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16. Abstract

Instrument panels in many general aviation aircraft are becoming increasingly crowded, presenting the pilot with an instrument scanning problem. Because most aircraft instruments require use of central (foveal) vision, the pilot must look directly at each instrument to obtain needed information, taking time that may not be available during an instrument approach to published minimums. It was thought that the problems of adequate scanning of the instruments might be alleviated by reducing and changing the size of certain instruments and utilizing the pilot's peripheral vision. An in-flight study of pilot performance was conducted while using an experimental instrument display. The display was used in flight by low-time and high-time professional pilots. The major findings of this study indicate that pilot performance with the high-contrast instrument display, which employs a vertical and horizontal format and occupies substantially less space than conventional instruments, is equal to pilot performance with conventional instruments, in spite of little familiarization time and without regard to pilot experience. No difference in stress (as measured by heart rate) was evident between the experimental and conventional displays. Subjective reaction of the pilot-subjects to the new type display was favorable. Panel space requirements can be reduced by at least 25 percent by use of the design concepts outlined in this study.

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PILOT PERFORMANCE AND HEART RATE DURING IN-FLIGHT USE OF A COMPACT INSTRUMENT DISPLAY

I. Introduction.

The complexity and number of instruments placed in instrument panels present a considerable problem to pilots in scanning these instruments in increasingly complicated flight situations. Instrument landing approaches are particularly vulnerable to delays in pilot response because of the relatively low altitudes and the minimal time available for decision making. During an instrument landing system (ILS) approach, for example, the average general aviation jet aircraft is only 15 to 20 seconds from the runway threshold when the pilot "breaks out" under a 200-foot ceiling at the middle marker. With an approach speed of about 200 feet per second, the pilot who spends 1 or 2 seconds reading each instrument has little time or altitude to correct errors that may have developed during the approach.

Generally, pilots handle the exacting requirements of an instrument approach extremely well; however, there have been enough approach and landing accidents to suggest that instrument panel design should be reevaluated with a view toward simplifying flight-data displays.

Most aircraft instruments require the use of central (foveal) vision for acquisition of precise information. The angular range of central vision is limited to less than one-half degree of subtended angle.[1] Beyond this angle, visual acuity diminishes rapidly; at 40° to the side, acuity is reduced by about 95 percent. Thus, the pilot's reading (foveal) vision covers an area of about 1 square inch at a distance of 28 inches —the average distance between the pilot's eyes and his instrument panel. Because of this ocular limitation, the pilot must look directly at each instrument to obtain needed information.

Milton, Jones, and Fitts[2] measured eye movements of pilots during instrument approaches and found that the time of visual fixation on an instrument varied from 0.86 second to 0.34 second, depending on the information required. Interestingly, 41 percent of the pilot's visual fixation time (including transfer of his gaze from some other fixation point) was spent on the ILS cross-pointer while only 15 percent was devoted to the attitude indicator, 25 percent to the heading indicator, 10 percent to the airspeed indicator, and only 2 percent each to the altimeter and vertical speed indicator.

The reasons for these differences in fixation time are unknown; it is possible that difficulty in interpreting the readings of the instruments may be a factor, or perhaps the priority assigned to instruments for a given phase of flight is responsible. However, this latter possibility does not equate well with the little time (2 percent) given to the altimeter during flight near the ground in the latter part of an instrument approach.

Obviously, time for scanning the instrument panel is an important factor during an instrument approach. Also, additional equipment increases the area and number of indicators to be scanned. Accordingly, it was thought that reducing the size of certain instruments, changing their shapes, making them more readable, and utilizing the pilot's peripheral as well as his central vision for acquisition of information[3] would alleviate these problems, and that compressing these instruments into a small area would also reduce the time needed to scan the instruments.

A review of past efforts in the field of instrument design brings out some interesting information. One document, "A History of Aircraft Cockpit Instrumentation, 1903–1946" by Douglas

R. Nicklas,[4] bears special mention. This vividly interesting documentation of aircraft instrument development contains a bibliography of 384 papers, articles, and reports. Nicklas states: "In a series of tests covering the period 1903–1906, the Wright brothers employed a Richard anemometer, not primarily to determine airspeed as in later years, but to measure the length of their flights. For a number of years to come, most pilots depended on the force of the wind in their faces to determine airspeed." He also states that the first real instrument in an aircraft is reported to have been an oil pressure gauge, to warn against impending engine malfunction.

Although most early instruments were round faced, some instruments with vertical scales were tried as early as 1923 in a DeHavilland P–302 airplane. Because of insufficient length of the fixed scales, they were soon abandoned.

In the late 1920's Lt. James H. Doolittle, supported by the Guggenheim Fund, endeavored to simplify the instrument panel by having the pointers of the round-faced directional indicators form a vertical line when the aircraft was flying straight and level and all pointers affected by pitch form a horizontal line in normal flight attitude. Doolittle's main objective was simplification. He sought to relieve the pilot of all unnecessary interpretations.

At the end of his report, Nicklas points out that during the years covered by his study, too little time had been spent exploring integration of the variables in the cockpit, and he suggests that even a modest effort in this direction would be well worthwhile.

It was felt that a new instrument display, designed to reduce the time needed for instrument scan by utilizing the pilot's peripheral vision, would enhance safety by reducing the potential for work overload. The effect of such a display should be to decrease the pilot's anxiety during an instrument approach. This lowered anxiety should cause a reduction of sympathetic excitation, which in turn should be directly reflected in the pilot's heart rate. The heart rate, in this sense, is used as an indicator of short-term stress and should contribute insight into a pilot's perception of the progress of an instrument approach. A study was therefore designed to measure, quantitatively, pilot performance and heart rate during ILS approaches made under two conditions: (1) with a conventional instrument display and (2) with a new peripheral vision flight display (PVFD) panel, which was first conceived by Hasbrook in the late 1960's.

II. Methodology.

The experimental PVFD panel was designed to provide early visual indications of changes from desired values of certain flight parameters. These parameters were airspeed, vertical speed, glidepath and localizer deviation, heading, and altitude.

High contrast is important for seeing changes in the relative positions of objects, particularly those in the peripheral visual field; therefore, large moving black pointers and aircraft symbols were used against large white backgrounds. It is of interest that many early aircraft instruments also had white dials with black numerals and pointers.[3] This contrast scheme was reversed when fluorescent paint was introduced to help pilots see the instruments during night flight.

Since control of the aircraft's pitch and roll attitude is obtained primarily by reference to the attitude indicator, this instrument was made the focal point of the panel (A, Figure 1); it was placed directly in front of the pilot and as high on the panel as practicable. The airspeed, glidepath, and vertical speed indicators were placed on either side of the attitude indicator so that pitch changes would produce vertical movement of the pointers in these instruments. The localizer and heading indicators were placed immediately below the attitude indicator so that lateral flight deviations would be shown by lateral movement of the pointers.

The airspeed indicator (B, Figure 1) was made in a vertical format with a movable tape so that the pilot could manually place the desired airspeed at the midpoint of the instrument scale; the moving pointer responded to changes in aircraft velocity and moved upward to indicate reduced airspeed and downward for increased airspeed. When the black pointer was at the midpoint of the instrument, the pilot was assured of being at the selected airspeed without the necessity of reading the numerals on the instru-

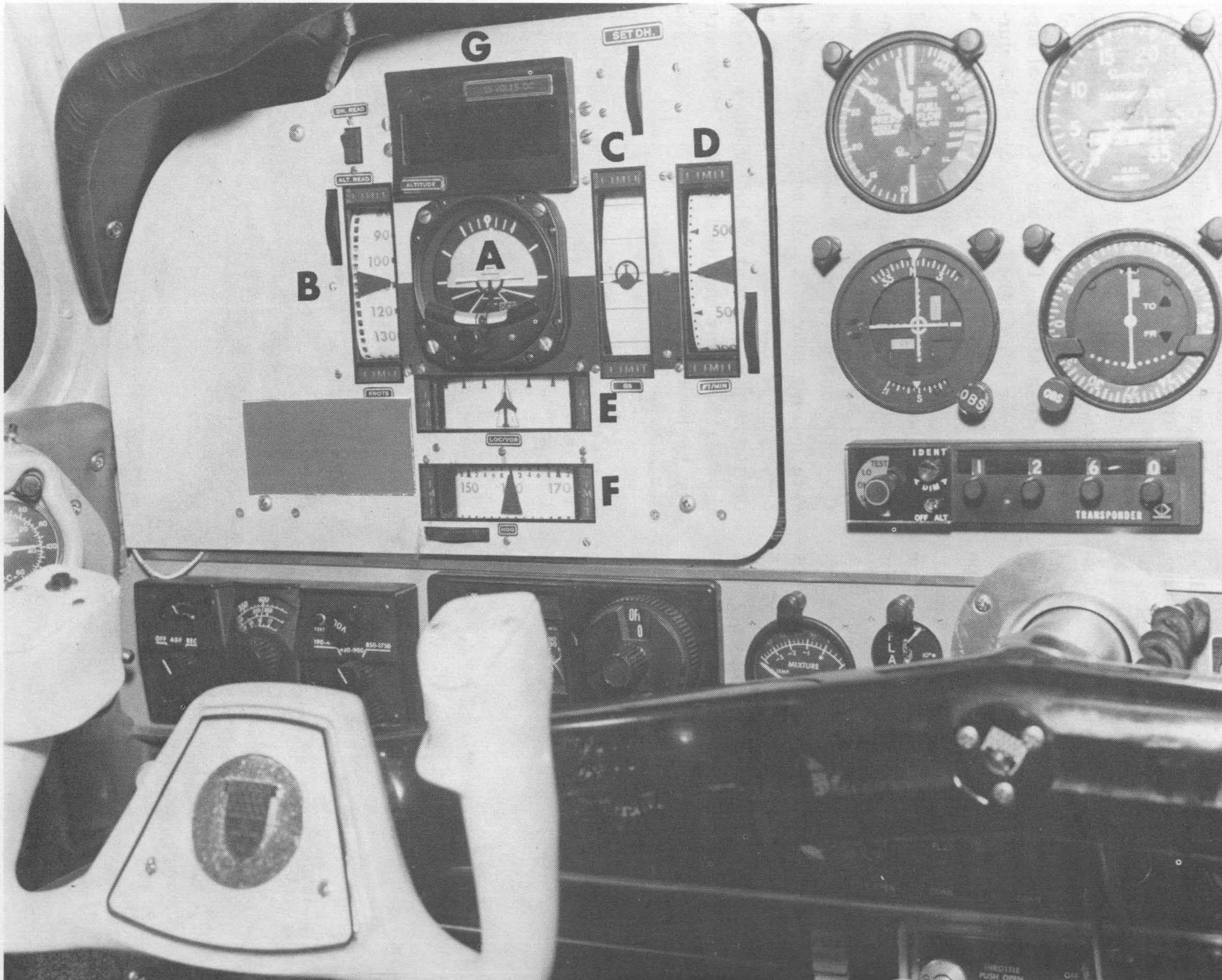

FIGURE 1. Peripheral vision flight display (PVFD), installed in Beechcraft Bonanza 35A, used to measure pilot performance during ILS approaches. A—Attitude Indicator, B—Airspeed Indicator, C—Glidepath Indicator, D—Vertical Speed Indicator, E—Localizer Indicator, F—Heading Indicator, and G—Altimeter.

ment tape. Pointer position rather than numerical readout provided the pilot with airspeed information.

The glidepath indicator (C, Figure 1) was also arranged vertically, with a fixed red "bull's-eye" depicting the centerline of the glide slope portion of the ILS. The instrument, located to the right of the attitude indicator, utilized a black two-dimensional symbol of an aircraft as seen from the rear. This aircraft symbol moved upward when the real aircraft went above the glide slope centerline and moved downward when the real aircraft went below the glide slope centerline.

The instantaneous vertical speed indicator (IVSI) (D, Figure 1) was located to the right of the glide slope indicator. It was also in a vertical format with a movable tape and moving black pointer that permitted the pilot to set the desired vertical speed at the midpoint of the instrument. The pointer moved upward for decreased vertical speed and downward for increased vertical speed.

Total horizontal distance across the four instruments (airspeed, attitude, glidepath, and vertical speed) was 8.10 inches.

The horizontally shaped localizer indicator (E, Figure 1), which also could be used as an omnibearing indicator (OBI) for VOR navigation, was located immediately below the attitude indicator. It was equipped with a fixed localizer (or VOR radial) centerline, depicted as a narrow-based triangle, and a moving aircraft symbol as seen from above. Deviation of the real aircraft to the left of the localizer centerline during a front-course ILS approach produced a leftward movement of the aircraft symbol.

The heading indicator (F, Figure 1), placed immediately below the localizer instrument, consisted of a horizontal case with a lubber line in the center and a moving, servoed tape imprinted with heading numerals. An adjustable moving black pointer indicated deviation away from a desired heading preset at the lubber line and also showed which way the pilot should turn to correct his heading.

FIGURE 2. Beechcraft Bonanza 35A used in peripheral vision flight display study.

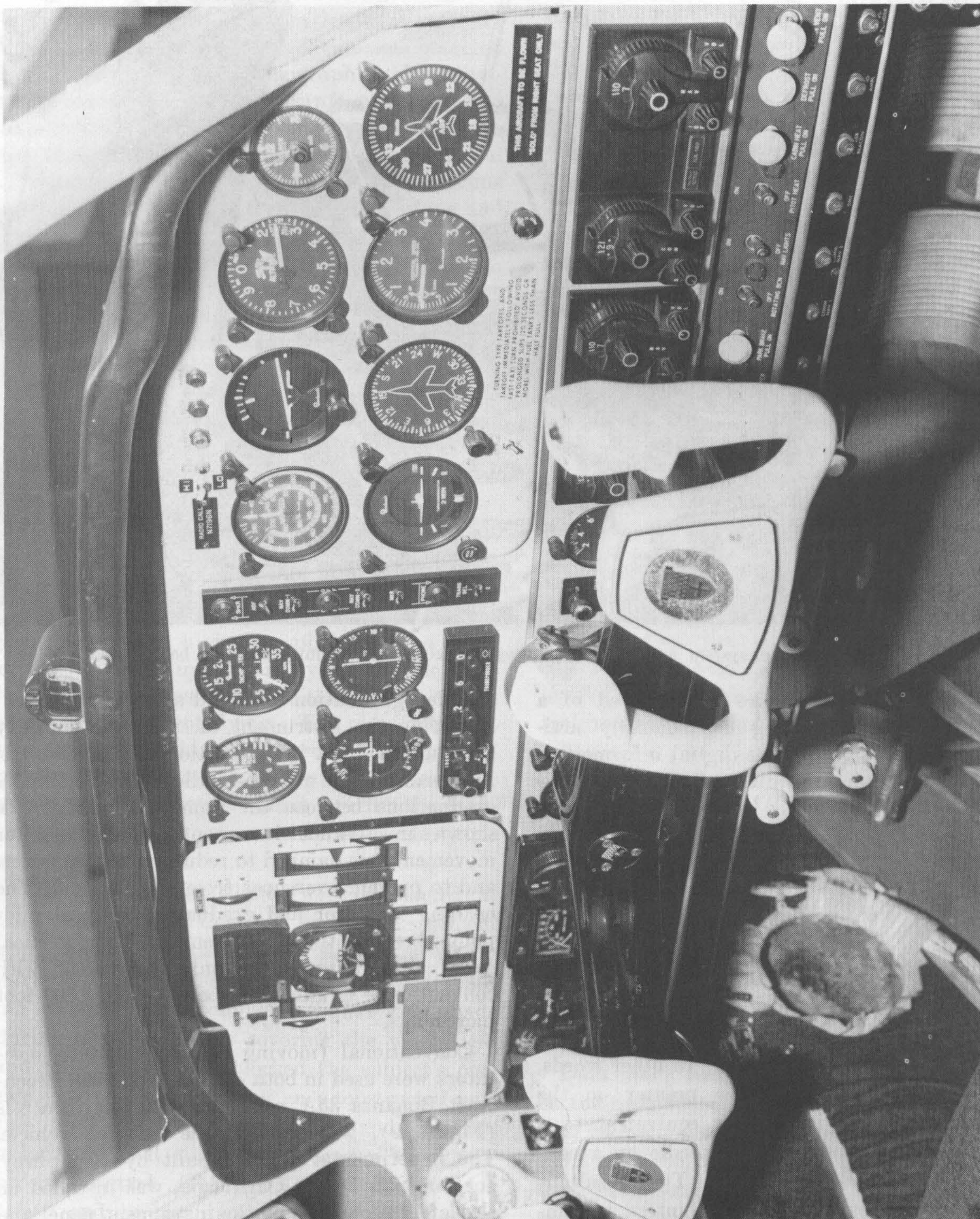

FIGURE 3. Comparison of areas occupied by peripheral vision flight display (left) and conventional panel (right).

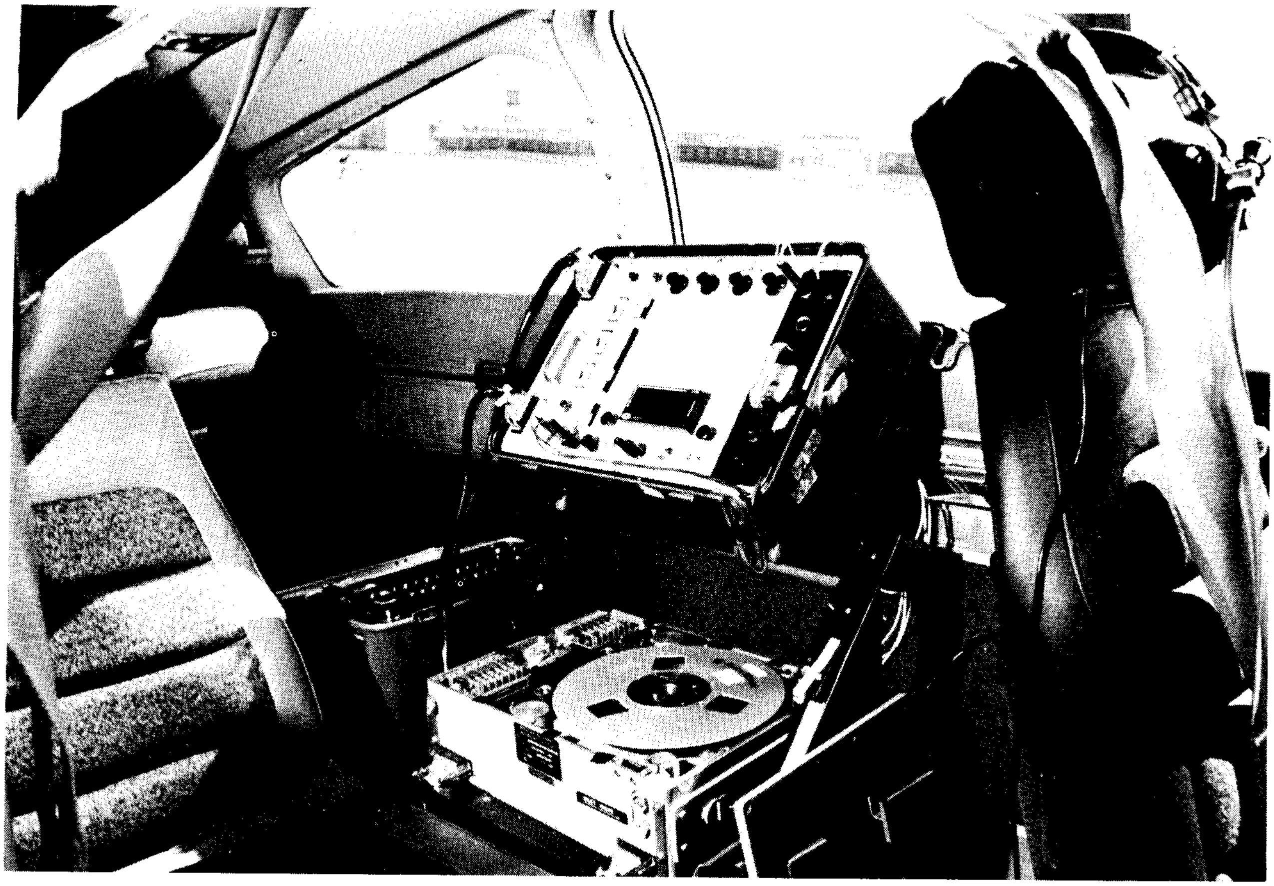

FIGURE 4. Data acquisition system and signal sampling and conditioning units installed behind pilot's seat.

The altimeter (G, Figure 1) consisted of a horizontal case containing electronically activated Nixie tubes to provide digital information. The instrument, located directly above the attitude indicator, was placed so that the altimeter would be in the pilot's line of sight as he looked for the runway after breaking out below clouds. The vertical distance from the top of the altimeter to the bottom of the heading indicator was 8 inches.

With the exception of the vertical speed indicator, the rate of movement (sensitivity) of the pointers and symbols was twice that of most conventional flight instruments. In other words, a half-inch movement of the pointer on the PVFD airspeed indicator was equivalent to a quarter-inch movement of the needle on a conventional airspeed indicator. The resultant quickening of movement of the pointers, in combination with high contrast and large pointers, was designed to cause an increased awareness through the use of peripheral vision.

Index graduation was used sparingly to avoid cluttering the instrument faces and to simplify and quicken pilot interpretation of the readings. For example, the airspeed indicator had no index graduations between the numerals, which were shown in 10-knot increments. Also, pointer movement was damped to reduce vibration effects and to prevent overshoot from acceleration. The heading indicator had graduations only at midpoints between the 10° increments. The vertical speed indicator was the only instrument with conventional graduation between its 500-foot increments.

Conventional (moving horizon) attitude indicators were used in both displays. A 1968 Beechcraft Bonanza 35A, equipped with dual controls (Figure 2), was used as the research vehicle. The experimental PVFD, built by Humphrey, Inc., of San Diego, California, was installed on the left (pilot) side of the instrument panel and the conventional display was moved to the right section of the panel (Figure 3). A Humphrey, Inc., data acquisition system with a signal-conditioning module and an Astro-Science model 2000, 14-channel analog tape recorder was installed in the left rear seat area (Figure 4).

Twelve channels of information were recorded during the study. Pilot heart rate was obtained by use of an ear plethysmograph, which eliminated muscle artifacts. Aircraft pitch and roll data were obtained from suitable pickoffs from the aircraft primary attitude indicator. Vertical and lateral deviations from the ILS centerline were obtained directly from the glide slope and localizer signals. Altitude, airspeed, and vertical speed data were obtained from special high-resolution pressure transducers connected to the aircraft's pressure and static air system. Vertical acceleration data were taken from a high-resolution accelerometer installed near the center of gravity of the aircraft. Deviations from the desired heading were obtained from the gyro-stabilized remote compass. Control-wheel movement data (left and right, fore and aft) were derived from mechanoelectric transducers connected to the aircraft's control cables. Event signals were inserted on a separate data channel by the use of a manual switch.

Twenty professional pilots were used as subjects; half were high-time pilots with a mean of 1,267 hours of instrument flying, and the other half were low-time pilots with a mean of 104 hours of instrument flying. The mean total flying time of the high-time group was approximately 9,000 hours; the mean of the low-time group was 1,023 hours. Mean age for the high-time group was 50 years; that of the low-time group was 42 years.

The experimental flights were conducted at Oklahoma City, Oklahoma, and all instrument approaches were made at Will Rogers World Airport to either runway 17-R or 35–R, depending on wind direction. All flights were made during daytime. Slats covering the windshield and left side window blocked the subject's outside view while permitting an unobstructed outside view for the safety pilot and research technician. All flights were under radar approach control (RAPCON) surveillance for safety and to facilitate integration of the repeated approaches with other air traffic.

Prior to flight each subject was given a briefing paper describing the PVFD and the routine to be accomplished during the flight. The sequence in which the PVFD panel and the conventional panel were flown was counterbalanced to control possible sequence effects. Each subject was allowed 30 minutes of familiarization flight time—15 minutes at the start of the flight to become familiar with the aircraft's flight characteristics and, later, 15 minutes to become acquainted with the operation of the PVFD instruments prior to their use.

Each subject made two simulated ILS approaches using the conventional panel and five using the PVFD panel. During the first two PVFD runs, the slats were not used and the subjects were coached in the use of the PVFD panel by the safety pilot. The last three PVFD approaches were made with the slats in place. Since the subjects had many hours of experience with the conventional instruments, it was thought that two approaches using the conventional display would be sufficient. Preliminary work indicated that five approaches using the PVFD would be the minimum acceptable. It was also of interest to find out how well the subjects could perform with limited experience with the PVFD.

The subjects flew the aircraft at all times except for a 2-minute rest period on each downwind leg. The safety pilot handled all air traffic control communications throughout the flights. The subjects were instructed to use an approach and go-around speed of 110 knots, with landing gear down and 5° of flap extension. The minimum descent altitude was designated as 100 feet above runway elevation, and this altitude was to be maintained until after crossing the runway threshold, at which time the safety pilot instructed the subject to increase power and go around. The vision-restricting slats remained in place at all times except for the two PVFD familiarization approaches.

Data were recorded from the time of entry on the final approach to 20 seconds after passing the runway threshold during the go-around. Data runs consisted of the two approaches with the conventional display and the last three of the five approaches with the PVFD. Statistical comparison of peformance was based on data from the last conventional panel approach and the last PVFD approach.

III. Results.

During an ILS approach, the ultimate result of the pilot's control of the aircraft's pitch and roll attitude, heading, vertical speed, and airspeed can be measured in aircraft deviation around the centerline of the glide slope and localizer beam. Therefore, data for such deviations were used for the first statistical analyses.

Glidepath deviation data taken from the following approach points and/or areas were subjected to statistical test by comparing: (a) mean deviation (algebraic and arithmetic) between the outer and middle markers (approximately 120 seconds of flight), (b) arithmetic means during the last 30 seconds prior to reaching the middle marker, (c) total range below and above the glide slope centerline during the last 30 seconds prior to reaching the middle marker, (d) means at the middle marker (algebraic and arithmetic), and (e) the largest deviation below the glide slope centerline at any point between the outer and middle markers.

Comparison of the glidepath deviation data for the PVFD and conventional displays showed no significant differences in deviation between the two displays, nor did the amount of pilot experience influence the degree of glide slope deviation noted with the two different displays. However, the high-time group did have a slightly smaller arithmetic mean deviation than the low-time group ($P \leq .05$) regardless of the display used while operating between the outer and middle markers.

Localizer deviation data taken from the following approach points and/or areas were statistically analyzed by checking: (a) arithmetic means between the outer and middle markers, (b) arithmetic means at the middle marker, (c) total range left and right of the localizer centerline during the last 30 seconds prior to reaching the middle marker, and (d) the largest deviation between the outer and middle markers.

Comparison of the localizer data for both displays showed no significant difference in deviations ($P \geq .05$), nor was any difference in performance on the two displays noted as a function of pilot experience.

Heart-rate data were examined for statistically significant differences during use of the two displays; none was found at a probability level of less than 5 percent. However, in keeping with the results of previous studies of pilots during simulated ILS approaches, there was a statistically significant increase in heart rate ($P \leq .01$) as the middle marker was approached, regardless of which display was in use at the time.

Airspeed control with the two displays was closely comparable (see Table 1). The high-time pilots showed a mean difference of less than 1 knot in minimum airspeed on the two displays;

TABLE 1. Minimum Airspeed (Knots)

	PVFD	Conventional
High-time group	104.29	103.71
Low-time group	102.87	102.20

for the low-time group the difference between displays was less than 0.6 knots. The mean airspeed ranged from approximately 6 to 8 knots below the selected airspeed of 110 knots.

The mean airspeeds between the outer and middle markers are shown in Table 2. The difference between displays for the high-time group is less than 1 knot; for the low-time group the difference is less than 2 knots. The means for the range in variation of airspeed during use

TABLE 2. Mean Airspeed (Knots)

	PVFD	Conventional
High-time group	110.10	109.40
Low-time group	108.37	106.78

of the two displays also are small (see Table 3), with less than 2 knots between any combination of experience level and type of display.

TABLE 3. Mean Range in Airspeed (Knots)

	PVFD	Conventional
High-time group	11.46	11.30
Low-time group	10.58	9.49

Analysis of the pitch and roll control data shows that pilot performance with both displays was similar.

After the flights, the subjects were asked to rate the specific PVFD instruments. Seventeen of the twenty subjects provided usable responses.

The overall ratings are shown in Table 4. It shows that, with the exception of the altimeter, ratings of excellent and good were used more often than fair and poor to describe the pilot's

TABLE 4. Pilot Rating of PVFD Instruments*

PVFD	Excellent	Good	Fair	Poor
Airspeed indicator	15	2	-	-
Glide slope indicator	9	7	1	-
Localizer indicator	8	8	1	-
Vertical speed indicator	5	8	3	1
Heading indicator	5	5	6	1
Altimeter	1	4	5	7

*Three pilots did not complete rating scale on PVFD instruments

subjective likes and dislikes of the specific instruments.

When the subjects were asked if they experienced any particular difficulty adjusting to the PVFD, 18 provided usable responses. Of these, seven said no, three gave a qualified no, five said yes, and three said some or a little. Of those experiencing one or more difficulties, five mentioned use of the altimeter, one apparently disliked the increased sensitivity of the instruments in general, and six were initially bothered by the movement relationship of the glide slope and localizer instruments; i.e., flying the symbols to the center of the instruments rather than flying to the needles as with the conventional cross-pointer instrument.

Almost all the subjects thought they would have benefited from more practice with the PVFD panel; however, this does not seem to be borne out by performance data.

When the subjects were asked what particular instruments or features of the PVFD, if any, were specifically found advantageous compared to the conventional display, the following were specified by the number of subjects listed: airspeed indicator, 10; glide slope indicator, 6; layout and size of PVFD, 5; localizer indicator, 4; vertical speed indicator, 4; movement relationship, 3; heading indicator, 1; and sensitivity of movement, 1.

When the subjects were asked if they thought they performed as well, better, or worse with the PVFD compared to their performance with the conventional panel, the following responses were given: better, a little better, 7; as well, about the same, 6; slightly less, not quite as well, 3; worse, 1; don't know, 1.

When asked if they had confidence in the quality and reliability of the PVFD, 16 subjects said yes, 1 said not at first, and 1 said no (one instrument malfunctioned during one approach with this subject).

When the subjects were asked their opinion of the PVFD with respect to its potential and practicality for use in general aviation aircraft, 13 gave positive responses with and without specific exceptions, such as the altimeter. Five subjects compared the PVFD panel to a conventional flight director system.

IV. Discussion.

Use of the PVFD system resulted in performance equal to that of the standard display, even though the pilots had very little experience with the system. Many of the pilots said that the instrument approach was simplified. Several subjects also said the display was more "natural" than the conventional display. Upward movement of the airspeed needle (indicating decreasing speed) with upward movement of the aircraft's nose was mentioned as an example of "naturalness." Lateral movement of the aircraft symbols during deviation from the localizer centerline, and vertical movement during deviation from the glide slope centerline, seemed more natural than flying toward the needles of conventional cross-pointer indicators.

The instrument evoking the most adverse comments was the digital altimeter; these comments were directed toward low luminance, poor contrast in the high ambient light of the cockpit, rapid movement of the digits, and lack of a moving needle for rate information-design details that could be readily corrected in a second-generation display.

The vertical speed indicator was judged to be too sensitive; compression of the scale by a factor of two would make it comparable to the standard IVSI.

Combining the functions of the localizer and heading indicators was suggested as a means of overcoming some adverse effects of the heading indicator.

Ease of interpretation of the natural movements of the pointers and symbols (as noted by many of the subjects) and the lack of need for extensive familiarization time suggests that this type of display might decrease the time required in learning to fly by instruments. Also, there is a strong subjective impression that this type of display reduces the need for wide visual scanning of the instruments and provides early visual warning of minor flight deviations, thereby possibly reducing the overall workload and fatigue.

Further design evaluation of the present PVFD indicates that it could be reduced in size, possibly enhancing its visual effectiveness. Building the PVFD as a single unit with modular inserts and combining the heading indicator with the localizer indicator would reduce the space required by an additional 35 percent. This would result in a primary instrument flight display that would not only require 50 percent less panel space, but also would place essential information in a narrow visual cone of attention and thus reduce the need for wide visual scanning. Also, the performance obtained in this study by use of the PVFD suggests a means for increasing the visual effectiveness of flight direction instruments and head-up displays used in military and air carrier aircraft.

V. Summary.

A high-contrast instrument display, employing a vertical and horizontal format requiring substantially less space than conventional round-faced instruments, provided equal pilot performance (regardless of the type of display used) without requiring a large amount of familiarization time. This was true for both low- and high-time pilots. Heart-rate indications of stress were not influenced by the type of display used; it is clear, however, that heart rate increases as the pilot approaches the runway threshold, regardless of the display.

Since pilot reactions were generally favorable to the PVFD, and since there are no performance or stress penalties associated with the use of the display, it would appear that this design can be employed to reduce the size of the area required for presentation of primary flight information by at least 25 percent. This would also serve to reduce the total area of key instruments required for scan in approaches to landing under IFR conditions.

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