such as those derived from optic flow, in the guidance of human locomotion?

Our displays generally provided rather impoverished flow information, but glide slope control was nevertheless good under conditions that were intended to represent normalcy. Although the addition of optic flow information might be expected to enhance at least stability, if not bias, performance in approach to a display that contained only an aiming point and a horizon was quite good, and the addition of a runway outline that could have provided information about relative rates of flow before and beyond the aimpoint did not help. Nevertheless, we are reluctant to dismiss kinematic information that is potentially available from optic flow as being of no functional significance. Lintern and Koonce (1991) and Lintern and Walker (1991) have shown that the addition of more complex detail around the runway does enhance the stability of approach performance, as did the addition of parallel lines in this experiment. One plausible account of this effect is that the information from invariant relations in the optic flow was strengthened to such an extent that it was usable for glide slope control.

In addition, there is some evidence that sensitivity to static information emerges from experience with kinematic information. Using a planetarium in which apparent celestial rotations can be distorted, Emlen (1975) has demonstrated that adult migratory birds normally orient toward static patterns of star clusters. However, the development of this ability requires exposure to normal celestial rotations, during which the positions of specific star clusters are calibrated with reference to the celestial rotational axis. Emlen suggested that kinematic information becomes a secondary or redundant source of information but that its availability is critical to normal development.

Lintern and Kugler (in press) proposed a similar view in relation to the development of perceptual learning in neural networks by arguing that symbolic, rate-independent structures evolve lawfully from the exercise of dynamic, rate-dependent processes. By this account, appropriate calibration of a static source of information can occur only in the presence of kinematic or flow-rate information. This implies that those who are inexperienced with any particular locomotory skill need good representations of optic flow to learn it, whereas experienced individuals do not—a hypothesis that remains essentially untested in the field of human perception and action.

Design and Use of Flight-Training Simulators

The data reported here suggest that in a simulator for teaching aircraft landings, accurate representation of the horizon-aimpoint angle is essential and, more generally, that emphasis in scene design should be on abstract relationships rather than on high-fidelity representation of specific objects or details. One interpretation of our data, based on the observation that specification of an implicit horizon did not entirely eliminate the effects of a distortion in the explicit horizon, is that emphasis should be placed on explicit representations. However, control on the basis of an implicit horizon seems to be the more robust skill, and one potential contribution of simulation is to emphasize the instruction of skills that may be more robust but more difficult to acquire. Development of sensitivity to an implicit H-angle might require extensive experience with a veridical implicit horizon and a nonveridical explicit horizon. In many areas, such as the Great Plains of the United States, natural environments with a nonveridical visible horizon are almost nonexistent.

Despite the apparent adequacy of static information for the control of action, it would be premature to assume that kinematic information need not be represented in a flight-training simulator. It remains possible that sensitivity to static invariants develops only through experience with kinematic invariants. The implications of this possibility for simulation design are, however, by no means clear. On the one hand, we might find that young adults who present themselves for flight instruction have already established sensitivity to appropriate static invariants, in which case simulation of kinematic invariants would not be essential. On the other hand, invariants derived from kinematic properties of the optic array provide the more general solutions for the perceptual support of control actions. Reliance on static invariants may represent an expedient solution that is not readily generalized to other activities. Our pitch-angle effect may be indicative of such an expedient solution—one that might create difficulties in transition to a new aircraft type or in the practice of engine-out approaches for a multiengine aircraft in which approach speeds are higher and pitch attitudes lower. It is for this type of instruction that adequate simulation of kinematic properties may be essential. Clearly this is an area that requires close examination.

A further implication of our discussion is that simulation instruction might be more efficient if the critical functional invariants could be made more salient. The basic research in perceptual learning has shown that enhancement or contrast of critical features enhances sensitivity to those features (Gibson, 1969). Much of the challenge associated with the acquisition of flight control skills relates to problems in perceptual learning (Lintern, 1991), which is viewed here as enhancement of sensitivity to functional invariants and calibration of those invariants to the capabilities of the controlled system, so emphasis of these two aspects in the design and use of simulators is likely to enhance training efficiency.

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