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SYMBOLS

General symbols:

L   significance level (specified value)

p   significance level (probability)

α glidepath angle

γ flightpath angle

Δ unit stimulus deviation

Symbols and subscripts that describe the linear statistical model used for data analysis:

A   main effect of first factor (range)

B   main effect of second factor (glidepath)

C   main effect of third factor (aim point)

e   model error

Y   response

$\hat{Y}$ predicted response

μ overall mean

( )   parentheses indicate interactions between enclosed factors

Subscripts:

i   stimulus level index of first factor (range)

j   stimulus level index of second factor (glidepath)

k   stimulus level index of third factor (aim point)

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PILOT ESTIMATES OF GLIDEPATH AND AIM POINT DURING SIMULATED LANDING APPROACHES

C. W. Acree, Jr.

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SUMMARY

The aircraft landing approach is the most difficult and dangerous phase of flying. Better knowledge of the perceptual response of pilots to deviations from a nominal landing approach would be of help in developing better simulation and training techniques. Because deviations in the vertical plane present, in theory, the greatest perceptual difficulties, experiments were performed to measure pilot perceptions of glidepath angle and aim point during simulated landing approaches. Safety, cost, and convenience favored the use of a fixed-base cockpit simulator, with landings prerecorded on video tape from a runway model board and projected with a video projector. Subjective estimates of the magnitudes of the approach deviations were obtained, and analysis of variance techniques were used to construct statistical models of the pilots' responses. Pilots could estimate glidepath angular errors quite well but had difficulties estimating aim point errors. Two possibilities seemed most likely in explaining the inaccuracies of aim point estimates: fundamentally poor perception of aim point, and pilot preference for realigning with the originally desired glidepath to correct for aim-point errors. The data make plausible the hypothesis that pilots are little concerned with aim point during most of an approach, concentrating instead on remaining close to the nominal glidepath and trusting this technique to guide them to the proper runway touchdown point.

INTRODUCTION

The goal of these experiments was to obtain the perceptual responses of pilots to deviations from a nominal landing approach. In practice, deviations in the vertical plane are the most important, and in theory the most difficult to determine (Naish, 1971). The experiments tested perception of altitude displacement deviations from a nominal glide slope, and aim point deviations from a nominal touchdown point. All experiments were run on a simulator. The method of magnitude estimation, coupled with analysis of variance techniques, allowed maximum efficiency in data collection and analysis.

Running the experiments on a simulator instead of using a real aircraft allowed major reductions in time and cost, and provided important improvements in safety and in precision of the visual stimuli. Because it was desired to eliminate all seat-of-the-pants and time-integrated motion cues (to force the subjects to concentrate on their instantaneous visual perceptions), only brief segments of landing approaches were actually shown to the subjects, and there were no motion cues. The subjects did not attempt to control the aircraft or correct approach errors. Although this took the subjects "out of the loop," it was completely acceptable for these experiments; moreover, it reducted the time required of the study subjects.

The subjects sat in a fixed-base cockpit simulator and looked out of the pilot's window at a rear projection screen which covered the entire field of view. A video projection system projected recorded black-and-white television scenes onto the screen, simulating the view out of the cockpit during a landing approach of a light aircraft. The television scenes were recorded on video tape with a moving camera and model terrain board visual scene generating system. Preliminary experiments established the feasibility of the method before data were collected.

The subjects made verbal estimates of the directions and magnitudes of the deviation stimuli in terms of a subjective numerical scale of -10 to +10. The full range of the estimation scale was established by showing the subjects a set of stimuli with deviations more extreme than in the main experiment. There was a problem in keeping the experiment consistent because different subjects required different lengths of time to make their estimates. This problem would have been aggravated if the subjects had been required to make multiple estimates. Consequently, each subject saw the full set of stimuli twice — once for glidepath and once for aim point — and thus had to make only one estimate at a time.

This paper is based on work done by the author in the Man-Vehicle Laboratory and the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. The research was performed under NASA Grants NGR 22-009-701 and NSG 2230, which were administered and monitored by Ames Research Center and Langley Research Center.

METHOD

Definitions

From among the variations in terminology in the literature and among potential subjects, the following definitions were chosen for use in instructing the subjects. The "glidepath" is the path through space from the aircraft to the nominal runway touchdown point located 300 m beyond the runway threshold. The "nominal" (or correct) glidepath is the "glide slope," defined here as being at 3° from the horizontal. The "flightpath" is the extension through space of the aircraft's instantaneous velocity vector. The "aim point" is the place on the ground intersected by the flightpath (see fig. 1). In a nominal approach, the glidepath, flightpath, and glide slope all coincide, and the aim point is the runway touchdown point.

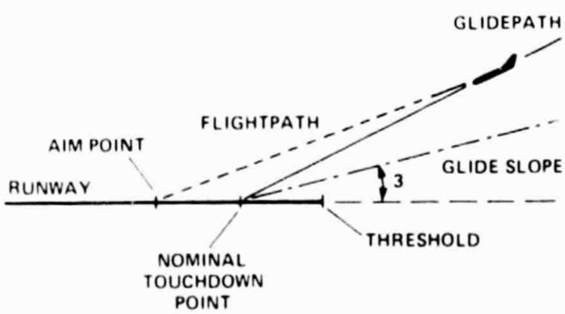
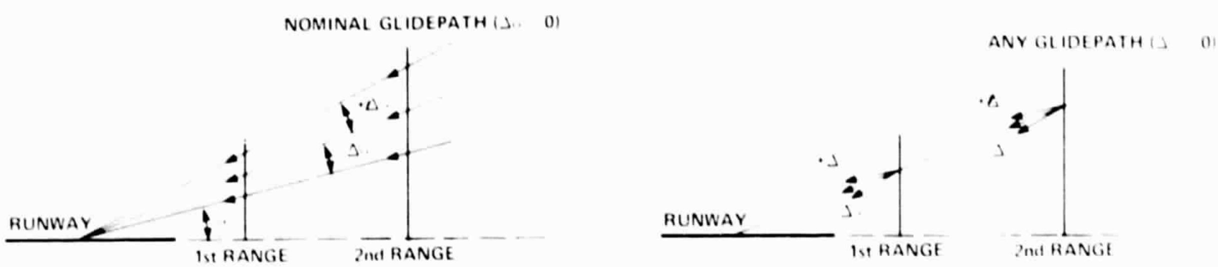


Figure 1.- Illustration of terms describing a landing approach (angles are exaggerated).

Pilots have direct control over the attitude of an aircraft, but have only indirect control over altitude or aim point. Yet pilots usually think of approach errors in terms of (1) height above or below the nominal glide slope, and (2) aim point distance from the nominal touchdown point. Height and distance measures of error vary with ground distance (range) from the runway, unlike angular measures which remain constant. Furthermore, aim point errors vary highly nonlinearly with changes in flighpath angle. These are fundamental problems presenting stimuli to the subjects, and in their estimation of that stimuli.

It was decided to base the stimuli on angular deviations, but to allow the subjects to respond in terms of height and distance. Subjects were told of the angular basis of the deviations, but were asked to estimate glidepath errors as being "high" or "low" with respect to the glide slope, and aim point errors as "long" or "short" with respect to the touchdown point. This introduced the risk of complicating the experimental results in exchange for reducing confusion of the subjects.

The experiments were constructed as a full factorial design with three main effects: glidepath, flightpath, and range. Although range was not estimated by the subjects, it had to be treated as an independent variable for proper analysis. The stimuli were defined as deviations from the nominal approach (see fig. 2). All stimulus levels were integral multiples of some unit deviation Δ. For glidepath (α) and flightpath (γ), the unit deviation was 0.5°. Flightpath deviations were defined relative to the total glidepath, so that the nominal aim point (corresponding to $\Delta\gamma = 0$) was always the touchdown point for any $\Delta\alpha$ (it was independent of glidepath). The deviations were combined; for example, there could be a positive $\Delta\alpha$ and a negative $\Delta\gamma$, each of a different magnitude, and the combined stimuli could appear at more than one distance. All possible combinations were presented in random order.



(a) Glidepath deviations. (b) Flightpath deviations.

Figure 2.- Illustration of stimulus deviations. (For clarity only three levels of stimuli are shown at two ranges; angles are exaggerated.)

Description of Equipment

A television projection system that accepts standard 525-line black-and-white video signals from a cable line input was used. The projector unit uses Schmidt optics: a small (15-cm), very high intensity cathode ray tube projects onto a spherical mirror, which reflects the light back through a corrector lens, then to the screen. This puts a 230- by 305-cm image at a focal length of 580 cm, the optimum distance for best resolution with this system, yielding a standard 3:4 aspect ratio picture. With the screen 370 cm from the viewer's eye, the image covers a 34° × 45° field of view. (See figs. 3 and 4 for diagrams of the layout.)

Visual simulators at Ames Research Center and Langley Research Center generated the television pictures, which were recorded on 19-mm (0.75-in.) video cassettes. Both simulators have large-scale models (terrain boards) of airports and their surrounding terrain, and television cameras that translate in three dimensions to follow scale motions of aircraft. The television pictures showed a view of the modeled areas resembling that seen from a real aircraft cockpit. For these experiments, the cameras followed a preprogrammed set of motions under computer control. The Ames terrain board simulator used for the final set of tapes has a model scale of 600:1.

Approaches were made to a model of a 60- by 2,400-m runway, simulating a light, fixed-wing aircraft flying at 70 knots.

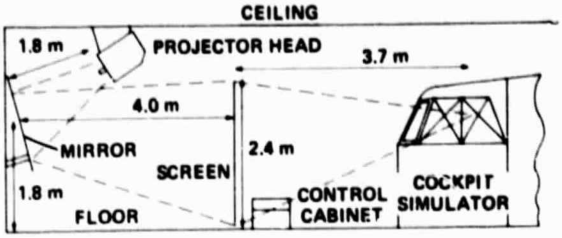


Figure 3.- Side view of simulator and projector layout.

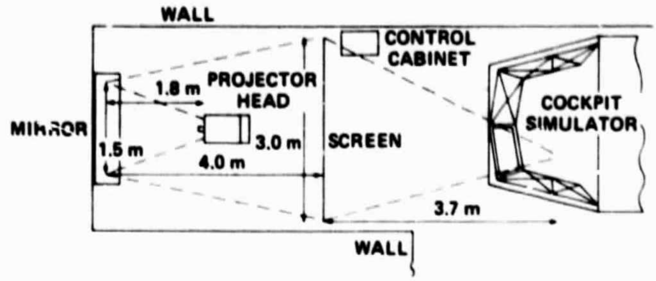


Figure 4.- Overhead view of simulator and projector layout; all cockpit windows except the left forward window are blacked out.

Subjects

Five subjects were used in the formal experiments. Their age, vision, and flight experience are summarized below.

Subject	Age	Vision	Rating(s) and flight experience
A	47	20/20	Flight instructor, instrument, commercial multi-engine instrument, 1,200 hr military jet, 150 multi, 1,000 light civil
B	29	20/20	Flight instructor multi-engine instrument, 1,000 hr military transport, 500 military jet, 2,000 light civil, 500 helicopter, 250 other
C	43	20/15	Commercial multi-engine instrument, 800 hr military jet, 400 light civil
D	28	20/20	Commercial single engine instrument, 850 hr military jet, 200 light civil
E	30	20/15	Commercial multi-engine instrument, 1,400 hr military jet, 200 light civil

EXPERIMENTAL DESIGN AND PROCEDURE

Magnitude Estimation

Magnitude estimation provides a maximum of usable data from psychophysical experiments of limited strength. Perception is difficult to measure: even those perceptual processes of which an experimental subject is conscious may not be easily described by him. The method of magnitude estimation assigns an arbitrary scale of units to the range of stimuli presented to the subject, then requires the subject to estimate the level of each separate stimulus in terms of the assigned scale. The resulting data are one step removed mathematically from the actual physical stimuli and preceptions, but they give numerical data when such data are not otherwise obtainable in a reliable or convenient form. As emphasized by Stevens (1966), the key requirement is that there be a statistically reliable correspondence between stimulus and estimate.

These were partition experiments, with the judgment scale set by two end-anchors, and with the stimuli and estimates all lying between those two points (Poulton, 1968). End-anchors are stimuli chosen to lie beyond the stimuli used for data collection. This eliminates distortions commonly found at the ends of the judgment scale (Anderson, 1974). Numerical labels (subjective units) of -10 to +10 were applied to the stimuli extremes, which were shown at the beginning of each experimental session to establish the subject's judgment scale.

The arbitrariness of the judgment scale does not pose as big a problem as might first appear. Virtually no system of physical units is internally natural to the subject; it is a verbal and mathematical convention. Therefore, the judgment scale may be more usefully constructed for experimental convenience than to match a subject's habitual usage. The 21 point (-10 to +10) range used here is considered simple enough for subjects to readily accept, while giving sufficiently small increments for useful accuracy (Angerson, 1974).

Choice of Stimuli

If the flightpath angle was in error, the actual glidepath angle would change during an approach. To prevent this effect from influencing the results of these experiments, a limit was placed on the allowable glidepath angle change during any given approach segment. For a fixed approach speed, this determined a maximum viewing time for each segment.

Work by other researchers (Gold and Hyman, 1968; Wempe and Palmer, 1970; and Gold, 1973) indicated that pilots could estimate glidepath angle with group standard deviations ranging from 0.25° to 0.6°; experienced naval carrier pilots gave the most accurate estimates. It was therefore decided to limit the maximum possible change in glidepath stimuli to twice the minimum value, or 0.5°. The aircraft simulated here was a light, single-engined aircraft approaching at 70 knots, which set time limits of 4.66 sec at the 900-m range and 9.33 sec at the 1,800-m range, thus keeping angular glidepath changes for a given stimulus approximately the same at each range. The time was kept the same for all runs at the same range to avoid giving the subjects an artificial clue for the glidepath and aim point estimates. Pilots also estimated aim point with group standard deviations of 0.25° of flightpath angle (Gold and Hyman, 1968; and Gold, 1973), so the aim point stimulus increments were set at twice this value, or 0.5°.

The shorter time of 4.66 sec was more than enough for stabilized estimates of aim point. Palmer (1969) reports little change in error scores for estimates of aim point in an artificial visual field at viewing times longer than 1.5 sec. A gap of 5 sec between each run gave the subjects time to state their estimates.

Numerical values for the stimuli in the experimental design were as follows:

Glidepath: ±3°, nominal
±0.5° and ±1.0° deviations
(±1.5° scale calibration end-anchors)

Flighcpath:	nominal = total glidepath
	±0.5° and ±1.0° deviations
	(±1.5° scale calibration end-anchors)
Range:	900 m and 1,800 m

Except for end-anchor runs, all possible combinations of stimuli were presented in random order. Note that the data runs constitute a full factorial design, but the calibration runs do not, because there are no interactions. Information on range effects was limited, but this was tolerable for these experiments.

There were 32 data runs (full factorial) and 10 calibration runs (one each of nominal and end-anchor points at each range), or 126 runs total including three replications.

As the glidepath changes at a fixed range, different portions of the extreme foreground come into the subject's view. This potentially presents another artificial glidepath angle clue besides run time (e.g., if the top of a tree is visible, the glidepath is low). To compensate for this effect, small variations were included in the ranges. The variations were just large enough to make a foreground object that was 10% as high as the total vertical field of view disappear between two views at different variations. This required variations of ±3% and ±6% of range, depending on the glidepath. One of the three replications of each stimulus at each range was given a positive variation, one a negative variation, and one no variation, all chosen at random so that any effects due solely to the variations would average out in the data analysis. Starting points were chosen to make the views coincide with the desired range exactly at the middle of the run.

Experimental Procedure

Each subject was shown the same two video tapes in the same order: glidepath runs first, then aim point runs. Both tapes began with similar sequences of orientation, training, and practice runs. A long orientation run began at the nominal touchdown point and ran backward up the glide slope to 3,000 m; a second approach segment covered the same range going down normally from 3,000 m to 0 m. Four training runs then showed the two most extreme stimuli, positive and negative, at ranges of 900 m and 1,800 m. These were the end-anchors to which the subjects were told to assign magnitudes of +10 and -10. A short orientation run (2,300 m to 800 m) followed, then several practice runs (eight for the glidepath tape, seven for the aim point tape). Any problems with understanding the experiment or getting adjusted to the experiment were worked out with the subject here. The experiment was always halted at this point to give the subject a chance to ask questions before proceeding with the data runs.

Next, the 126 data runs were shown to the subject. The data runs were identical copies for both glidepath and aim point tapes, taking 25 min per tape.

The subject estimated glidepath angle as being "high" or "low" with respect to the nominal glide slope, and aim point as "long" or "short" with respect to the nominal touchdown point, basing his magnitude estimates on the +10 to -10 scale. To keep the subject interested and to raise a competitive spirit, scores of the subject's performances were kept and revealed to him during the experiment. The score was the number of estimates in the correct direction and was announced by the test monitor after every 10 runs.

Printed instructions were shown to each subject. These are reproduced in the appendix.

ANOVA and the Statistical Model

To achieve maximum efficiency in the design of the experiment and the analysis of the data, a full-factorial Type I analysis of variance (ANOVA) model was chosen (Crow et al., 1960; Snedecor and Cochran, 1967).

A general linear model ANOVA program was used. It uses a statistical model of the form.

$$Y_{ijk} = \mu + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + e_{kjk}$$

where

Y_{ijk} = response at stimulus levels ijk

μ = overall mean

A_i = effect of first factor (range) at stimulus level i

B_j = effect of second factor (glidepath) at stimulus level j

C_k = effect of third factor (aim point) at stimulus level k

$(AB)_{ij}$ = interaction between first and second factors at stimulus levels ij

$(AC)_{ik}$ = interaction between first and third factors at stimulus levels ik

$(BC)_{jk}$ = interaction between second and third factors at stimulus levels jk

$(ABC)_{ijk}$ = interaction of first, second, and third factors at stimulus levels ijk

e_{ijk} = effects not accounted for by the model (error)

Deleting the error term, e_{ijk}, gives the model for $\hat{Y}_{ijk}$, the predicted response.

The model is considered linear because all of its factors are additive, but it does not assume any particular response function. It constructs a best-fit model to individual points, rather than an assumed curve, and so avoids distorting the results with prior assumptions. Nonlinear relationships between stimulus and response are thus fully revealed. Of course, if any important combination of variables were to be left out of the model, the results would be questionable (the error terms would become very large), but this is true of any method of analysis.

All main effects and interactions are assumed to have zero means:

$$\sum_i A_i = 0, \quad \sum_{i,j} (AB)_{ij} = 0, \quad \text{etc.}$$

Also, the errors e_{ijk} are assumed to have independent zero mean normal distributions. Any actual response biases are lumped into the overall model mean μ.

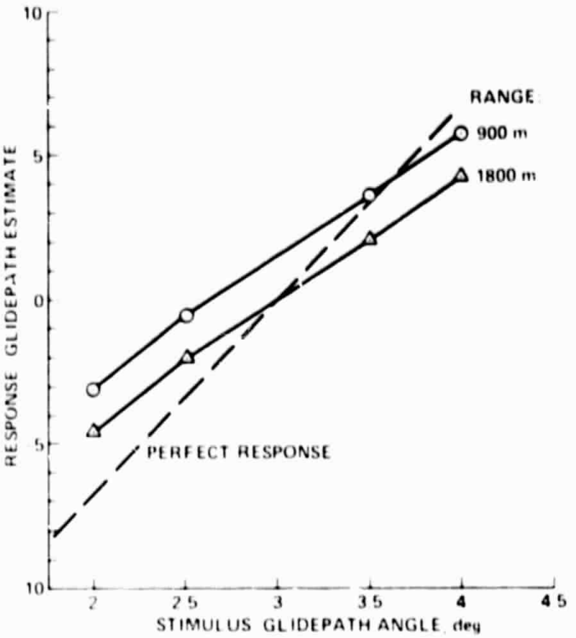
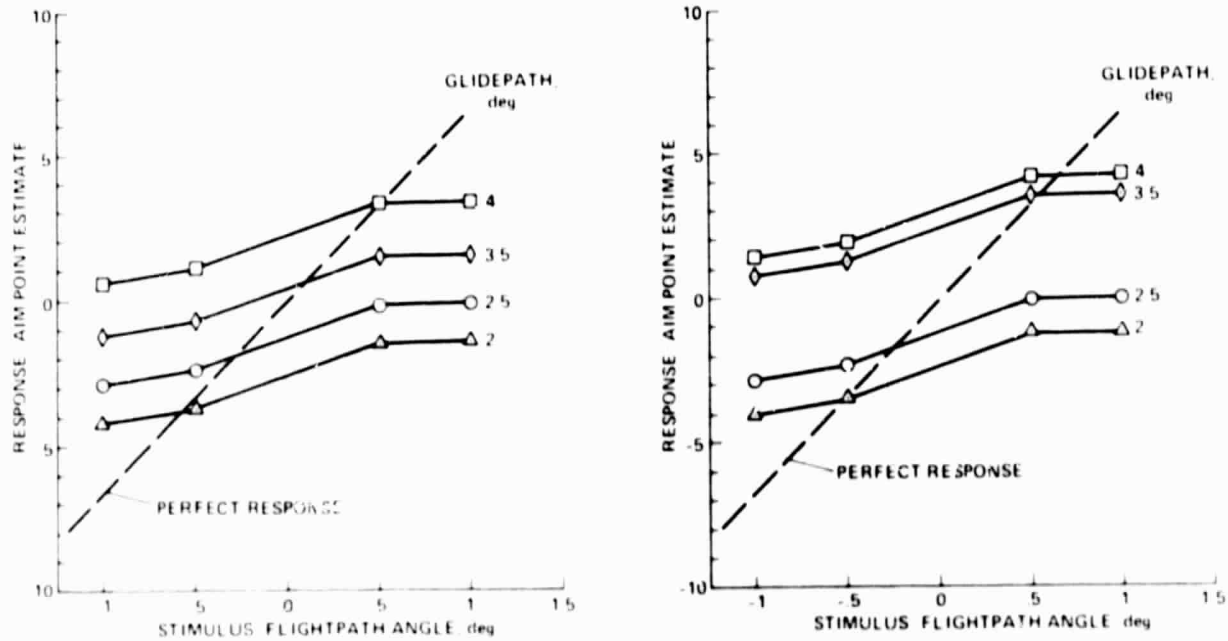


Figure 5.- Glidepath estimate model. Significant effects: glidepath and range ($p < 0.005$); mean = 0.73; model rms error = 2.24.

Responses predicted by the model are plotted point-by-point against relevant stimuli, with all statistically significant model terms being taken into account. This gives a graphical representation of the important functions within the model (figs. 5 and 6). The model is not intended to establish any cause and effect relationships, but to determine instead the relative statistical importance of the different visual stimuli.

A 5% significance level (here written $p < 0.05$) was chosen. This level is commonly used in experiments such as these with good results. As it turned out, all experimental main effects were significant at the 0.05 level. Where a factor is significant at some other level L, it is given in parentheses: ($p < L$).

For these experiments, the analysis was done iteratively. Only obviously nonsignificant factors ($p > 0.25$) were pooled into the error variance on the first



(a) Range = 900 m.

(b) Range = 1,800 m.

Figure 6.- Aim-point estimate model. Significant effects: aim point, range, and glidepath ($p < 0.005$); range/glidepath interaction ($p < 0.05$); mean not significant; model rms error = 2.75.

iteration; the new error variance was then used to recalculate the significance level of all marginally significant factors. Only then were final judgments made. The ANOVA program was rerun with nonsignificant factors suppressed, as a check on the accuracy of the original analysis; no important changes were noted.

RESULTS

Summary plots

Results of the experiments are summarized by figures 5 and 6. The vertical axis is the modeled subject response, in subjective units. The horizontal axis is the actual value of the stimulus, in physical units. Modeled responses are shown instead of actual responses to give a clearer representation of significant main effects and interactions. The lines connecting data points on the plots serve only to illustrate the patterns in the responses. The statistical modeling method used here does not predict responses between data points.

The overall average, or mean, of all subject estimates of either glidepath angle or aim point is given, when significant, in figures 5 and 6. Significant effects other than the mean are given with their significance levels. Also given is the model rms error, a statistical estimate of the overall standard deviation for all subject estimates. The model rms error includes errors caused by misfitting of the model curves and is therefore slightly larger than the true standard deviation.

Results for Modeled Responses

The glidepath estimates were nearly linear with glidepath angle (see fig. 5). It is convenient to define sensitivity as the total change in the estimates, in subjective units, relative to the defined estimate scale (-10 to +10), divided by the total change in stimulus magnitudes relative to the maximum range (set by the stimulus end-anchors). This gives a nondimensional number which may also be described as the ratio of percentage change in response to the percentage change in stimulus. A perfect subject would have a sensitivity or slope equal to 1.0. The subjects in this experiment had an average sensitivity of 0.66. This reduced sensitivity, represented by a reduced slope of the plotted response curves, is referred to here as "scale compression." The effect was also seen by other researchers, who reported glidepath sensitivities of 0.88 (Gold and Hyman, 1968) and 0.82 (Gold, 1973).

The aim point estimates were nonlinear, with noticeably reduced sensitivities at the extremes of the stimuli (see fig. 6). Scale compression was more severe than for the glidepath estimates. The subjects had an average aim point sensitivity of 0.24. This reather low sensitivity to aim point stimuli was also noticed by other researchers, who calculated sensitivities of 0.39 (Gold and Hyman, 1968) and 0.41 (Gold, 1973).

These results are reasonably consistent with the other reported experiments. In all cases, the aim point sensitivities were less than half those for the glidepath. It should be noted here that scale compression is not necessarily a result of perceptual processes. Failure to follow an artificial scale is common in many types of psychophysical experiments, particularly in magnitude estimation experiments in which no attempt is made to match stimuli to favored sets of response values (Poulton, 1968). The scale compression exhibited here probably results from the experimental method used, at least for glidepath estimates.

As for statistical results, range had a significant effect ($p < 0.005$) on the glidepath estimates. This is seen in figure 5 as an increase in the glidepath estimates at the greater range by about 1-1/2 units. Although slightly less than the model rms error of 2.24, the increase was consistent and therefore significant.

Range and glidepath angle each had significant effects ($p < 0.005$) on the aim point estimates, and the interaction between range and glidepath was also significant ($p < 0.05$). Aim point estimates increased slightly with increasing range owing to the range effect, and increased markedly with increasing glidepath angle owing to the glidepath effect (fig. 6). Differences in estimates between adjacent glidepath stimuli were usually less than the model rms error of 2.75, but were sufficiently consistent to be significant. Since flightpath is measured from the current glidepath, the glidepath effect on aim point measurement is a real perception effect and not an artificial result of geometry (see fig. 2). The range/glidepath interaction caused the curves to be less evenly distributed at the greater range, grouping into pairs at high and low levels of glidepath stimuli (compare figs. 5(a) and 5(b)). (Note that the glidepath stimuli themselves are not evenly distributed: there is no stimulus at 3°.) In all cases, the slopes of the curves (sensitivities) decreased at the extreme stimulus levels.

Discussion of Glidepath Estimates

It appears from figure 5 that pilots can estimate glidepath angle in a consistent linear fashion. Scale compression was noticeable. As discussed above, it is most likely a result of the experimental method.

The increase in glidepath estimates at greater ranges is more difficult to explain, especially because it contradicts the range-independent results obtained by Gold and Hyman (1968). The answer may lie in the visual system used. Textural details are thought to be important in judgments of altitude, at least at close range (Barnes, 1978). The low resolution of the video system used in these experiments may not allow a sufficiently clear presentation of textural quality in the displayed image, and the discontinuous nature of the stimuli would exaggerate apparent differences in textural details between the two ranges. This would increase the relative effect of any textural cues at the closer range, leading to lower glidepath estimates than at the greater range.

Discussion of Aim Point Estimates

Several aspects of the modeled aim point responses are discussed below. Noticeable are a very small effect of range on estimated aim point magnitude, a compression of the estimation scale, and a reduced sensitivity of the extremes of the stimuli. There is also clustering of response curves at high and low values of glidepath stimuli at the longer range, and greater sensitivity of aim point responses to changes in glidepath angle than to changes in aim point itself.

It is apparent that the subjects were not estimating ground distance, but were responding primarily to changes in flightpath angle, as was desired. This is not to say that absolute ground distance had no effect at all; indeed, the estimates did increase slightly with increasing range from the runway, but by an order of magnitude less than the actual change in absolute aim point distance. At double the range, the aim point ground distance associated with a given flightpath angular error should also double, but the estimates increased barely 20% (compare figs. 6(a) and 6(b)), and usually changed much less. Comparing these curves with the plot of estimate of ground distance for a perfect pilot (fig. 7), it can be seen that they do not even have the same shape, the modeled estimate curves being approximately antisymmetric instead of continuously increasing in slope. So the pilots were able to distinguish very well between ground distance to the aim point and flightpath angle, although their estimates of magnitude were inaccurate. Other minor ground distance effects were evident in an interaction between range and glidepath effects, discussed below.

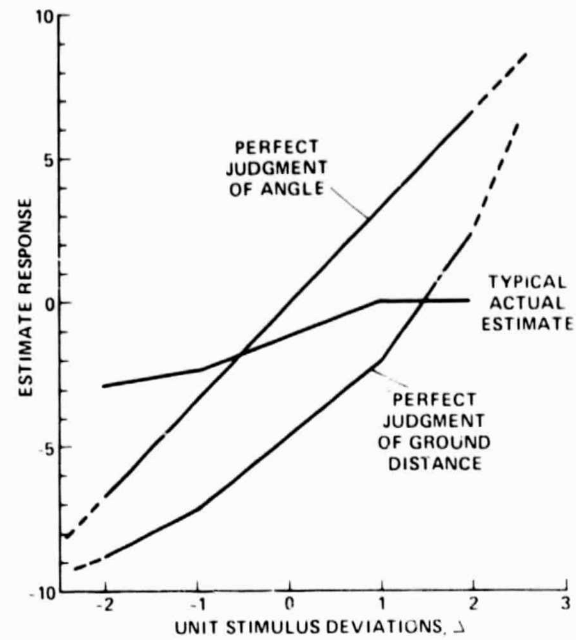


Figure 7.- Comparison of judgment of aim point angle and ground distance by a perfect pilot and a typical pilot. The lower curve shows the effect of trigonometric nonlinearities on aim point ground distance, given linear angular stimuli.

The scale compression is again entirely reasonable here. The reduction in sensitivity at the extremes of the stimuli may be a result of the practice of trying only to null out any errors during actual approaches, rather than somehow using exact magnitudes to determine aircraft control inputs, especially in this case in which the errors in aim point are difficult to estimate relative to others such as altitude and lateral alignment (Naish, 1971). If ground distance is used at all in the perception process, even if mentally normalized with respect to total range from the runway, the high nonlinearity of the stimuli (ground distance versus flightpath angle) could be confusing, so that on the average the subjects could distinguish well between different directions only, but not different magnitudes.

The tendency to fly approaches using a nulling technique — that is, mentally defining a proper approach as one that takes the aircraft back to the nominal glide slope — was mentioned by several subjects as feeling natural, even though the proper approach is then variable and depends on the initial error. Nulling behavior helps explain the previously mentioned effect of glidepath stimuli on aim point estimates. For any given flightpath angle, higher glidepath stimuli are associated with larger aim-point estimates (fig. 5). As the size of the glidepath error increases, so does the size of the flightpath angle needed for correction, but in the opposite direction (e.g., the higher a pilot is, the steeper he must dive to get back to nominal glide slope). But in this experiment, the nominal glidepath merely took the aircraft to the touchdown point and did not intersect the glide slope until touchdown; hence, the nominal flightpath angle was smaller than desired by the subjects (see fig. 8). This [illegible]le nominal flightpaths (and their associated aim points) look too long at high [illegible]epaths and too short at low glidepaths.

Airspeed, angle-of-attack, power, and altitude are of more immediate concern to a pilot than aim point, at least in conventional aircraft during standard landing approaches. Even in aircraft carrier landings, where achieving an exact touchdown point is essential, pilots are trained to de-emphasize aim point cues and to

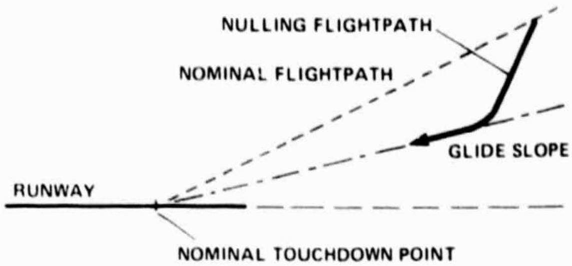


Figure 8.- Illustration of a nulling approach (angles are exaggerated).

concentrate instead on staying on the glide slope and keeping within their aircraft's performance limits. The trained behavior of getting back on the nominal glide slope as quickly as possible and then following it to touchdown could cause the response behavior seen here.

Another possible explanation for the effect of glidepath angle on aim point estimates is that subjects could not accurately detect absolute aim point errors — either in ground distance or in flightpath angle — but could detect only relative changes. In the experiments, all flightpath angles were referenced to the current glidepath, not the nominal glide slope. If the subjects could not properly determine the actual flightpath, they might base their estimates on the expected or average flightpath, due in part to confusion over what was a proper flightpath or aim point. The responses would then be dominated by the statistically averaged stimulus, which had an absolute flightpath angle of 3° below the horizon. This would again result in longer aim point estimates at higher glidepaths and shorter estimates at low ones.

In principle, a judgment of aim point can be made directly by using the "expansion" or "streamer" effect. All points on the ground will appear to expand outward from the aircraft's actual aim point. In conjunction with a reference, such as a windshield frame, this provides a cue for determining the aim point; it is sometimes called the "gunsight method" (Hasbrook, 1975). But its theoretical accuracy is very low, and the method is nearly useless until the pilot is almost over the runway (Naish, 1971). This is supported by other experimental work, which showed poor accuracy of aim point judgment (Palmer, 1969). Although they can be clearly seen by most pilots, expansion cues would provide no more than a coarse indication of aim point, at best.

The term "streamer effect" is sometimes also used to describe peripheral vision motion cues (Hasbrook, 1975). There were none in these experiments, for the subjects only had a direct forward view out of the cockpit. In any case, it appears that such cues would be of little help in determining the aim point until very close to the ground. Expansion and streamer cues would probably be of most use in making final corrections for the flare.

It was thought that pilots may estimate flightpath angle by looking for changes in glidepath angle. The experiments were set up so that the maximum change in glidepath angle seen during any landing approach run was only 0.25°, or the expected standard deviation of pilot's estimates of glidepath (Gold and Hyman, 1969). These changes would therefore be marginally detectable, but the pilots could in fact detect changes in aim point. Furthermore, trigonometric nonlinearities cause faster rates of change of instantaneous glidepath angle for any nonzero flightpath deviation as the average glidepath angle increases. Although this should cause increased sensitivity at high glidepaths and statistical interactions between aim point and glidepath, neither of these effects was seen in the data.

The possibility that pilots rely on perception of vertical velocity (rate of descent or sink rate) when estimating aim point was considered. In these experiments, the downward vertical velocity was on average higher at high glidepaths, so that according to the hypothesis, aim point estimates should have been lower at high glidepath stimuli. But exactly the opposite results were obtained. There should also have been interactions between aim point and glidepath as a result of trigonometric nonlinearities, but, as mentioned above, none were found in the data.

The magnitude and the range of the aim point estimates changed little with range from the touchdown point, but the distribution across glidepath stimuli changed appreciably. The clustering at the greater range, with high glidepath curves closer together than low glidepath curves, is consistent with the nonlinearities expected in absolute ground distance aim point estimation. It is possible that pilots may look for absolute ground distance errors, and correct them for total range from the runway to get angular estimates. The poor accuracy of such information makes it of questionable usefulness; moreover, this is almost certainly mot the most important perceptual mechanism.

Apparently, pilots can estimate aim point errors reliably, but not very accurately. However, these experiments do not allow a distinction between the two possibilities: a preference for nulled approaches, and poor accuracy of aim point perception. Moreover, the two are not mutually exclusive, and depend on the pilot's training and experience. If pilots cannot rely on their own perceptions of flightpath angle, they may be strongly dependent on simply being on the right glidepath, trusting it to eventually take them to the correct aim point. Aim point itself may be of little concern until the flare, which was not included here. Nevertheless, there was still a definite and consistent sensitivity to changes in flightpath angle (hence aim point).

CONCLUSIONS

Glidepath angle presented no major difficulty in estimation to the subjects. The estimates made by the pilots in these experiments were usually quite linear although not highly accurate. Two principal response patterns were noted: (1) a change in the magnitude of the glidepath angle stimulus was usually met by a smaller change in the subject's responses; and (2) glidepath estimates were higher at greater ranges from the runway. However, the first of these two response phenomena is thought to have resulted from the method of magnitude estimation used for measuring the subjects' perceptions and the second from an imperfect visual system.

Aim point errors were difficult to estimate. Although the subjects could reliably detect large changes in flightpath angle, their sensitivity to small deviations was very low. Glidepath angle strongly influenced the magnitudes of the aim point estimates, which were longer at high glidepaths, but the sensitivity to changes in flightpath angle was not affected by glidepath. Range from the runway had little effect. There was some evidence that aim point ground distance along the runway played a minor role in the estimation process. The data did not support the possibility that pilots use either vertical velocity or changes in glidepath angle to estimate aim point.

These experiments were not sufficiently comprehensive to allow strong, detailed conclusions concerning causes and effects; nevertheless, worthwhile inferences may be drawn. Although the results for aim point estimates are due in part to the same problems with magnitude estimation as were noted for glidepath estimates, the poorer performance indicates that other factors must be involved. One possibility is that pilots prefer to null their approaches to the correct glide slope and do not normally concern themselves with aim point until near the flare. Another is simply that pilot perceptions of aim point are inaccurate.

Since pilots seem to prefer to use a nulling technique to stay on a preselected glide slope (because of difficulties with perceiving aim point and not just because of training conventions), pilots flying difficult approaches will need cockpit aids to determine their true aim point. STOL and multisegment approaches would present the worst problems, especially without increased aircraft performance margins. Pilots cannot control aim point as readily as glidepath; the latter can be chosen to intersect a desired aim point, then simply followed down to that point. Any artificial aim point display should be integrated with a glidepath display to be readily usable, for the aim point helps define the desired glidepath.

APPENDIX

INSTRUCTIONS TO SUBJECTS FOR LANDING APPROACH ESTIMATION EXPERIMENT

The purpose of this experiment is to determine your ability to detect errors in glidepath and aim point during aircraft landing approaches. The experiment has two sets of video-taped landing approach runs. To save time, only a short segment of each run is shown. During each set, you will be asked to estimate either glidepath or aim point errors for each run. Both kinds of errors may occur simultaneously, but you should estimate only the one asked for. Tell the test monitor your estimate at the end of each run. He will write it down for you so that you can concentrate on watching the approaches. Since altitude along the glidepath and aim point miss distance depend on initial distance from the runway, you should base your estimates on the angles of the glidepath and aim point vector errors. (See the descriptions below and the figures on the next two pages.) [Same as figs. 1 and 2]

Each set of runs begins with two orientation runs to show you the touchdown point and a correct approach. Four scaling runs follow to show you the largest errors in that set for either glidepath or aim point. You should call the maximum positive and negative glidepath errors "10 high" and "10 low," respectively, and estimate all glidepath errors in terms of this scale. For example, a positive glidepath error half as large as the maximum should be estimated "5 high." Similarly, aim point errors should be called "long" or "short." Except for orientation runs, there are no normal approaches (with error equal to 0).

The "glidepath" is the path through space that would take you to the runway touchdown point. The correct glidepath is the "glide slope," which here makes a 3° angle to the horizontal. For any given path error, the difference in altitude will change with distance from the runway, so you should estimate angular error of the glidepath (the glidepath error angle). If you are above the glide slope, call the error "high," and if you are below the glide slope, call it "low," with the appropriate magnitude.

The "flight vector" is the direction you are moving through space. The "aim point" is the place on the ground that you will reach if you continue along your present flight vector. The correct aim point is simply the runway touchdown point; to reach it, the flight vector must be exactly aligned with the glidepath. In an actual aircraft, only the instantaneous flight vector angle can be controlled directly, not the ultimate aim point, and this experiment is set up accordingly. For any given flight vector angle error, the ultimate touchdown point depends on the initial distance from the runway. Also, the absolute size of the aim point error is not symmetrical for initial symmetrical flight vector angle errors. So you should estimate the error of the flight vector angle, rather than the ground distance of the resulting aim point. Estimate the directions of the error as being "long" or "short" with respect to the touchdown point.

Note that it is possible to reach the correct touchdown point even if the glidepath is incorrect, and that the aim point can be in error even if you start out on the proper glide slope. If the flight vector is not aligned with the glidepath, you may notice a slight change in the glidepath during the run. If so, simply estimate the average glidepath, or that at the middle of the run.

A score of your performance during the test will be kept. You will not be scored on correctly estimating the exact size of the error, just the right direction (high/low, long/short). Your score is simply the total number of estimates in the right direction. Your score does not represent your actual abilities as a pilot in a real aircraft and will be kept confidential.

The runs average about 7 sec each (5 to 9 sec), with 3 sec between runs, so you should make your estimates quickly. You will have several practice runs, and you may repeat the scaling and orientation runs, if you wish.

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