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AURAL GLIDE SLOPE CUES: THEIR EFFECT ON PILOT PERFORMANCE DURING IN-FLIGHT SIMULATED ILS INSTRUMENT APPROACHES	May 1971
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16. Abstract

Forty instrument rated Commercial and ATR pilots with 250 to 12,271 flight hours each flew ten simulated ILS approaches in a single engine, general aviation aircraft. Divided into five groups, each group used a different glide slope cue display in combination with a modified "T" instrument panel configuration. Two types of aural glide slope cue displays were utilized; (1) voice, and (2) Morse code signals.

No significant differences were found among the five groups relative to accuracy in glide slope tracking. There was no apparent improvement with practice. The presence of glide slope cues resulted in the aircraft being flown slightly higher across the middle marker than when only the conventional visual display was utilized. Localizer performance showed a slight but significant initial decrease in the presence of glide slope cues with respect to only one performance measure. This difference was minimized as a function of the number of approaches flown. No significant differences appeared among groups with regard to stress levels as measured by heart rate and heart rate changes. Mean heart rates declined over successive approaches but increased during each approach. Transition from the conventional visual crosspointer display to the aural (voice) glide slope cues was achieved with a minimum of familiarization and with no apparent difficulty.

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AURAL GLIDE SLOPE CUES: THEIR EFFECT ON PILOT PERFORMANCE DURING IN-FLIGHT SIMULATED ILS INSTRUMENT APPROACHES

I. Introduction.

Many aircraft accidents involving fatal and serious injuries have occurred during instrument approaches through low clouds and precipitation when pilots have inadvertently flown their aircraft too far below the centerline of the electronic glide path, striking terrain or obstructions short of the runway.[5 7] In such accidents, "pilot error" has often been listed as the primary cause. Unfortunately, the predisposing factors that may have been responsible for many of these so-called pilot error accidents frequently escape detection because of the subtle and intricate human factors relationships associated with the complex man-machine system.

Obviously, the basic cause of such accidents is the pilot's lack of awareness of his unusually low altitude. This may be due to his inability to see the approaching ground because of unexpected visibility restrictions, malfunction of pertinent instrument displays, his failure to scan appropriate instruments frequently enough to obtain necessary altitude-position information, or to his inherent human limitations to acquire, process, and translate necessary information within the constraints and demands of the total system task.

A 1949 study[6] of Air Force pilots with a wide range of flying and instrument experience showed that 41% of the pilot's visual fixation time was devoted to the crosspointer indicator during "raw data" (Non Flight Director) instrument approaches in a C–45 aircraft. The directional gyro, attitude indicator, and airspeed indicator accounted for an additional 50%.

Surprisingly, *only 2% of visual time was devoted to the altimeter*, and, the frequency of reference to this vital instrument averaged only three per minute. The remaining 7% was devoted to other instruments and to related visual tasks. A more recent study[8] on airline pilots making "raw data" instrument approaches in a DC–8 simulator (with six degrees of freedom and a primary flight display arranged in a conventional "T" configuration) shows that the attitude indicator and ILS crosspointer instrument may account for as much as 70–80% of visual fixation time. And, even these large percentages may be conservative under certain circumstances. For example, it has been observed by experienced check pilots that a pilot who is fatigued or under emotional stress tends to fixate on some one indicator, leaving the other instruments virtually unattended for long periods of time.

If these findings are representative of the visual scan-time pattern of the instrument rated pilot population as a whole, it appears that pilots allocate most of their attention to those instruments—the attitude indicator and crosspointer indicator—whose individual cues are considered to be most critical to the total task. It is not clear, however, whether this disproportionate concentration of time is a function of a limited *visual* information intake capacity or if it is the result of the pilots selectively limiting their information intake to a level compatible with their *total* data processing capacity. Also, this time allocation may be a function of the display interface. Human factors deficiencies in this area can range from legibility problems to incompatible response requirements. The effects of these shortcomings may combine to seriously limit the pilots' ability and capacity to acquire and process needed visual information as rapidly as required during the approach.

As a search of the literature indicates, there is an abundance of data available on aircraft cockpit displays but frequently much of it has been, and continues to be, inadequate for practical design application.[2] And, even if basic design deficiencies were remedied, it is possible that pilots would continue to concentrate their *visual* attention on a very limited number of displays.

If this were found to be the case, then consideration should be given to using alternate sensory channels for acquisition of certain applicable flight information.

The feasibility of using alternate sensory channels as a substitute for, or to augment, the visual mode has been investigated by many researchers. The auditory channel has received considerable attention over the years, beginning as early as 1936.[1 4] Auditory signals, when used for presentation of *flight* information, as opposed to *warning* information (as in an annuciator) have been most successful when used to present only a *single* flight parameter such as heading or bank angle. Attempts to develop multi-dimensional auditory flight displays, on the other hand, have proven less successful.

Considering the promising results of single auditory displays, as well as experience with such systems as Ground Controlled Approach (GCA), Precision Approach Radar (PAR), and the Adcock Low Frequency Radio Ranges, it was decided to adapt some of the features of such systems to provide an automated airborne auditory glide slope display. By providing auditory cues as a source of glide slope tracking information, it was hypothesized that such cues (in addition to, or in lieu of, the conventional glide slope display) might reduce or substantially eliminate a pilot's dependence on visual glide slope cues—giving him more visual time to devote to other instruments, thereby possibly improving his overall performance. On the other hand, if there was little or no improvement (despite comparable ability in using aural cues) it would appear future research attention should be directed toward a more extensive and detailed study of the pilot's total performance capacity in relation to the task requirements and characteristics of the ILS system, the dynamics of the aircraft, and the aircraft control-display relationship.

In the work reported here, the research was necessarily limited to studying the performance effect of using auditory cues for the single parameter of glide slope information. Unfortunately, due to equipment design and other limitations, data could not be obtained on any changes that may have occurred in the pilots' visual scan pattern as a result of using the auditory cues.

II. Equipment and Methodology.

Research Devices: A four place, single engine, general aviation type airplane (Fig. 1) was used

FIGURE 1. Aircraft used in study of effects of aural cues on pilot performance during simulated instrument approaches.

in the study. The instrument panel, typical of many such installations in aircraft equipped for precision (ILS) instrument approaches, utilized a modified "T" configuration of the primary flight instruments (Fig. 2). This modification involved the relocation of the vertical speed indicator (Arrow 1) to the right of its normal position so as to provide a more central location for the glide slope/localizer indicator (Arrow 2). Quick removal "slats" (Arrow 3), installed above and to the left of the instrument panel prevented the pilot-subjects from looking outside, effectively simulating an instrument environment without interfering with the safety pilot's outside vision.

The electronic equipment generating the aural glide slope cues and the battery powered seven channel Model 417 Lockheed recorder were mounted behind the pilot's seat. A research engineer monitored the equipment from an adjoining seat and supplied indexing and reference data to the recorder.

The A/N cue generating device consisted of an electronic code generator whose signal and ratio of volume output was controlled by the output of the glide slope radio receiver. The on-course tone in the A/N system was produced when the signal ratio was equal. The voice cue device consisted of a two track stereo tape player and an on-course tone (1020 Hz) generator.

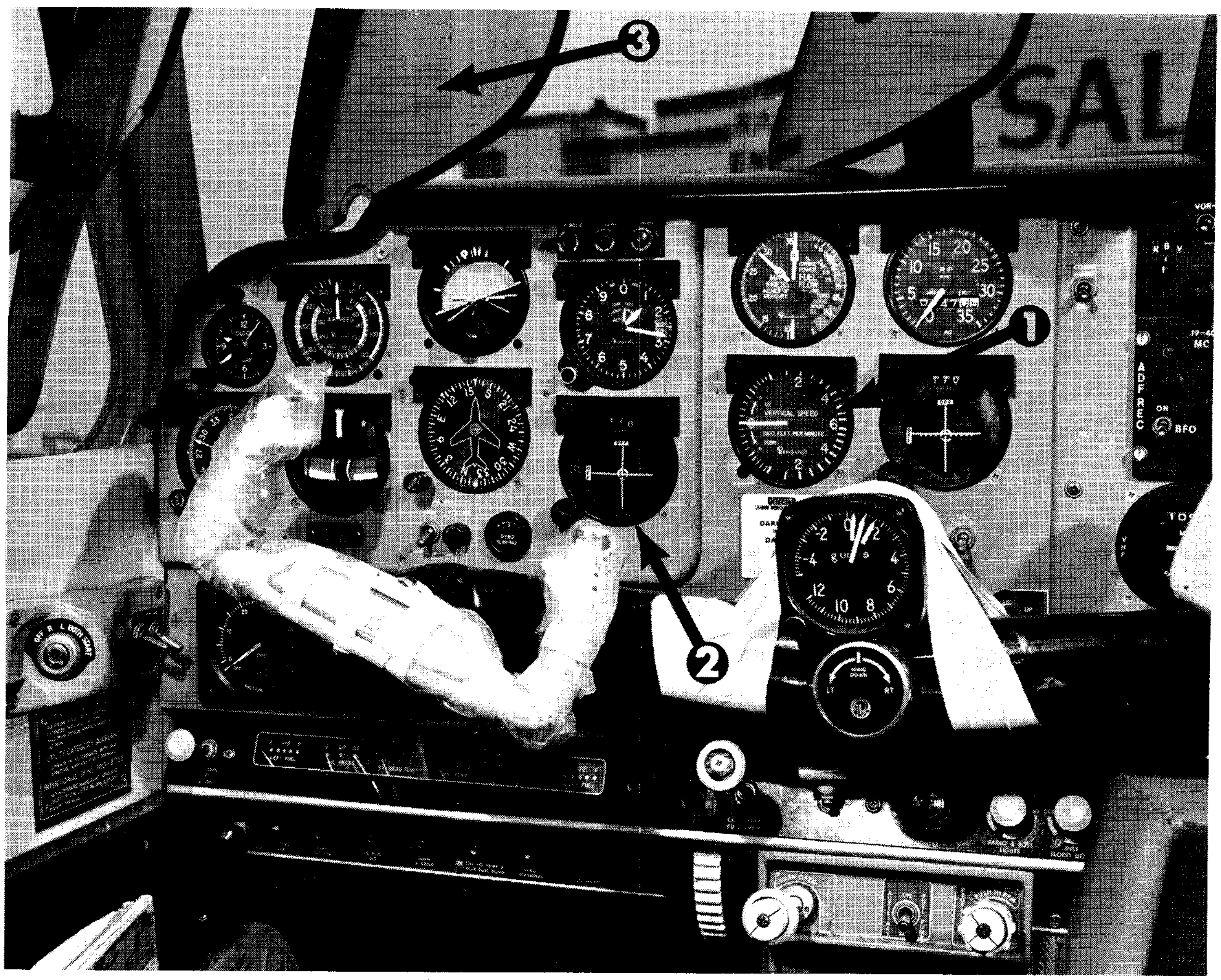

FIGURE 2. Primary flight instruments in research aircraft were arranged in "T" configuration with exception of vertical speed indicator (Arrow #1), which was moved to the right to permit a more centrally located glide slope/localizer indicator (Arrow #2). Removable "slats" (Arrow #3) simulated instrument weather environment for subjects without interfering with safety pilot's outside vision.

Switching between the continuously operating voice tracks was accomplished by inversely varying the volume of the two tracks according to the signal ratio output of the glide slope receiver.

The control wheel was wrapped with a non-conductive thin film plastic material to prevent grounding of the subject's EKG (heart rate) signal output, which was obtained through appropriately attached electrodes on the subject's chest.

Data Recorded: Data recorded during the flights consisted of vertical and lateral deviations from the centerline of the glide slope/localizer beams, aircraft bank angle, vertical acceleration of the aircraft, subjects' heart rate, aural cue inputs, and event information such as time of passage over geographical "fixes," calibration checks, and other observer comments.

Subjects: Forty pilots with current FAA airmen medical certificates and FAA instrument ratings served as subjects. The subjects were divided into five matched groups based on their reported number of hours of instrument flying experience. Some arbitrary weight was given to recency of experience, as well as to total flying hours of those subjects who reported the same approximate level of instrument experience. This method was employed to assure relatively matched groups with regard to experience and initial ability while retaining a statistically valid sampling of the subject population. Subsequent statistical tests on selected measures showed no significant differences among groups with regard to initial performance ability.

Flying experience of the subjects ranged from 250 to 12,271 hours, with a mean of 4,732 hours; age ranged from 26 to 61 years with a mean of 43.5 years. Nineteen subjects had commercial pilot ratings, twenty had airline transport ratings, and one was a private pilot. Eighteen possessed instructor ratings.

ILS Facilities: Two instrument landing system (ILS) facilities were used for the study. One facility served runway 35L at Will Rogers World Airport, Oklahoma City, Oklahoma. The other, a training facility, served runway 17 at the Chickasha, Oklahoma airport. Approximate elevation angle of both glide slope centerlines was 2.5 degrees. The choice of facility for any given flight was dictated by the prevailing wind at the time of the flight. Subsequent examination of the data showed no apparent systematic bias as a result of the use of either facility.

Experimental Procedure: Prior to flight each subject was briefed by use of standard instructions on the manner in which the flight would be conducted, the nature of the task, and the required performance. In the aircraft, the aural cue system was demonstrated briefly by use of a simulation mode of operation until the subject was familiar with the type of glide slope display he would be using during the experimental approaches. He was also given a lightweight headset to wear to exclude all external radio communications, minimize extraneous cockpit noises, and permit the safety pilot to communicate with the subject via the interphone. The subject adjusted the volume of the auditory glide slope signal to the level he preferred.

The aircraft was taxied to the active runway by the safety pilot and after "run-up," the slats were put in place. The take-off and initial climb-out were made by the safety pilot. About 1½ minutes after take-off, with trim set in climb configuration, control of the airplane was given to the subject with instructions to climb to, and maintain, a specified altitude. After retrimming the aircraft at the designated altitude, the subject executed a series of left and right medium banked turns. Following these maneuvers, the safety pilot extended the landing gear and set the flaps, power and RPM in landing approach configuration. The subject then practiced a partial power descent to approach altitude, varying power as needed to maintain a specified rate of descent.

Regardless of his degree of familiarity with the aircraft, each subject received a total of only 20 minutes in-flight practice involving the above mentioned identical maneuvers. Limiting this familiarization period to an "under-the-hood" environment appears to have been effective in reducing performance variations which might have been expected from lack of experience with the type aircraft used in the study.

Ten straight-in ILS approaches were performed at approximate 10 minute intervals (Fig. 3). Prior to each approach, the safety pilot flew the aircraft onto the centerline of the glide slope/

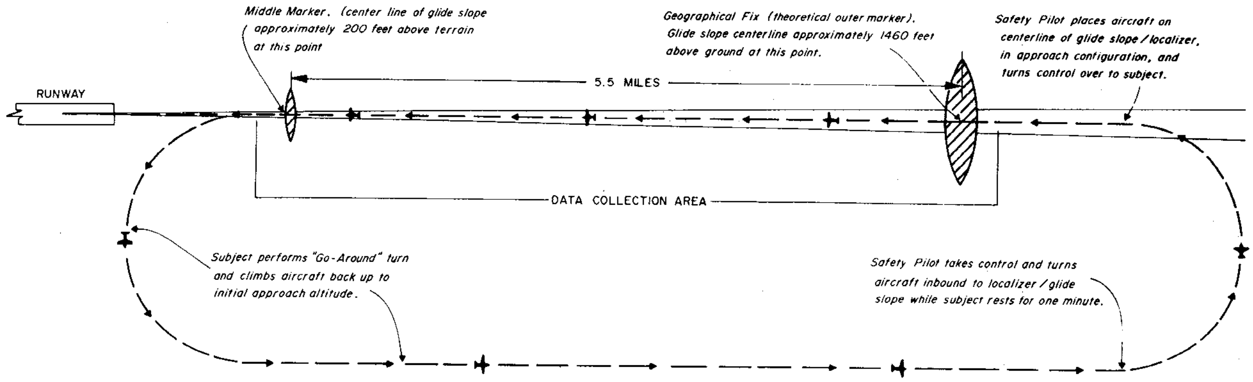

FIGURE 3. Flight path used during simulated instrument approaches. Each circuit required approximately ten minutes.

localizer "beam" at a point above a geographical ground fix. Speed, power, landing gear and flaps were set in approach configuration before handing over control of the aircraft to the subject. Thus, all subjects commenced their approaches in similar approach geometry from the same point in space without the stress and responsibility of navigating to that point. Upon completion of each approach (past the middle marker) the safety pilot raised the landing gear and flaps and instructed the subject to "go-around."

After go-around, the aircraft was flown back to the initial approach altitude by the subject. He was then given a one-minute rest period while the safety pilot made a 180 degree turn inbound to the glide slope/localizer centerline, where the procedure was repeated.

All air traffic control transmissions were excluded from the subject's headset during the approaches. This, along with relieving the subject from chart reading, communication and other activities normally associated with an actual approach (as well as prior instructions to concentrate primarily on the tracking task rather than monitoring engine gauges and other such ancillary duties) was done to minimize uncontrolled variables that might influence the subject's ability to track the glide slope/localizer centerline.

The flight was terminated after the tenth approach—with the safety pilot landing the aircraft.

Glide Slope Display Modes: Each group of subjects used only one of the five different glide slope displays during the experimental approaches (#4 through #8). These were:

Subject Group and Display Mode	
A	Visual Display—Glide slope information provided solely by conventional crosspointer instrument.
B	Aural/Voice Display—Glide slope information provided by taped voice phrases and on-course tone.
C	Aural/Code Display—Glide slope information provided by Morse code signal and on-course tone.
D	Visual and Aural/Voice Display—Displays A and B combined.
E	Visual and Aural/Code Display—Displays A and C combined.

The auditory glide slope displays included a 1020 Hz tone as an "on-course" cue when the aircraft was on the approximate centerline of the glide slope. This continuous tone was present over a deviation range equivalent to the glide slope needle being within the "bull's-eye" portion of the crosspointer instrument. Larger deviations from glide slope resulted in cessation of the 1020 Hz tone and a concomitant initiation of an "off-course" aural cue. In the voice (female) mode presentations (individually and in combination with the conventional display) the aural cues consisted of the taped phrases "you are high" or "you are low" when the aircraft deviated more than one dot above or below the glide slope centerline. The phrase, repeated at two-second intervals, increased in volume as the magnitude of deviation increased. The code cues consisted of a continuous series of the Morse code "A" (• ▬) when the aircraft deviated above the glide slope and the Morse code "N" (▬ •) when the aircraft was **below** glide slope. As with the voice mode display, the volume of the signal increased with increasing deviation and decreased as the aircraft approached the glide slope path. An idealized profile of the change in volume of the auditory cues in relation to deviation is shown in Figure 4. These changes in volume also provided qualitative information on the rate at which the aircraft deviated away from, or approached, the glide slope path.

The subjects flew their approaches according to the protocol presented in Table 1. All groups flew the first two approaches with only the conventional visual glide slope display. Approach #1 provided orientation to the mechanics of the task. Performance in approach #2 established a baseline proficiency level as well as a basis for evaluating the adequacy of group matching of initial proficiency.

The subjects in group A, using only the conventional (visual) display during the ten approaches, served as the control group.

Groups B, C, D, and E flew approach #3 with a variation of the experimental display that would be used in approaches #4 through #8. Thus, the subjects in groups D and E were forced to rely solely on auditory cues for glide slope tracking in approach #3. It was hoped this would encourage use of the auditory cues during approaches #4 through #8 when the combined displays were available. There was no way, of course, to determine which display or what ratio of cues—audio and visual—were used when a combination of both was available.

III. Results

The basic glide slope data for all approaches by the five groups are summarized and tabulated in the appendix. For the purpose of statistical

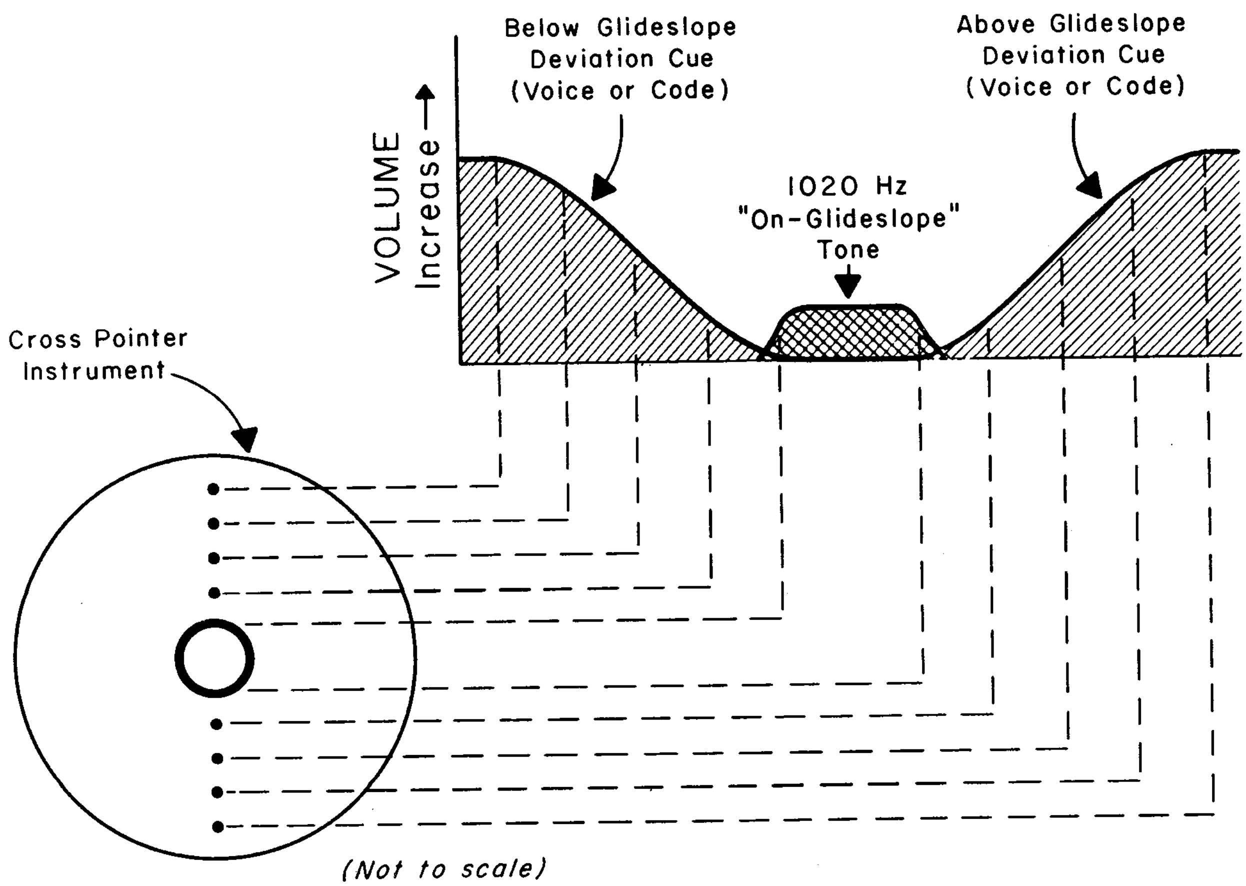

FIGURE 4. Idealized illustration shows relationships of volume of aural cues to aircraft deviation above or below glide slope centerline. A 1020 Hz tone provided "on-course" guidance.

SUBJECT GROUP (8 PILOTS EACH)	APPROACH SEQUENCE				
	1 & 2	3	4 THRU 8 (EXPERIMENTAL)	9	10
A	⊕	⊕	⊕	⊕	⊕
B	⊕	⊕ V/T	V/T	⊕ V/T	⊕
C	⊕	⊕ C/T	C/T	⊕ C/T	⊕
D	⊕	V/T	⊕ V/T	V/T	⊕
E	⊕	C/T	⊕ C/T	C/T	⊕

LEGEND:

⊕ = VISUAL CUE (CROSS-POINTER INDICATOR).

V/T = AURAL CUES (VOICE AND ON-COURSE TONE).

C/T = AURAL CUES (CODE SIGNAL AND ON-COURSE TONE).

⊕ V/T = VISUAL AND AURAL VOICE CUES (WITH ON-COURSE TONE).

⊕ C/T = VISUAL AND AURAL CODE CUES (WITH ON-COURSE TONE).

TABLE 1. Sequence of display presentations used by the five groups during ten instrument approaches.

analysis, the accuracy of glide slope tracking was evaluated on the basis of three separate criteria; these were:

1. Percent time on glide slope between the outer and middle markers. The aircraft was defined as being on glide slope when deviation from glide slope centerline did not exceed a magnitude comparable to keeping the glide slope needle within the periphery of the "bull's-eye" on the crosspointer instrument.

2. A composite performance score expressed as a percentage. Scores were derived by multiplying weighted ranges of deviation from glide slope centerline by the duration of the deviation.

3. The largest single deviation from glide slope centerline during each of ten successive time segments of the approach. Length of these segments was a function of total approach time between the markers. (Note: All measures of deviation discussed in this report refer to deviations expressed in terms of comparable needle/dot indications, regardless of whether such visual cues were available to the subjects, during the experimental approaches #4 through #8.)

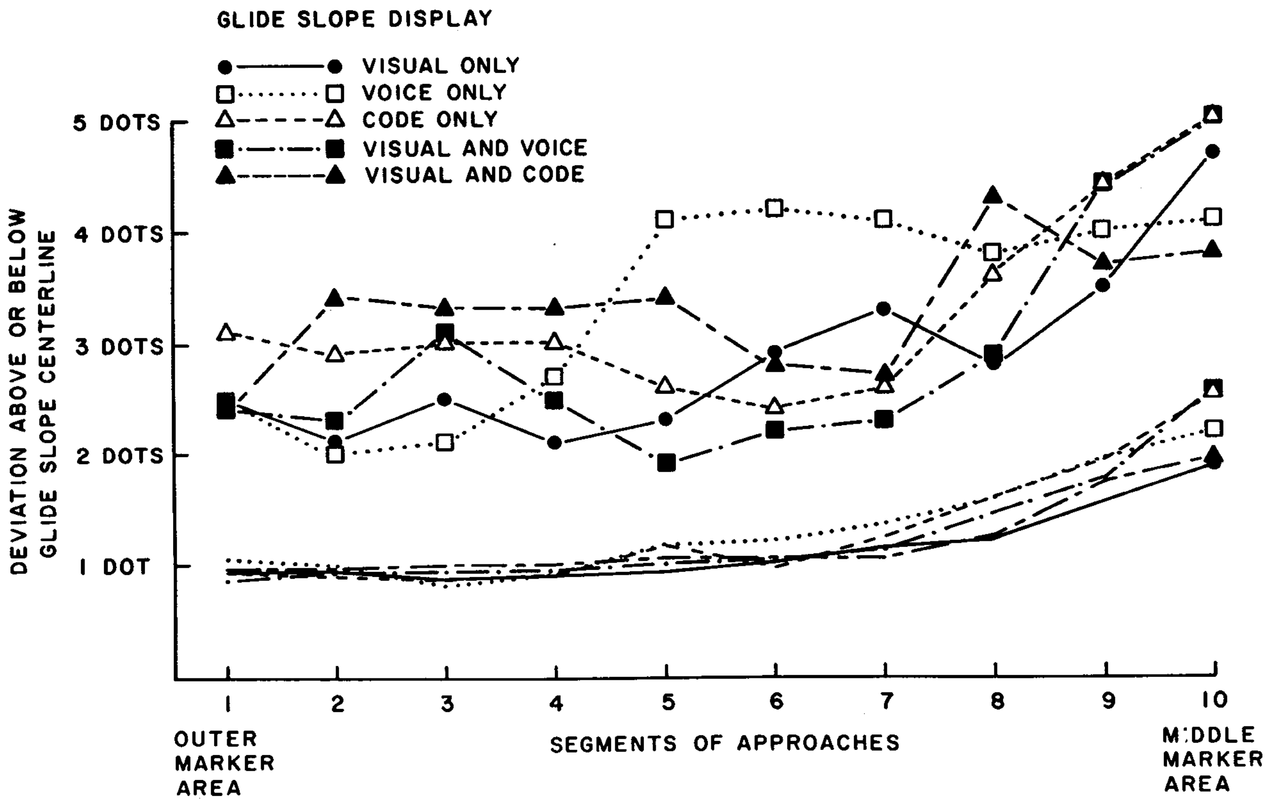

FIGURE 5. Maximum deviations in either direction from glide slope centerline during approach segments. The upper group of curves indicate the largest single deviation during any experimental approach (#4 through #8) by any subject in the respective groups. The lower group of curves represents the combined means for all experimental approaches for all five groups.

TABLE 2.—Maximum Deviations From Glide Slope Within Successive Segments of Approach. (Analysis of Variance)

Source of Variation	df	MS	F	P
Between Subjects	(39)			
Groups	4	232.29	<1	
Subjects/Groups	35	553.78		
Within Subjects	(1,960)			
Segments	9	3,889.74	76.99	<.01
Segments X Groups	36	68.40	1.35	
Segments X Subjects/Groups	315	50.52		
Approaches	4	59.81	<1	
Approaches X Groups	16	64.67	<1	
Approaches X Subjects/Groups	140	80.98		
Approaches X Segments	36	25.60	<1	
Approaches X Segments X Groups	144	26.17	<1	
Approaches X Segments X Subjects/Groups	1,260	27.99		
TOTAL	1,999			

TABLE 3.—Percent Time Deviation to Right or Left of Localizer Centerline Did Not Exceed One Dot (Comparable to Needle Remaining Within Instrument "Bulls-eye").
(Analysis of Variance)

Source of Variation	df	MS	F	P
Between Subjects	(39)			
Groups	4	3,335.45	2.71	<.05
Subjects/Groups	35	1,231.59		
Within Subjects	(160)			
Approaches	4	508.33	2.82	<.05
Groups X Approaches	16	240.69	1.33	
Approaches X Subjects/Groups	140	180.49		
TOTAL	199			

Analyses of variance showed no significant differences among the groups with regard to the accuracy of glide slope tracking on the basis of any of the three criteria outlined above. Figure 5 shows the means of the maximum deviations and the single largest deviation by any subject within the respective groups during the ten successive segments of the approach. In the absence of significant differences among approaches, data for approaches #4 through #8 have been combined. Table 2 summarizes the analysis of variance for the same data. Not unexpectedly, there were significant increases (P=<.01) in maximum deviations as the middle marker was approached. This increase only becomes apparent during the last half of the approach. Essentially the same results are obtained if the direction as well as the magnitude of the deviations are included in the analysis. The algebraic means tend to average slightly below glide slope for most of the approach but above centerline during the last two segments preceding the middle marker.

Accuracy of *localizer* tracking performance was examined on the basis of the same three criteria used to evaluate glide slope tracking performance. The results for percent time on localizer are presented in Figure 6 and Table 3 which summarize the analysis of variance. Significant differences appear among the five groups, with the one using the conventional (visual only) display exhibiting consistently better performance than the other four groups. Interestingly, the groups utilizing the visual display in combination with the voice or code cues exhibited somewhat better *localizer* performance than those using only auditory glide slope information. Also, there was a statistically significant (P=<.05) improvement in performance as a function of the number of approaches flown. Although there was no significant interaction between groups and approaches, the improvement tended to occur more predominantly in the groups employing *auditory cues as their sole source of glide slope information.* Differences among the five groups were therefore less pronounced at the end of the experimental sequence than at the beginning.

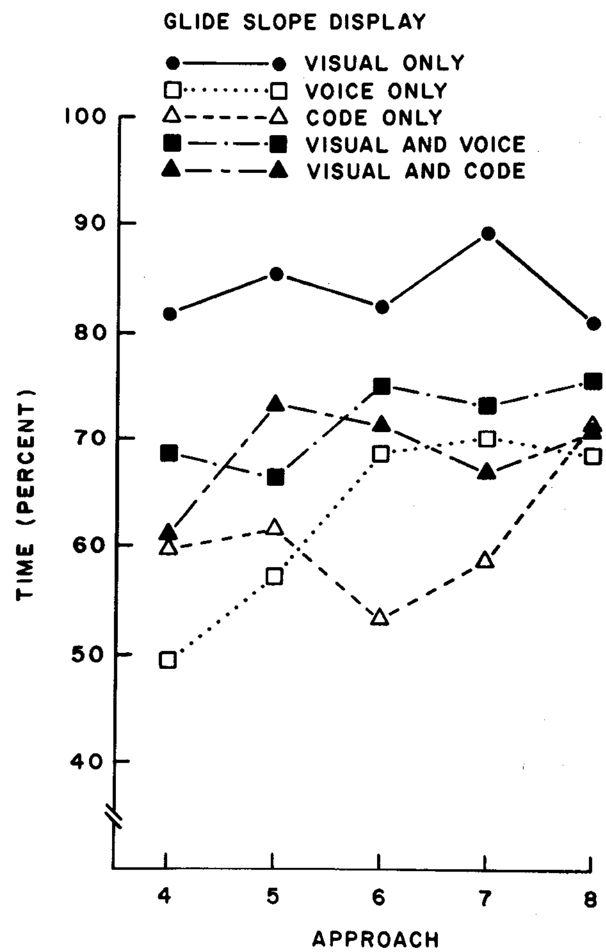

FIGURE 6. Time (percent) in which localizer deviation did not exceed one dot.

The weighted *localizer* deviation scores did not yield statistically significant differences among the five groups. However, there was a significant (P=<.025) improvement in performance as a function of the number of approaches flown. Again, this improvement tended to be concentrated in the groups using some form of auditory glide slope display but the interaction between groups and approaches was not significant.

The results for maximum localizer deviation within successive segments are presented in Figure 7 and the analysis of variance is summarized in Table 4. No significant differences appear among groups but there is a significant (P=<.05) improvement in localizer performance as a function of the number of approaches flown. As with glide slope performance, however, there was a significant (P=<.01) increase in maximum deviation from localizer centerline as the middle marker was approached.

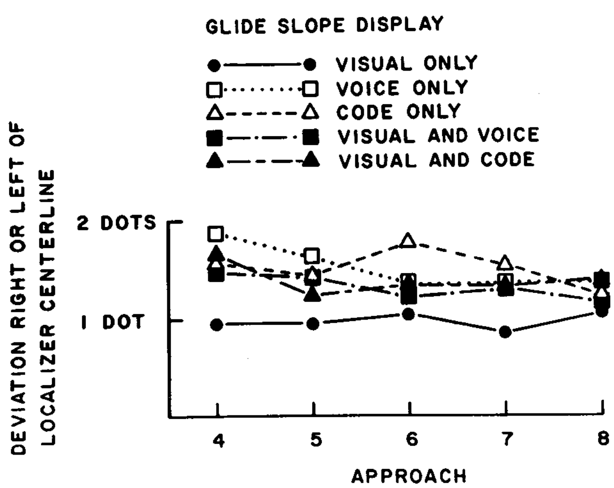

FIGURE 7. Means of maximum deviation right or left of localizer centerline, for all segments combined within groups.

Examination of magnitude of deviation from glide slope and localizer centerlines at time of aircraft passage over the middle marker shows no significant differences among groups or among approaches. However, if both magnitude and direction of glide slope deviation at the middle marker are analyzed we get the results shown in Figure 8. Analysis of variance of these data is summarized in Table 5. Significant differences (P=<.05) appear among groups. The algebraic means of the deviations from glide slope centerline indicate that the group using only *visual* glide slope cues tended to cross the middle marker slightly *below* glide slope. On the other hand, the group using the conventional display in conjunction with *voice* cues averaged one to two dots *above* glide slope on all five approaches.

Because the tracks flown by the aircraft frequently exhibited pronounced vertical oscillations near the middle marker, it was decided to compare the maximum limits of the total range of the oscillations during the last thirty seconds of the approach. The results are illustrated in Figure 9 in terms of an equivalent range of dots on the crosspointer instrument. Analysis of variance showed no significant differences among groups or among approaches.

TABLE 4.—Maximum Deviations From Localizer Within Successive Segments of Approach.

(Analysis of Variance)

Source of Variation	df	MS	F	P
Between Subjects	(39)			
Groups	4	1,907.91	2.36	
Subjects/Groups	35	806.81		
Within Subjects	(1,960)			
Segments	9	1,409.97	28.44	<.01
Segments X Groups	36	63.91	1.29	
Segments X Subjects/Groups	315	49.58		
Approaches	4	345.37	2.82	<.05
Approaches X Groups	16	164.79	1.34	
Approaches X Subjects/Groups	140	122.59		
Approaches X Segments	36	47.63	1.13	
Approaches X Segments X Groups	144	53.77	1.28	
Approaches X Segments X Subjects/Groups	1,260	42.17		
TOTAL	1,999			

Table 5.—Glide Slope Deviation at Middle Marker (Algebraic).

(Analysis of Variance)

Source of Variation	df	MS	F	P
Between Subjects	(39)			
Groups	4	1,614.57	2.97	<.05
Subjects/Groups	35	543.35		
Within Subjects	(160)			
Approaches	4	102.23	<1	
Groups X Approaches	16	234.05	<1	
Approaches X Subjects/Groups	140	241.20		
TOTAL	199			

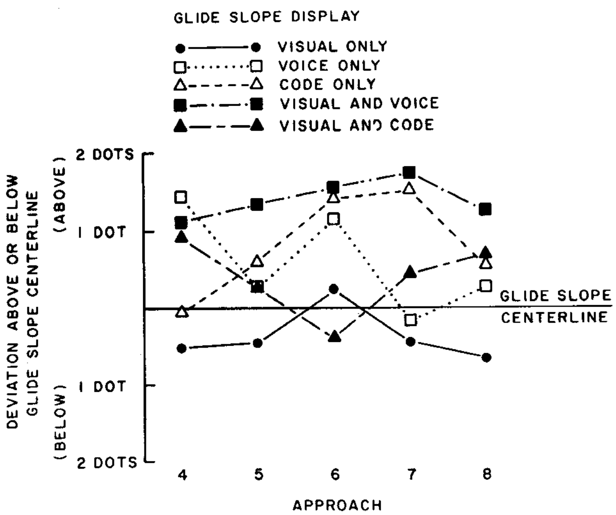

Figure 8. Mean glide slope deviation (algebraic) at middle marker.

It was originally thought that changes in bank angle might be useful as a performance measure. Unfortunately, the data as a whole did not lend itself to meaningful statistical treatment; large bank angle corrections were infrequent, while the almost constant but smaller turbulence-induced deviations made unreliable any effort to identify small pilot-induced bank angle corrections. It was also impossible to define or relate the effects of vertical acceleration on glide slope tracking performance and to variations in bank angle.

Heart rate data sampled from five 15-second segments spaced evenly along the approach (Figure 10) provided the results presented in Figure 11. The analysis of variance summarized in Table 6 shows that there were no significant differences among the five groups relative to heart rate and heart rate changes. However, there was a highly significant (P=<.001) *increase* in mean heart rate, as a function of progress from the outer marker to the middle marker, and a significant (P=<.001) *decrease* in mean heart rate across successive approaches.

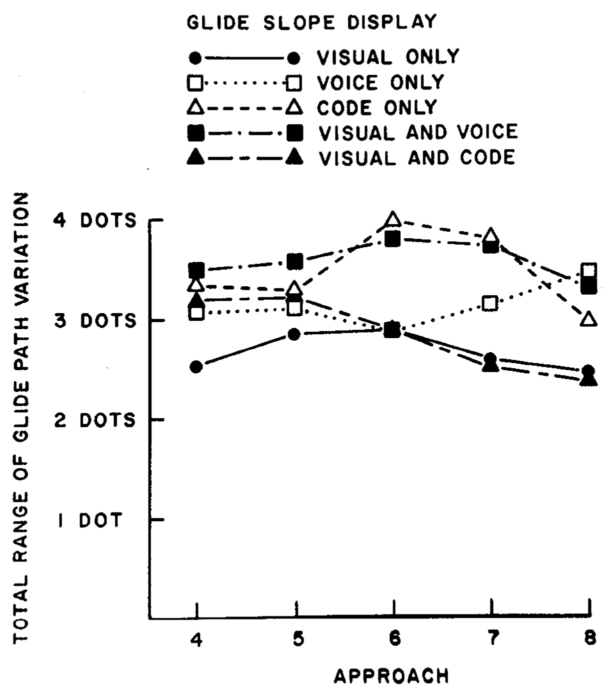

Figure 9. Means of total glide path variation during last 30 seconds of approach.

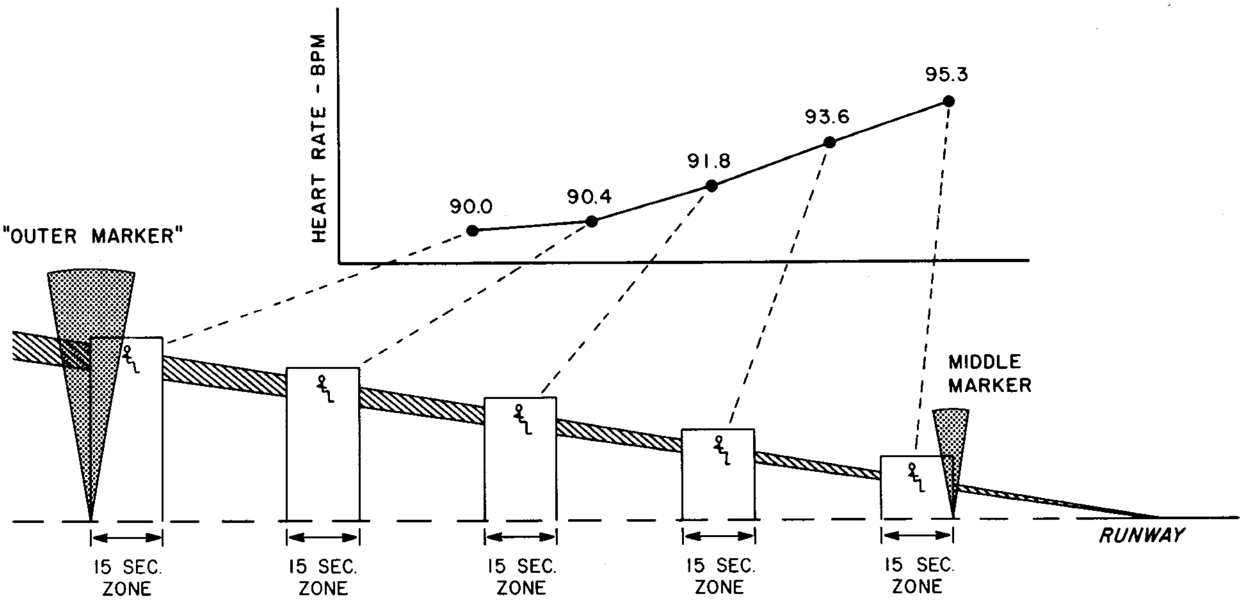

FIGURE 10. Heart rate data was collected continuously between outer and middle markers during approaches. Data used in this study were taken from five 15-second time zones spaced progressively to the middle marker.

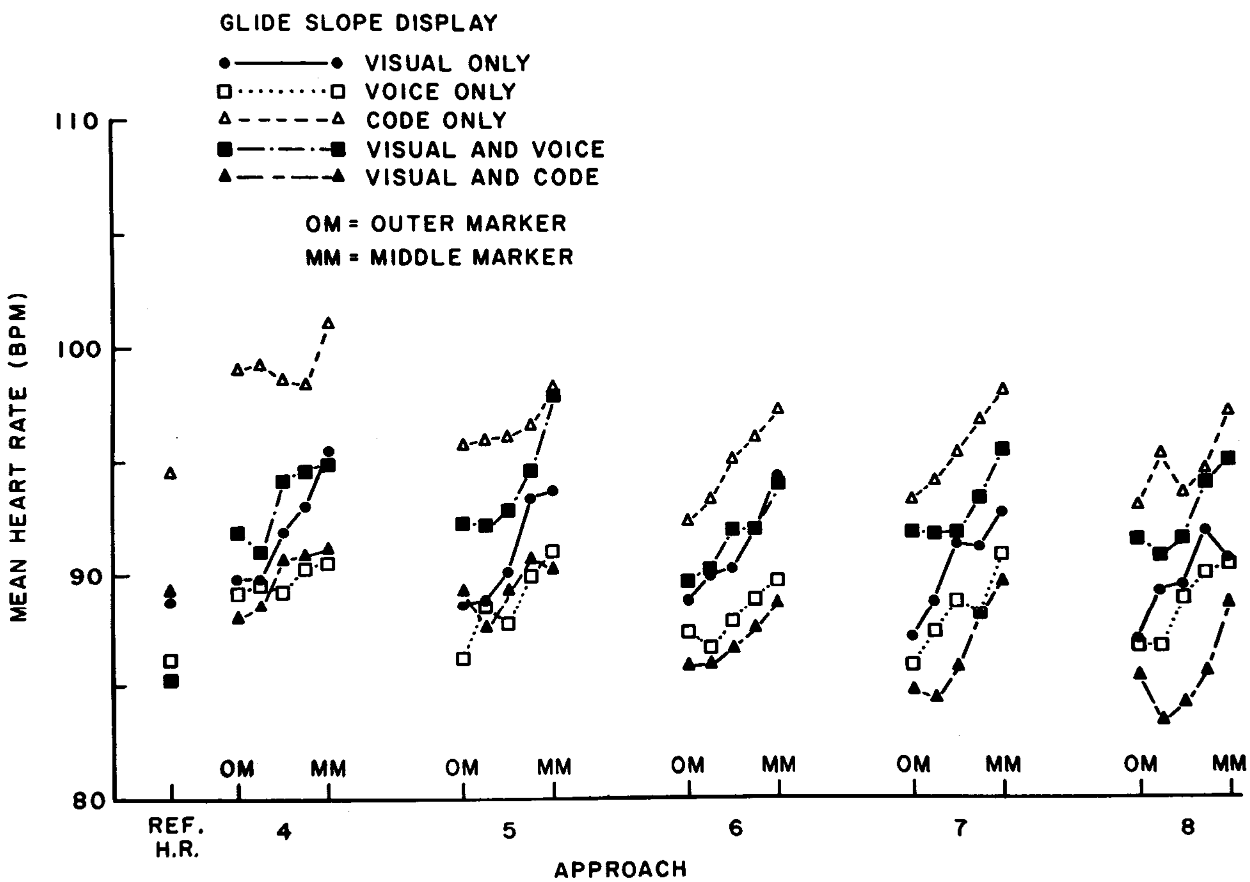

FIGURE 11. Mean heart rate during five 15-second time zones spaced along approach path from outer to middle marker.

TABLE 6.—Heart Rate During Five 15-Second Time Zones From Outer to Middle Marker.

(Analysis of Variance)

Source of Variation	df	MS	F	P
Between Subjects	(39)			
Groups	4	2,326.80	<1	
Subjects/Groups	35	4,545.05		
Within Subjects	(960)			
Approaches	4	247.23	8.28	<.001
Approaches X Groups	16	29.51	<1	
Approaches X Subjects/Groups	140	29.84		
Zones	4	506.97	28.96	<.001
Zones X Groups	16	8.24	<1	
Zones X Subjects/Groups	140	17.50		
Approaches X Zones	16	3.82	<1	
Groups X Approaches X Zones	64	5.86		
Approaches X Zones X Subjects/Groups	560	5.67		
TOTAL	999			

IV. Discussion.

This study has shown that auditory cues can be used as effectively as the conventional, visual, method for tracking the glide slope during an ILS approach. This is indicated by the fact that the tracking performance of all five groups was comparable, regardless of whether visual cues, auditory cues, or a combination of both were utilized.

Interestingly, although the conventional visual display and the experimental auditory displays proved equally effective by themselves, the availability of a combination of both types of displays did not result in improved performance. Of the several possible explanations for this lack of improvement, the most obvious possibilities are that the subjects relied primarily on only one of the two available displays, or that perhaps the audio was used only as an alerting cue while the conventional display was used for the tracking task. Another possibility is that the combination of two displays does not have an additive effect because the tracking information, although received through two different sensory channels, is essentially identical—providing no additional information to the pilot. This result would have been predicted by the "single channel" theory of attention. The present results suggest that the useful limits of the information are dictated more by the type, amount, and quality of the information, than by the sensory method of presentation.

It is also possible that the subjects were already performing at or near their individual performance capacities for the particular task of tracking the glide slope and localizer. This possibility is supported by several considerations. First, ancillary demands on the subjects were minimized in comparison to those required during an actual ILS approach under operational conditions; all subjects commenced their approaches from a "no-error baseline" on the centerline of the localizer and glide slope, and normal, but time consuming activities such as air traffic communications, navigation, and engine performance monitoring were completely eliminated—with primary emphasis placed solely on glide slope and localizer tracking. Second, the performance by all groups showed relatively few large tracking errors, and those that did occur were well distributed throughout the five groups.

If the performance of the five groups in this study is accepted as being representative of the best that can be obtained under *idealized* "raw data" instrument approach conditions, it appears that the difficulties encountered in "real life" situations (sometimes resulting in accidents) may be the result of a combination of complex task interactions that operate in such a way as to exceed the normal response capability of the pilot. A task that can be performed adequately, though perhaps not ideally, even under very favorable conditions, may well become too demanding when multiple task elements or emergency situations are added to a tracking task which already requires much of the pilot's total handling capacity.

Even under ideal conditions, such as in this study, tracking the glide slope centerline is a demanding task with a constantly changing control-display relationship and an ever increasing requirement for accuracy as the middle marker is approached. As shown in Figure 12, the horizontal glide slope needle moves vertically in reference to a "bull's-eye" and to a series of "dots" spaced vertically above and below the center of the instrument. The span of the bull's-eye is equal to a subtended angle of approximately 0.28 degrees, relative to the vertex of the angle at the point of intended touchdown (distance between the periphery of the bull's-eye and its center, and between each dot, is equal to a subtended angle of about 0.14 degrees). Since the distance between the top and bottom radii comprising this angle diminishes as the vertex is approached, it becomes evident that the vertical distance equivalent to a given "dot" displacement is a function of the distance between the aircraft and the vertex of the angle.

For example, the vertical envelope within which an aircraft must remain to keep the glide slope needle within the confines of the bull's-eye (2 dots) is about 167 feet at a point four miles from the middle marker (33,460 feet from the vertex), while at the middle marker (4,300 feet from the vertex) the same envelope comprises about 21½ feet. From this it can be seen that the task of keeping the glide slope needle within the center of the bull's-eye necessitates flying the aircraft within the constantly narrowing confines of an already narrow isosceles triangle. Therefore, the human performance requirements inherent in this tracking task constantly increase, in relation to (a) location of the aircraft at any given moment along the approach path; (b) response characteristics of the total aircraft-instrument system; and (c) velocity of the aircraft.

From this, it is also evident that for a given vertical displacement of the aircraft at a given forward velocity, both the *distance* and *rate* of

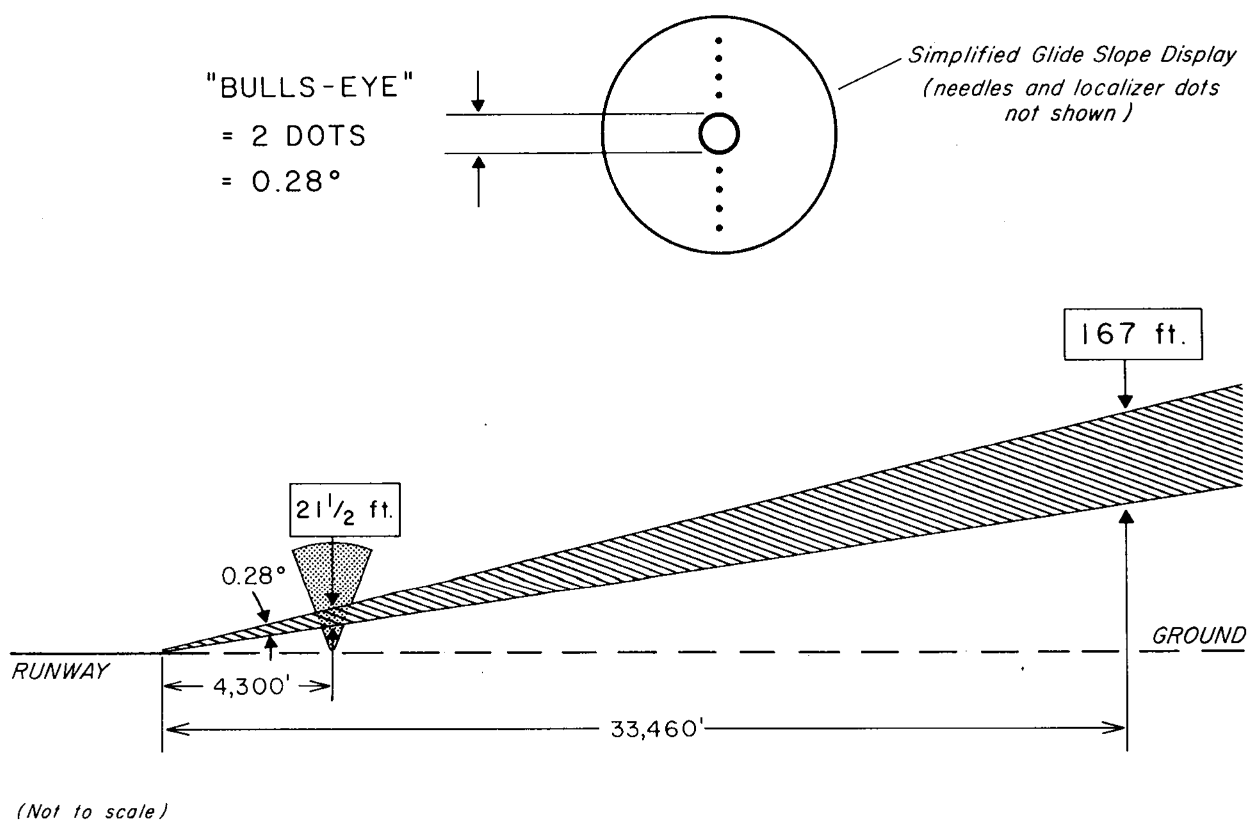

FIGURE 12. A two dot deviation, equal to a vertical displacement of the glide slope needle across the span of the crosspointer bull's eye, is equal to about 0.28 of subtended angle, resulting in a narrowing of the glide slope "beam" as the middle marker is approached.

movement of the glide slope needle across the face of the instrument will *increase* as the aircraft travels toward the middle marker. This means the pilot is faced not only with the necessity of constantly increasing the speed of his cognitive, intellectual, and reactive processes, but he must also cope with a constantly changing control-display ratio that requires *diminishing* amplitudes of control inputs to achieve a desired degree of corrective action. It is possible, of course, that this pacing stress may, under certain adverse circumstances, impair not only the quality of the pilot's tracking performance but also his performance of vital concomitant task elements.

The fact that the pilot's ability is taxed severely, even in the idealized approaches used in this study, is indicated by the comparatively large deviations from the glide slope path—often with rapid oscillations—during the last 20 to 60 seconds of the approach prior to reaching the middle marker. Apparently, if the pilot continues to utilize the display for tracking rather than as a trend indicator during this latter part of the approach, he tends to overcontrol the aircraft, intensifying the oscillatory motion. This, in turn, results in increased amounts of time being spent on correcting the ever enlarging deviation errors, causing the rapid development of what might be called a critical "out-of-phase" situation. Thus, the additive demands placed on the pilot's attention can result in selective detraction of time from and/or frequency of reference to, other vital instruments, as well as to other tasks associated with making a safe approach.

The results of this study also suggest that it may not be simply a matter of demand on *visual* time alone that leads to minimizing of attention to other instruments. The comparable performances of the groups using only *auditory* glide slope cues suggests that it may be a more fundamental problem of total information handling capability or perhaps, in the case of glide slope information inputs, it may be that the combination of changing magnitude and rate of cue input may exceed human ability to process the input information rapidly enough to assure a high degree of tracking accuracy during the last few critical seconds of the approach. Unfortunately, the present study could not determine how much visual time was "saved" by presentation of auditory glide slope cues since it was necessary for the subjects to continue to visually obtain localizer cues from the crosspointer instrument. It appears, however, that less visual time was devoted to this instrument during the aural cues approaches—since localizer performance initially deteriorated to some degree as attention was apparently shifted from visual glide slope information to that of auditory inputs. Although not statistically verifiable, there is also some indication that localizer information may be accepted by the pilot secondarily to glide slope information. If this is so, it would be helpful to know the ratio of deviation magnitudes required before localizer cues take precedence over glide slope cues. The fact that a gradual improvement in localizer performance took place as a function of the number of approaches flown (except for Group A using the conventional visual display) seems to indicate that the pilots "retrained" their scanning habits to acquire localizer information more for its own significance than as an incidental acquisition during the time they were using aural cues for glide slope information.

The small, but significant, difference found among the five groups relative to *direction of glide slope deviation* at the middle marker may be a spurious finding, since there was no comparable indication when the means for the approach segments were analyzed. A trend seems to appear in Figure 5 but analysis of the data proved it to be not significant. One possible explanation is that the subjects failed to allow for parallax effect between the glide slope needle and the instrument index markings. Parallax, in this instance, could easily range between one half and one "dot" depending on the position of the pilot's eyes in relation to the instrument. Lack of compensation for such parallax would, in effect, cause the pilot to fly his aircraft slightly below glide slope. On the other hand, absence of parallax with the auditory display would result in the aircraft being flown relatively higher. The parallax effect, if indeed present, is not so pronounced during the early part of the approach and is too inconsistent to be proven statistically significant by the measures employed in this study.

Absence of significant differences among the five groups with regard to heart rate and heart rate changes suggests there was little difference in stress among the groups. The spread of absolute heart rate values indicated in Figure 11 is not statistically significant and the differences between the reference "resting" values and those during the approaches are relatively small. Interestingly, the largest differences between heart rate reference values (established during level flight) and the mean rates during approaches was evidenced by Group D which used the combined visual and aural/voice display. The mean heart rates for the other groups tended to be at or very near the reference values—with the possible exception of the combined visual and aural/code group (E) whose mean rates declined below the reference rate on the last three of the five experimental approaches.

Both the increase in heart rate during the approaches and the decline in absolute heart rate on successive approaches were highly significant ($P = < .001$). The heart rate data for the five groups also confirm the data in an earlier report[3] which discusses the stress implications of increased heart rate during ILS approaches. It also suggests that regardless of the type of display cue, or the sensory channels used, the ILS tracking task—as presently structured—may approach, and sometimes exceed the desired response capability of the "average" instrument pilot.

As discussed earlier, because of the dynamics of the ILS system, the pilot must constantly increase his response rate—with concomitant decreases in amplitude of control input—to keep the aircraft on the centerline of the glide slope/localizer "beam" as he approaches the middle marker. In developing this study, it was thought that the use of aural glide slope cues—repeated at frequent intervals—might enhance the pilot's processing capacity, and thereby improve his glide slope tracking performance. It was also thought that the aural cues would lessen the pilot's visual work load, giving him more time to reference other instruments and thus improve his overall flight performance. Although these expectations were not fulfilled, several facts and suggestive indications emerged which may have important bearing on future studies as well as on display design.

First, the "A" and "N" Morse code signals can be misinterpreted, resulting in a delay in finally applying correct control inputs.

Second, *little or no specific practice was required for effective use of the voice cue display.* Tracking performance on the first approach, using the voice cues, was usually comparable to the performance levels on those approaches in which the visual display was utilized—despite many hours of previous experience with the conventional (visual) system.

Third, in combination with the conventional visual display, *the voice display can serve as an effective aural warning of excessive deviation below glide slope*—regardless of where the pilot may be looking.

Fourth, combined with the flight director system in more sophisticated aircraft, and deriving its input signals from the "raw data" stage of the aircraft glide slope receiver, the voice display can serve as a warning of excessive deviation should an undetected malfunction occur "down stream" in the computer section of the aircraft flight director display system.

Fifth, though not statistically verified because of limitations in the statistical design of this study, there is a rather strong indication that aural cues may serve to reduce the variability in glide slope tracking performance from one approach to the next by the same subject. This effect was particularly apparent among those subjects who did not exhibit a high degree of initial proficiency. Such an increase in predictability of performance could have important safety implications, even in the absence of any overall improvement in mean performance level.

To determine if ATC communications would interfere with effective use of the aural glide slope cues, and vice versa, approaches were made, using other pilots. Based on their comments and our subjective evaluation of their performance, it appears that pilots should have no difficulty in effectively carrying on two-way communications while using aural (voice) glide slope cues. This may be because of the nature of the cues; only recognition of the words "low" or "high" is important to performance of the tracking task.

Finally, in reviewing the results of this study, it is apparent that although the subjects' performance was related to what they saw on the crosspointer indicator and/or heard from the audio display, an equally important performance factor was the pacing, or speed, of presentation of cues—governed by the speed of the aircraft and by the dynamics of the glide slope/localizer transmitting system.

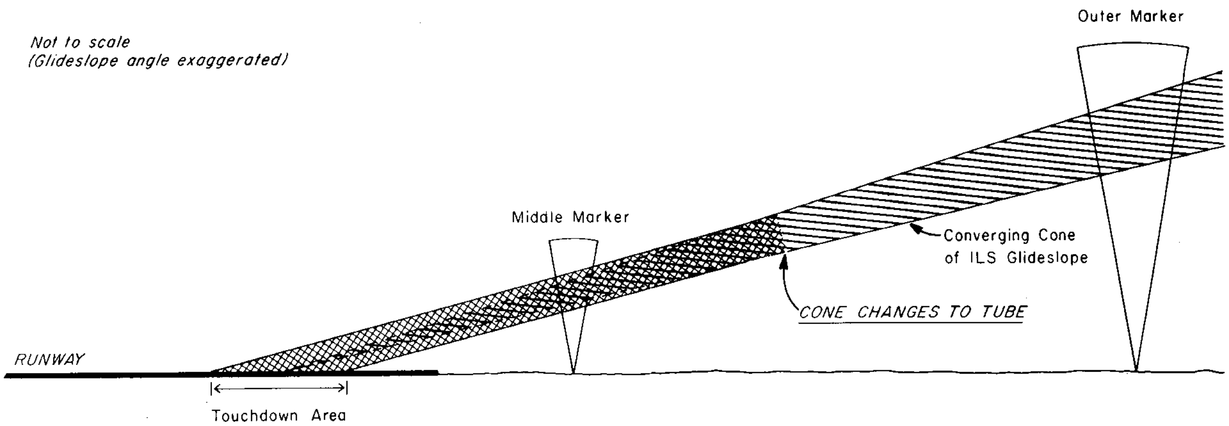

FIGURE 13. Man's response characteristics might be more compatible with display interface if rate and magnitude of needle movement were a function of a tubular, rather than a conical, ILS glide slope "beam".

Perhaps the total system would be more compatible with human response characteristics if the rate and magnitude of aural cue and/or of needle movement were a function of a tubular rather than a conical, ILS glide slope "beam" (Figure 13). The tubular concept would provide a constant, rather than a varying, ratio between needle movement and linear deviation from the glide slope and localizer centerline. Although such a design concept would provide more leeway for deviation during later stages of the approach, it is possible that over-response of the pilot would be minimized, with a concurrent reduction in tracking errors. This, in turn, might produce more accurate and more uniform performance.

V. Summary and Conclusions.

This study has demonstrated that instrument rated pilots can effectively utilize aural glide slope cues in lieu of, or in combination with, a conventional visual display for tracking the glide slope path during an ILS approach. No significant differences were found in accuracy of glide slope tracking among groups using the five different display modes consisting of visual and aural cues (voice or code) or a combination of both. Some small differences were found relative to the direction of glide slope deviation at the middle marker but they were of little practical significance.

Initial use of aural glide slope cues resulted in minor deterioration of *localizer* performance but performance improved with trials. Also, there was some indication that additional trials, beyond the ones flown in this study, might have resulted in localizer performance comparable to that with the conventional display.

Effective use of aural-voice-glide slope cues required little training or practice; their use in combination with conventional and flight director visual displays could warn a pilot of excessive deviation below the glide slope. The data, by interpretation, also suggest that any tracking difficulties experienced by pilots attempting to make a precise ILS approach are primarily related to the information processing limitation of the human, which is in turn governed by the dynamics of the glide slope and localizer system. Also, loss of precise tracking capability—at the middle marker and under the ideal conditions existing in this study—suggests that if operational variables requiring additional mental attention are added to the pilot's tracking task, his ability to cope effectively with the total task may be reduced.

In essence, the results of this study suggest the need for a fundamental analysis of the total man-machine approach system, for without this first step it will be difficult, if not impossible, to design a system which is basically compatible with the cognitive, intellectual and reactive characteristics of man.

REFERENCES

1. Forbes, T. W., W. R. Garner, and J. G. Howard: Flying by Auditory Reference ("Flybar"), OSRD Report No. 5123, 1 June 1945.
2. Fox, J. G., I. Ferguson, and I. D. C. Andrews: An Annotated Bibliography of Presentation of Information in Aircraft Cockpits, S & T Memo 3/66, p. 77–78. Technical Information and Library Services, Ministry of Aviation, May 1966. (Available as AD 634575).
3. Hasbrook, A. H., and P. G. Rasmussen: Pilot Heart Rate During In-Flight Simulated Instrument Approaches in a General Aviation Aircraft. FAA Office of Aviation Medicine Report No. AM 70–7, 1970.
4. Hodgson, D. A.: Preliminary Studies of Auditory Flight Control Displays. The Boeing Company Airplane Division Report No. D6–57104, June 1966.
5. Kirchner, O. E.: Critical Factors in Approach and Landing Accidents, (Part 1—Statistics). Project Report, Flight Safety Foundation, Inc., December 31, 1960.
6. Milton, J. L., R. E. Jones, and P. M. Fitts: Eye Fixations of Aircraft Pilots: Frequency, Duration, and Sequence Fixations When Flying the U.S.A.F. Instrument Low Approach System (ILAS), USAF Tech. Report No. 5839, October 1949.
7. Taylor, V. A.: Critical Factors in Approach to Landing Accidents 1959–1963. Interim Report, SAE-ASME Report No. 854C, April 1964.
8. Weir, D. H. and R. H. Klein: The Measurement and Analysis of Pilot Scanning and Control Behavior During Simulated Instrument Approaches, NASA Contrator Report NASA CR–1535, June 1970.

APPENDIX

Preface to Appendix Tables

The following tables summarize the glide slope data for each experimental group during each approach, including the pre- and post-experimental approaches. Values are the percent times spent in the respective deviation ranges by each group on each approach between the outer and middle marker.

EQUIV. RANGES OF GLIDE SLOPE DEVIATION / APPROACH # AND GLIDE SLOPE DISPLAY MODE		# 1 VISUAL ONLY	# 2 VISUAL ONLY	# 3 VISUAL ONLY	# 4 VISUAL ONLY	# 5 VISUAL ONLY	# 6 VISUAL ONLY	# 7 VISUAL ONLY	# 8 VISUAL ONLY	# 9 VISUAL ONLY	# 10 VISUAL ONLY
BELOW GLIDE SLOPE	OFF INDICATOR SCALE										
BELOW GLIDE SLOPE				1.4							
BELOW GLIDE SLOPE				2.5							0.3
BELOW GLIDE SLOPE		3.7	1.6	2.2	1.2	0.9	3.0	1.8	1.5	3.0	1.0
BELOW GLIDE SLOPE		24.1	25.8	14.4	15.9	23.8	9.9	13.0	15.0	19.3	22.1
ON G.S.		37.3	38.2	53.3	46.7	53.6	52.4	51.5	49.1	52.8	54.9
ON G.S.		23.9	30.2	22.5	20.7	18.6	28.0	26.2	25.1	21.7	18.2
ABOVE GLIDE SLOPE		6.7	3.3	3.0	13.4	2.1	5.9	3.5	6.2	1.5	2.8
ABOVE GLIDE SLOPE		2.1	0.9	0.3	2.1	0.9	0.5	3.6	2.8	1.0	0.7
ABOVE GLIDE SLOPE		1.0		0.1		0.2	0.1	0.5	0.3	0.5	
ABOVE GLIDE SLOPE		0.8		0.3			0.3			0.1	
ABOVE GLIDE SLOPE	OFF INDICATOR SCALE	0.3									

TABLE I. Group "A" data. Only crosspointer indicator was used for glide slope information during experimental approaches (Control Group).

Equiv. ranges of glide slope deviation / Approach # and glide slope display mode		# 1 Visual only	# 2 Visual only	# 3 Visual and voice	# 4 Voice only	# 5 Voice only	# 6 Voice only	# 7 Voice only	# 8 Voice only	# 9 Visual and voice	# 10 Visual only
Below glide slope	Off indicator scale										
Below glide slope				0.5	1.9						
Below glide slope		0.9		2.6	2.3			0.9	0.5		0.3
Below glide slope		4.2	6.0	3.2	3.3	1.3	1.9	5.1	4.9	0.3	0.4
Below glide slope		25.1	21.4	18.9	12.5	12.2	13.4	17.7	13.0	14.1	13.9
On G.S.		30.0	41.0	34.9	37.8	41.9	40.1	38.0	38.7	48.5	39.1
On G.S.		17.1	26.7	28.6	31.1	36.4	29.3	31.1	33.4	32.8	38.0
Above glide slope		7.6	3.7	8.8	8.6	5.4	13.2	6.2	6.6	4.3	5.6
Above glide slope		4.7	0.7	2.5	1.1	2.1	2.1	1.0	1.3		2.0
Above glide slope		8.0	0.5		1.1	0.7			1.5		0.8
Above glide slope		2.5			0.6						
Above glide slope	Off indicator scale										

TABLE II. Group "B" data. Voice cues and on-course tone were used for glide slope information during experimental approaches.

Equiv. ranges of glide slope deviation \ Approach # and glide slope display mode		#1 Visual Only	#2 Visual Only	#3 Visual and Code	#4 Code Only	#5 Code Only	#6 Code Only	#7 Code Only	#8 Code Only	#9 Visual and Code	#10 Visual Only
BELOW GLIDE SLOPE	OFF INDICATOR SCALE										
			0.2		0.2						0.3
		1.9	2.8	1.8	1.6	1.0	1.1	2.4	0.2	2.0	6.3
		22.9	10.0	9.9	8.2	9.8	12.4	12.0	10.5	8.4	13.1
ON G.S.		24.4	38.5	39.1	39.4	44.6	36.9	39.6	41.8	41.7	34.1
		19.3	26.3	32.0	40.9	30.5	38.7	32.5	33.7	37.6	25.6
ABOVE GLIDE SLOPE		14.9	16.4	11.4	4.7	4.7	7.6	9.9	9.4	7.6	15.7
		7.4	5.3	4.0	3.1	6.7	1.8	2.2	1.5	1.1	1.7
		5.6	0.3	1.8	1.0	2.4	0.9	0.2	1.1	1.2	2.5
		3.5	0.2		0.9	0.3	0.6	0.5	1.8	0.4	0.7
	OFF INDICATOR SCALE	0.1						0.7			

TABLE III. Group "C" data. Code signals and on-course tone were used for glide slope information during experimental approaches.

Equiv. ranges of glide slope deviation		Approach # and glide slope display mode: #1 Visual only	#2 Visual only	#3 Voice only	#4 Visual and voice	#5 Visual and voice	#6 Visual and voice	#7 Visual and voice	#8 Visual and voice	#9 Voice only	#10 Visual only
Below glide slope	Off indicator scale										
Below glide slope											
Below glide slope		0.4		0.6							
Below glide slope		1.4	4.9	1.7			1.1	1.0	1.7	1.9	1.4
Below glide slope		10.3	18.6	5.7	7.1	6.9	10.5	9.8	12.2	14.6	15.3
On G.S.		38.1	29.1	38.8	40.2	43.3	45.8	39.8	53.0	50.6	45.9
On G.S.		28.1	30.4	39.6	38.1	35.9	33.9	39.6	21.5	28.3	23.1
Above glide slope		16.9	13.1	9.4	11.8	9.5	5.0	7.0	7.6	3.6	8.4
Above glide slope		4.7	2.8	1.6	1.4	3.1	2.6	2.3	2.6	0.7	3.6
Above glide slope		0.2	1.0	0.9	1.0	0.7	0.5	0.3	0.6	0.4	1.8
Above glide slope				0.5	0.4	0.5	0.5	0.1	0.8		0.4
Above glide slope	Off indicator scale			1.2							

TABLE IV. Group "D" data. Voice cues and on-course tone were used in combination with crosspointer indicator for glide slope information during experimental approaches.

Equiv. ranges of glide slope deviation \ Approach # and glide slope display mode		# 1 Visual only	# 2 Visual only	# 3 Code only	# 4 Visual and code	# 5 Visual and code	# 6 Visual and code	# 7 Visual and code	# 8 Visual and code	# 9 Code only	# 10 Visual only
Below glide slope	Off indicator scale										
Below glide slope	●			2.0			0.3				
Below glide slope	●		0.7	2.5		0.9	0.6		2.2		0.1
Below glide slope	●	5.0	7.9	1.5	0.1	2.3	2.0	1.1	3.4	1.4	2.5
Below glide slope	●	18.1	18.8	13.0	11.8	13.0	17.6	8.3	15.0	4.3	18.3
On G.S.		33.7	33.9	42.3	46.5	48.1	55.7	53.9	50.2	50.5	45.1
On G.S.		28.8	28.2	23.0	27.8	24.2	20.0	30.2	22.8	30.8	27.7
Above glide slope	●	12.1	9.0	12.3	8.5	8.1	3.3	6.2	5.1	8.6	6.1
Above glide slope	●	1.8	1.5	3.0	4.4	3.2	0.5	0.3	1.0	1.8	0.2
Above glide slope	●	0.5		0.2	0.9	0.2			0.3	1.0	
Above glide slope	●			0.2						0.9	
Above glide slope	Off indicator scale									0.7	

TABLE V. Group "E" data. Code signals and on-course tone were used in combination with crosspointer indicator for glide slope information during experimental approaches.