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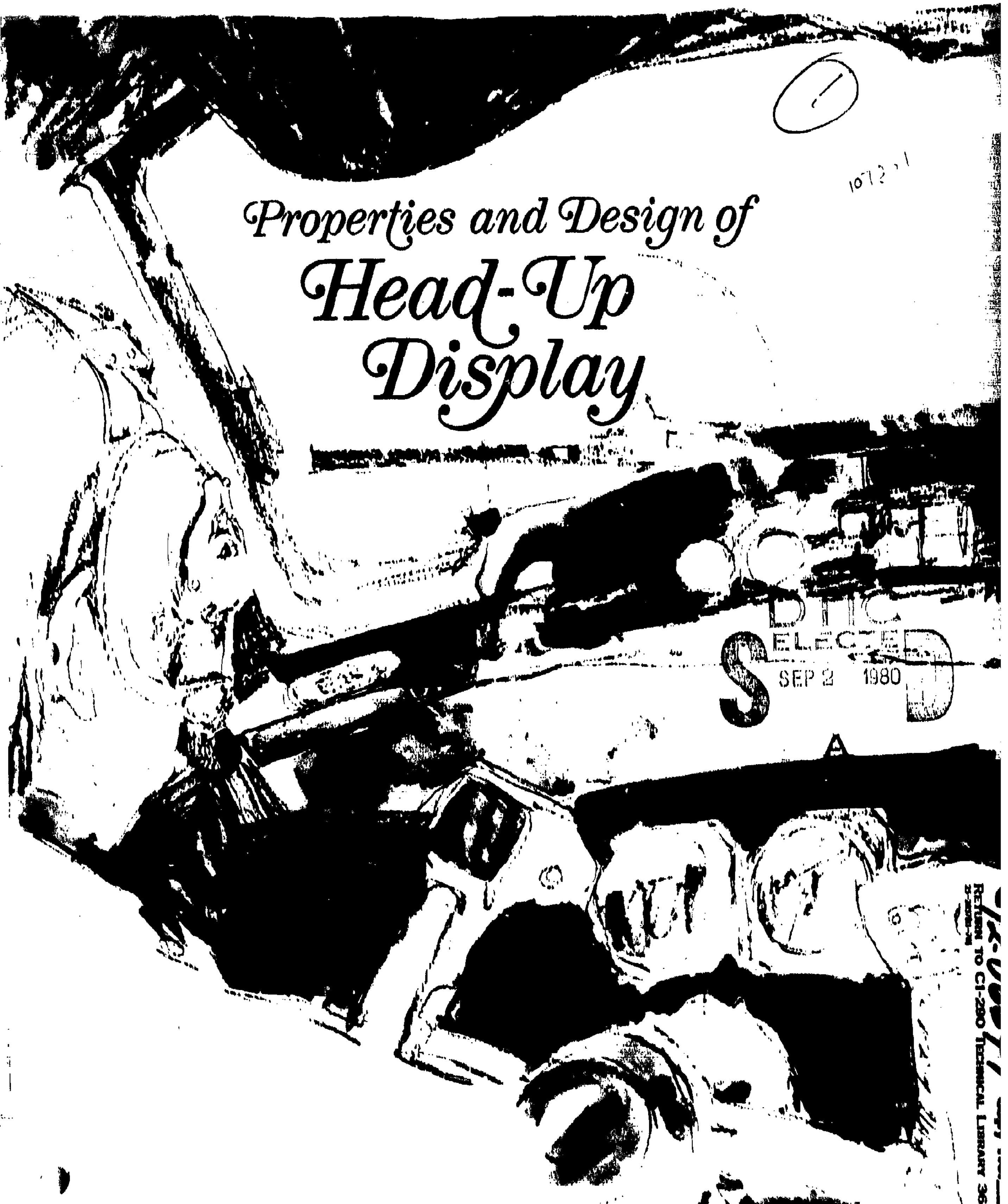
Properties and Design of Head-Up Display



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(6) # PROPERTIES AND DESIGN OF THE HEAD-UP DISPLAY (HUD),

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Head-Up Display Project

All-Weather Systems

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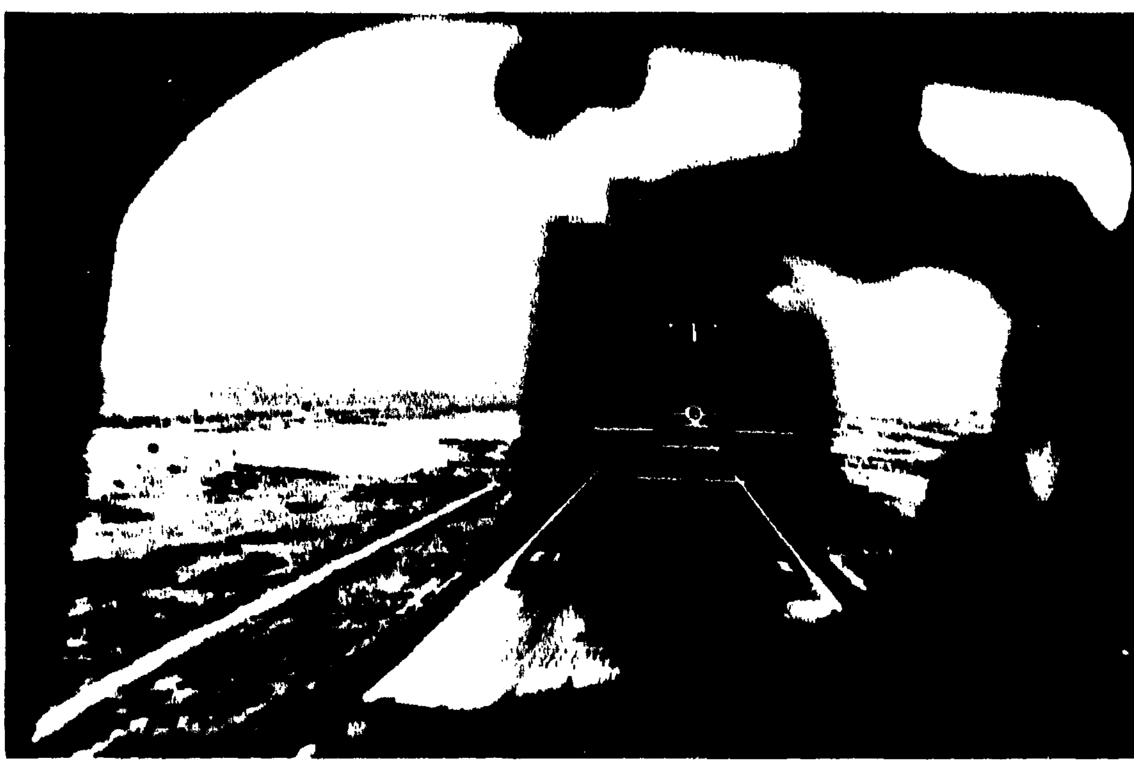
ABSTRACT

The Head-Up Display (HUD) has been developed from the well-known reflecting gunsight by applying electronic methods to the representation of flight path information, which is optically superimposed on the forward visual field. Previous investigations of the combination of information in superimposed fields are reviewed to show the relationship between properties and design of the HUD. An acceptable standard of safe usage is sought in the evidence of ability to perform concurrent tasks based on display and forward view. Design variables are the position and visible form of the display: constraints are the effects of errors and limitations, as they concern choice of symbol.

Position is shown to influence the efficiency with which display and forward view may be used. Pattern is shown to influence learning and tracking accuracy. Errors and limitations affect runway and flight vector symbols adversely, even when used in an auxiliary capacity, but have little effect on nonpictorial elements, or on director and attitude symbols satisfying particular conditions.

Properties resulting from the application of these results and other rules relating to the design, location, and control of symbols, allow the average user to learn very quickly, and to reach a relatively high level of performance without overconcentration. At the same time, the pilot is able to see where he is going, and the transition from instrument to visual flight is virtually eliminated.



PILOT'S VIEW OF HEAD-UP DISPLAY DURING APPROACH TO OAKLAND AIRPORT. Development of Category III landing system in DC-9 Series 30, May 1967. Experimental installation used for manual touchdown or for monitoring automatic landing.

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INTRODUCTION

Recent flight tests in a DC-9 Series 30 airplane have shown a manual, full-touchdown, all-weather landing capability[1] for the HUD, with small sink rates and longitudinal dispersions. This result is attributable to the quality of data sources and processing networks used in attempting to provide the best possible flight path information. It is also attributable to the display itself, where, as will be shown, an attempt is made to present this information in the best position and in suitable form.

The HUD was developed (in earlier studies) from the well-known reflecting gunsight, by applying electronic methods to the representation of a new class of information. It essentially transfers flight data from the conventional location in the instrument panel to a more convenient (but unusual) position, overlaying the forward view. The visual pattern seen by the user has a form obeying particular rules. It also satisfies certain necessary conditions and is generated by special techniques. The object of this work is to explain how the choice of display position, display pattern (or form), and method of generation are related to investigations in real and simulated flight, and how the system operates within the constraints imposed by practical considerations; in other words, to show the connection between design principles and properties of the system.

Presentation in the head-up mode is intended to bring together fields of information which are separate, and which may differ in form and content. Typical cases occur in high-speed, low-level flight, and in the landing approach, where it may be desirable to avoid having to separate instrument flight from visual flight, each with its own limitations, but rather to allow one to complement the other, continuously. Similar situations may arise in monitoring an automatic landing, in takeoff and in the overshoot, or wherever there is a need for the pilot's attention to be in two places at once.

In bringing together such widely different visual fields there may be some danger through interfering with the pilot's main information channel. It is therefore essential to be able to guarantee efficient combination of the two visual fields on the evidence of performing suitable tasks associated with each source of information. It will be necessary to show a capability for observing display and forward view concurrently, while bearing in mind the ease and efficiency with which the system can be used.

The subject is treated by deriving, first, the essential rules of position and form, on which the distinctive properties of the system are found to depend. Then attention is directed towards applying position and form rules within the limitations imposed by flight conditions and usage, with special regard for the choice of information and design of symbol. In brief, the main variables are the position and visible form of the display; the main constraints are found in the influence of errors and limitations, as they affect presented information.

DISPLAY POSITION

The pilot's flight instrument panel and forward view are visual fields occupying different positions. Each field may not be observed continuously because physical acts of directing and focusing the eyes are involved in changing the area of observation, and these acts can scarcely be accomplished instantaneously. It may, however, be possible to improve the chances of acquiring information from the separated visual fields by bringing them together, to the extent that these physical acts are eliminated. If this is true, the position of a display will influence the acquisition of information from both display and forward view, and this influence may be investigated if the total flow of information can be observed.

Evidence of information flow can be inferred from the performance of tasks based on the information presented, and the acquisition from two visual fields can be related to the performance of tasks uniquely associated with each field. However, if the fields are brought together, it becomes necessary to be able to distinguish between them for the purpose of discussion, and it will sometimes be convenient to refer to the forward view as the external field, or outside world, because its origin is normally external to any means for presenting information. On the other hand, presented information is conveniently described as occupying the display field, or the superimposed visual field.

EXPERIMENT 1. INFLUENCE OF RELATIVE POSITION OF SIMPLE VISUAL FIELDS

Separate visual fields may be brought together by placing them in the same position, and it will be shown that this method can be used whether the information content is low or high. In the special case of a simple display, e.g., one giving commands to go left or go right, other methods may perhaps be used, because a small amount of information can usually be represented by a crude visual pattern, which might be seen without direct regard (fixation) or even without focusing the eyes, and so the display could be placed off-axis or at an intermediate plane. It will be shown that either of these alternatives may be used to observe a simple display while observing the forward view, and it will be interesting to examine the relative efficiency of these three methods of bringing visual fields together.

The three relative positions of the visual fields were implemented for experimental purposes by mounting a gross and movable display at A, B, and C, Figure 1, where they bore different relationships to the forward view, or external field, which was a television screen. The display was presented in position A, in the direction and plane of the forward view, by mixing the output of two television cameras, one trained on the display and the other on visual material used for the external task. The display was presented on-axis, although out of focus, in position B near the windshield, by means of a semi-transparent reflector (alternatively, a transparent image-forming device could have been used). For the off-axis position C, the display was mounted in the conventional instrument panel.

The object of the experiment was, in effect, to determine whether, and how efficiently, two fields of visual information could be combined, or acquired concurrently, in each of the three relative positions. The degree of combination was estimated by measuring the performance of tasks linked to each field, with priority given arbitrarily to the external field. Subjects were required to recognize, with at least 95 percent success, a continuous stream of numerals, presented in the forward view at a size such that they could be seen only with central vision. The display task was to null apparent left and right movements of a rotating helical pattern of black and white stripes (having sufficient size, speed, and illumination to be visible in each field position). Performance

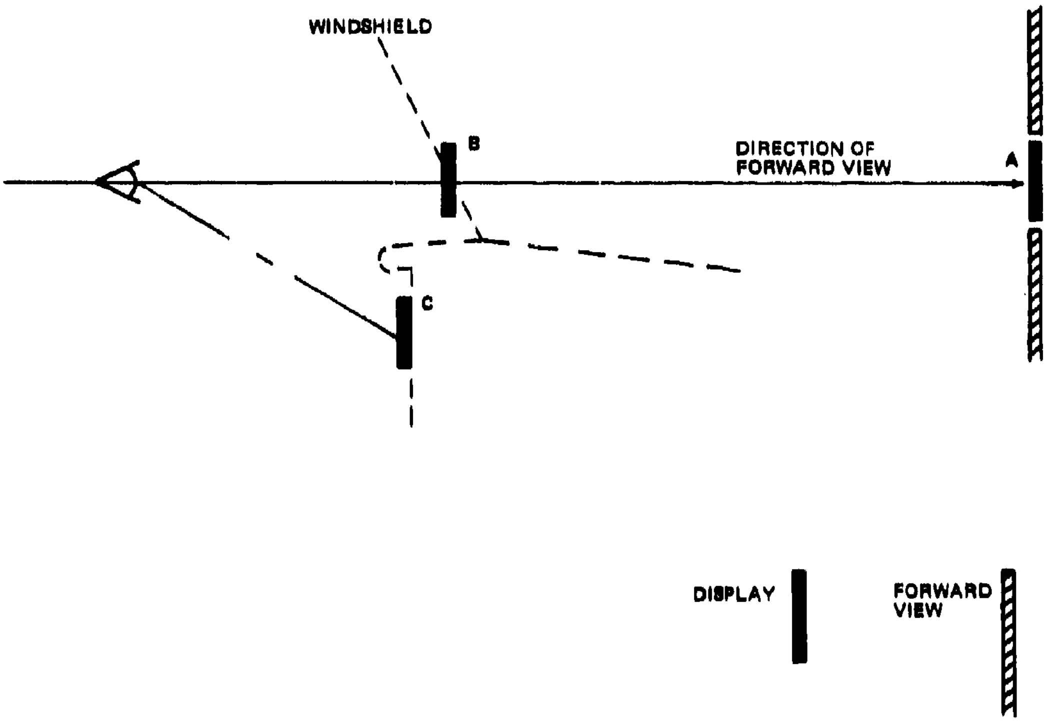


FIGURE 1. RELATIVE POSITIONS OF DISPLAY AND FORWARD VIEW (EXTERNAL WORLD) IN EXPERIMENT 1. Display mounted in conventional panel position, at C, in plane of windshield and direction of forward view, at B, or in direction and plane of forward view, at A.

levels for the tracking task were then used to estimate combination, provided the required level was achieved for the recognition task.

The visual tasks were carried out by 11 subjects, with the display driven in 5 ranges of apparent linear speed, left and right, for each position of the display, A, B, C, in random order. All subjects reached the required level for the recognition task during each 50-second period, while integrated tracking errors were recorded. Examination of tracking error scores, by analysis of variance, showed no significant differences arising through change of field position (A, B, C) in any of the speed ranges. In other words, tracking performance was not affected by the relative position of the display for any typical linear display speed, Table I. An alternative analysis was made on the basis of apparent angular speed of the display, and this showed an advantage for position A, the collimated display.

The more correct interpretative approach was considered to be the one based on linear speed, on grounds that the unit of information per unit time should be the passage of a display element (one stripe) through its own width, which clearly depends on linear speed. On this interpretation all display positions were equivalent, and display position may be considered to have no effect on the total information flow from the forward view and a simple display, when using an indicator designed to be visible by the abnormal viewing methods needed for off-axis and defocused display positions. However, the result is not general, because it depends on a particular information model, suiting a special type of indicator, and the nature of the indicator limits the capacity of the display field.

TABLE I

RESULTS OF ANALYSIS OF VARIANCE FOR TRACKING SCORES OF 11 SUBJECTS WITH 3 RELATIVE POSITIONS OF DISPLAY AND 5 RANGES OF LINEAR SPEED

PEAK SPEED (INCHES/SECOND)	DIFFERENCES FOR FIELD POSITION	DIFFERENCES FOR SUBJECTS
0.47	NOT SIGNIFICANT	NOT SIGNIFICANT
0.84	NOT SIGNIFICANT	NOT SIGNIFICANT
1.50	NOT SIGNIFICANT	NOT SIGNIFICANT
2.62	NOT SIGNIFICANT	NOT SIGNIFICANT
4.78	NOT SIGNIFICANT	SIGNIFICANT ($P = 0.05$)

Meaning of Head-Up

All of the display positions used in Experiment 1 can be called head-up because information is drawn from the display field in each case, while observing the external field with the head raised. But limitation of information capacity, imposed by out-of-focus and off-axis viewing, suggests that the term be reserved for the case where the display is superimposed in the same position as the forward view, and this practice will be followed here.

EXPERIMENT 2. INFLUENCE OF RELATIVE POSITION OF COMPLEX FIELDS

It is usually unacceptable to limit the information capacity of a display system, as is necessary for out-of-focus or off-axis presentation (B, C, Figure 1), since two-dimensional guidance is frequently required and other information may be needed in a supporting role, e.g., attitude, height, or speed. Also, unorthodox use of the eyes may not be advisable in real flight, especially for prolonged operations or in critical situations. On the other hand, it should be possible to use the eyes in the normal way if the presentation is made in the line of sight, at the distance of the center of interest in the forward view (A, Figure 1), and there should then be less cause for drastic limitation of information content.

These considerations of information capacity and ocular usage suggest that all relative positions of display and forward view may no longer be equivalent when the information ceases to be simple, but an identity of position may be preferable, especially if satisfactory answers can be given to the following questions. Can more complex fields of information be combined when they are presented in the same position? Are visual tasks linked with these fields unaffected when carried out together? To what extent is performance in this (head-up) mode superior to what can be achieved with a conventional (head-down) arrangement? In answering these questions it will be shown that display position is important for complex fields and influences the total flow of information.

The object of the second experiment was to find out the effect upon each other of more complex visual tasks, in head-up as opposed to head-down presentation. One task was to respond, as rapidly as possible, to a visual stimulus appearing at random positions and random times in a 30-degree external field, Figure 2. The other task was to follow, with the least possible mean modulus tracking error, two-dimensional command signals, which were supported by attitude information, and presented either by reflecting collimator in the external field position, or by direct view in the

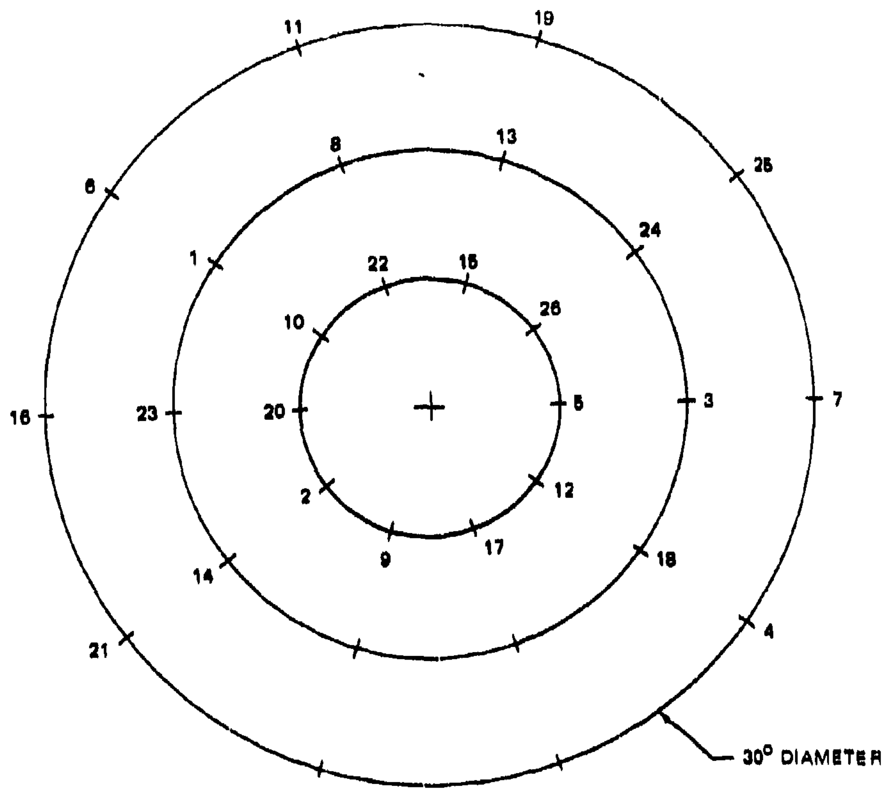


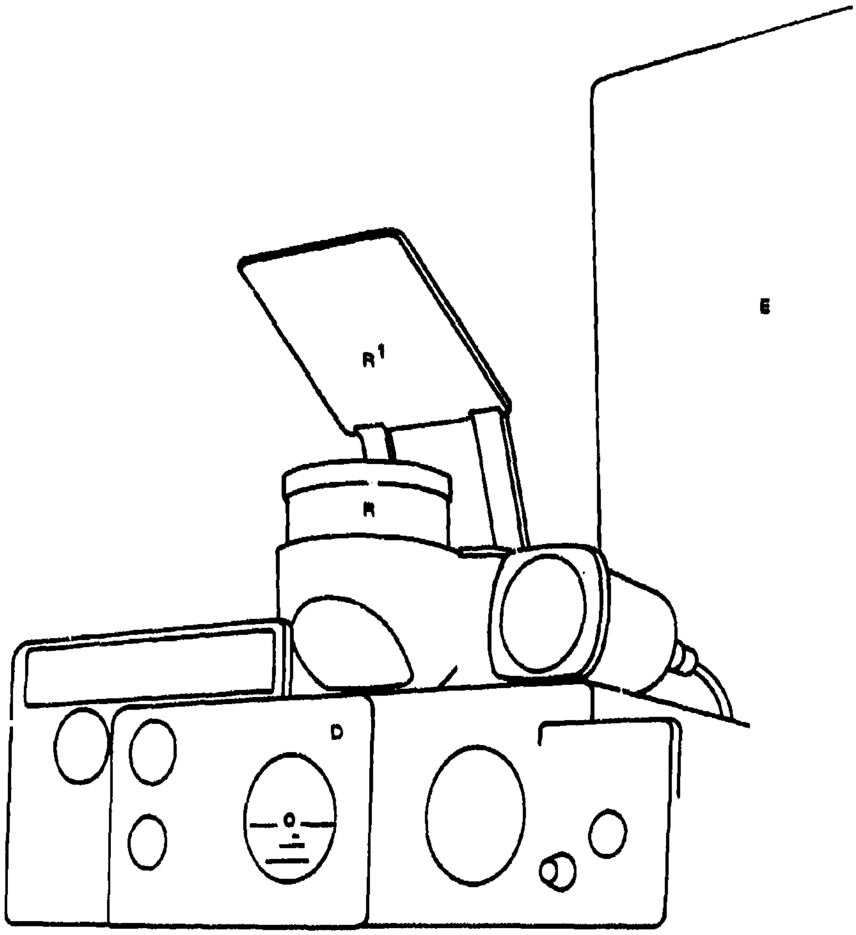
FIGURE 2. SEQUENCE AND POSITIONS OF VISUAL STIMULI IN EXTERNAL FIELD, EXPERIMENT 2.

instrument panel, Figure 3. The subjects were six pilots with at least 50 hours instrument flying experience. A balanced experimental design was used for performing the tasks by themselves and in parallel with each other, in both head-up and head-down modes.

For the head-up mode, comparison by t-test of performance of the *tracking task*, with or without the external task, showed no significant effect in either command channel (t_{05} = 0.708, 0.506).

The same comparison for the head-down mode showed significant differences in one (azimuth) channel, at the 5 percent level (t_{05} = 2.736). Thus the effect of adding the external task was only apparent in the head-down mode, where performance of the tracking deteriorated in one command dimension.

Analysis of variance was used before comparing mean acquisition times for three modes in which the *external task* was performed, viz. alone, concurrently head-up and concurrently head-down. Mode differences were highly significant (P = 0.001) and subject differences were insignificant. Means for the three modes, Table II, showed the additional tracking task to have a significant influence in the head-down mode, the two relevant acquisition times (1.23 sec, 3.86 sec) being separated by more than the 5 percent critical difference (1.29 sec), but there was no significant difference for the head-up mode. Head-up acquisition times were also more consistent than head-down times, as shown by coefficients of variation of 42 percent and 83 percent, respectively, and there were less missed responses. Thus the effect of adding the tracking task was again only



DISPLAY PRESENTED BY REFLECTING COLLIMATOR R, R[1]
AGAINST EXTERNAL FIELD E, OR BY DIRECT VIEW AT D.

FIGURE 3. HEAD-UP AND HEAD-DOWN PRESENTATION IN EXPERIMENT 2.

TABLE II
MEAN TIME FOR 6 SUBJECTS PERFORMING EXTERNAL TASK IN 3 MODES

	MODE		
	ALONE	CONCURRENTLY HEAD-UP	CONCURRENTLY HEAD-DOWN
MEAN TIME (SEC)	1.23	0.88	3.86

(5 PERCENT CRITICAL DIFFERENCE = 1.29 SEC)

apparent in the head-down mode, where times to acquire external stimuli were nearly 3 seconds longer and were more variable.

An incidental finding in this experiment was that the *tracking task* (alone) was performed equally well head-up and head-down, using the same display pattern and means of generation. In other words, with the same information content and visible form, the result is independent of display position for the case of a single field, though this is no longer true where two fields are involved. The single field result is important in applications of the HUD where the question of compatibility of head-up and head-down displays is relevant.

The main results of the second experiment show combination of more complex fields superimposed in the same physical position, by the absence of any measurable effect upon each other of the associated visual tasks. Head-up presentation appears capable of allowing the same level of observation in the external field as is ordinarily possible, and unimpaired performance in following instructions presented in the display field. This dual capability is an improvement on what is possible with conventional arrangements, and the influence of display position is shown by the elimination of a penalty of about 3 seconds in making external observations, while concerned with a complex display field.

Attention gaps of this order were observed by Ellis and Allan during conventional airfield approaches,[2] and the inference drawn from the present experiment is that pilots in the corresponding head-up situation might be able to observe the forward view while flying "on instruments," without large gaps of attention. The conditions of the present experiment, however, are different from those of flight, where the pilot would be concerned with the external field in a more critical manner, and further investigation is needed to establish the inference.

Meaning of Concurrent

It may not be possible to reduce attention gaps indefinitely, since it does not seem that attention may be given to more than one matter at exactly the same time[3]. However, the time taken to shift attention between fields having the same position is relatively small – sufficiently small to allow continuous tasks to be carried out together. We may then describe the tasks associated with each visual field as *concurrent,* without needing to specify simultaneous attention.

EXPERIMENT 3. CRITICAL OBSERVATION IN COMPLEX SUPERIMPOSED FIELDS

The information field used in Experiment 2 was more complex than in the first experiment, but could not be said to represent a real flight situation, particularly as regards the external field. In a visual approach, for example, the pilot is not simply concerned with detecting the onset of external signals but, rather, in judging the position and attitude of his aircraft (from the apparent shape and position of the runway), and the results of this more critical type of external observation are frequently used by the pilot for comparison with corresponding data derived from the display system.

Can the forward view be observed critically while occupied with a head-up display? Ordinarily, information is acquired from the display and forward view in different ways, and it is necessary to separate the corresponding visual processes by a definite transition between fields. However, if the external field can be observed critically, while occupied with the display field in a representative manner, there may no longer be any need for such a discontinuous process.

Critical observation was investigated in the laboratory by superimposing the display field on a simulated forward view, Figure 4. A reflecting collimator (suitably focused) was used to present the

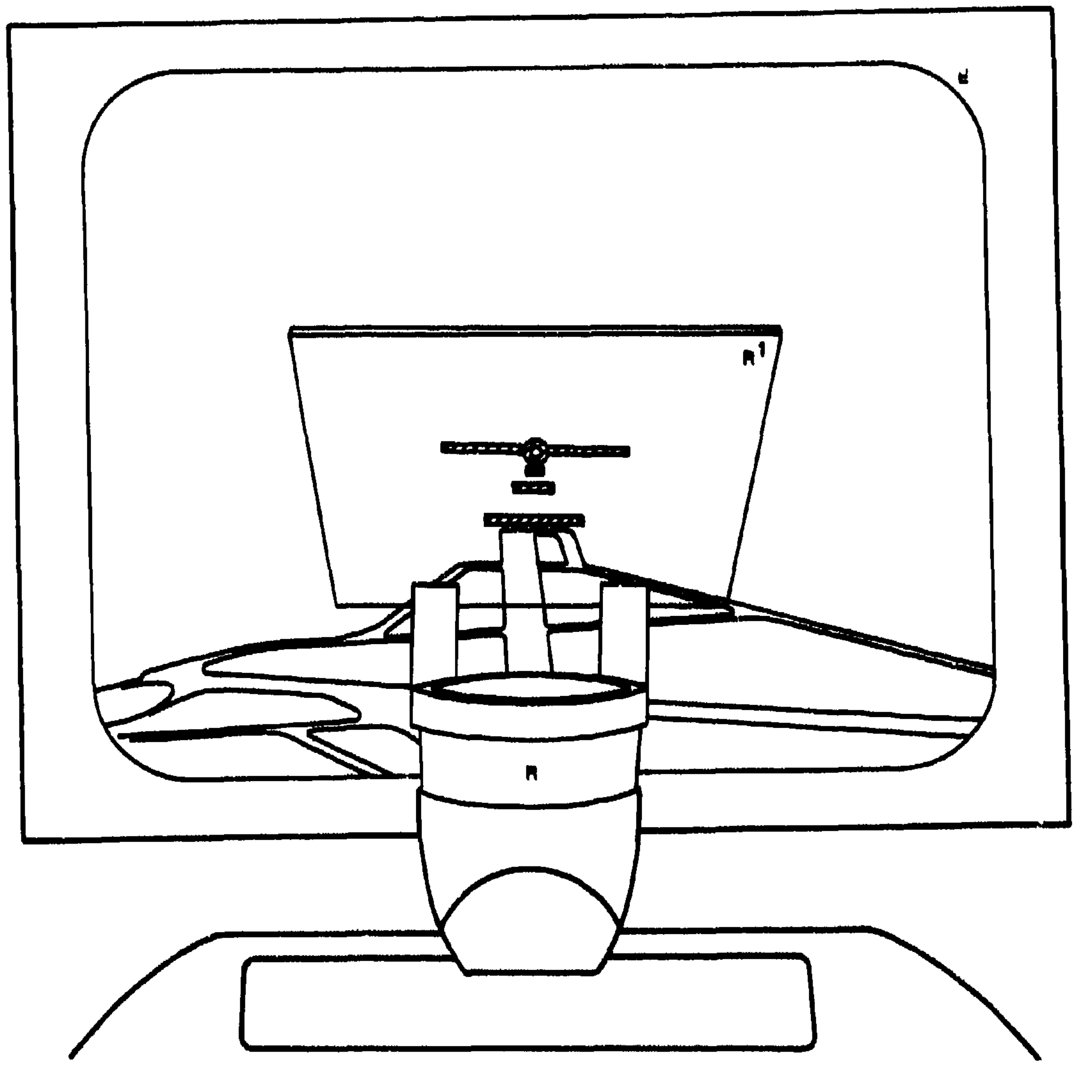


FIGURE 4. DISPLAY SUPERIMPOSED ON SIMULATED FORWARD VIEW BY REFLECTING COLLIMATOR IN EXPERIMENT 3.

display, as in the head-up mode of Experiment 2, and the forward view in flight was simulated, with 6 degrees of freedom, by a technique(4) that is now well known. An aircraft simulator was used to provide attitude information in the display and to drive the visual flight simulator. Command information was also displayed, for the purpose of taking subjects through a set program of maneuvers.

Subjects were asked to comply with displayed commands and to observe general features in the forward view. The set manouvers were carried out in the vicinity of a simulated airfield, Figure 5. Runway directions were crossed twice at angles of 20 to 40 deg between positions 5 and 6, and between 7 and 8, Figure 5, but after the tenth turn a runway was approached with only a small angular divergence, of the order of 3 deg. Completion of the maneuver program to this point required tracking with a mean modulus error less than 1 deg.

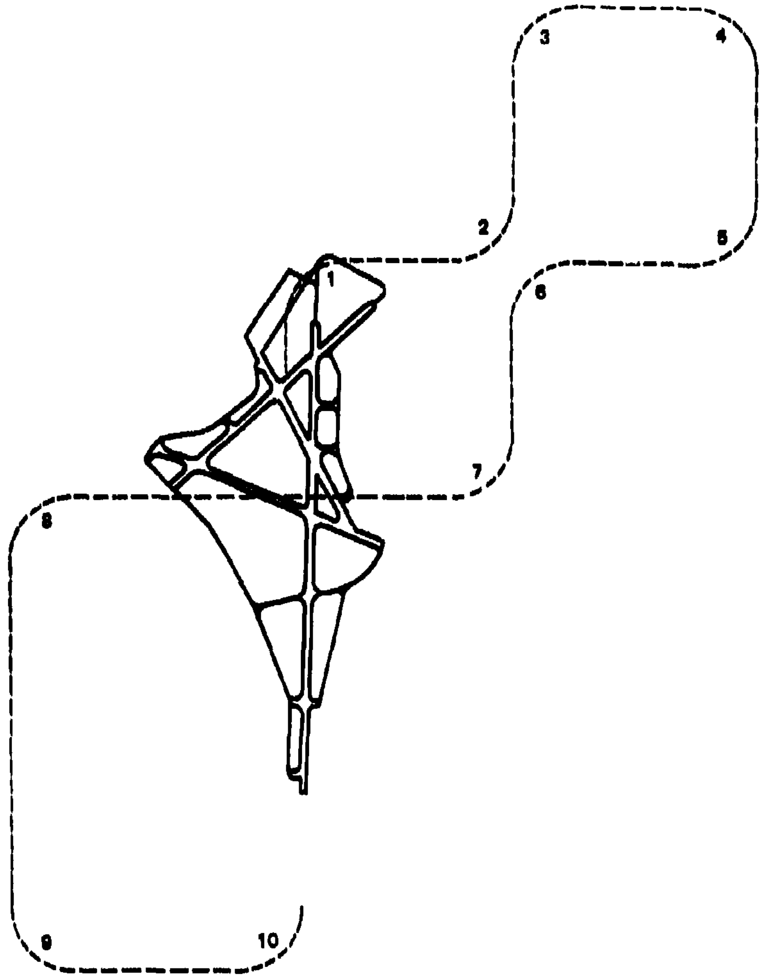


FIGURE 5. SIMULATED AIRFIELD IN EXPERIMENT 3. Set maneuvers (1 – 10) shown dotted.

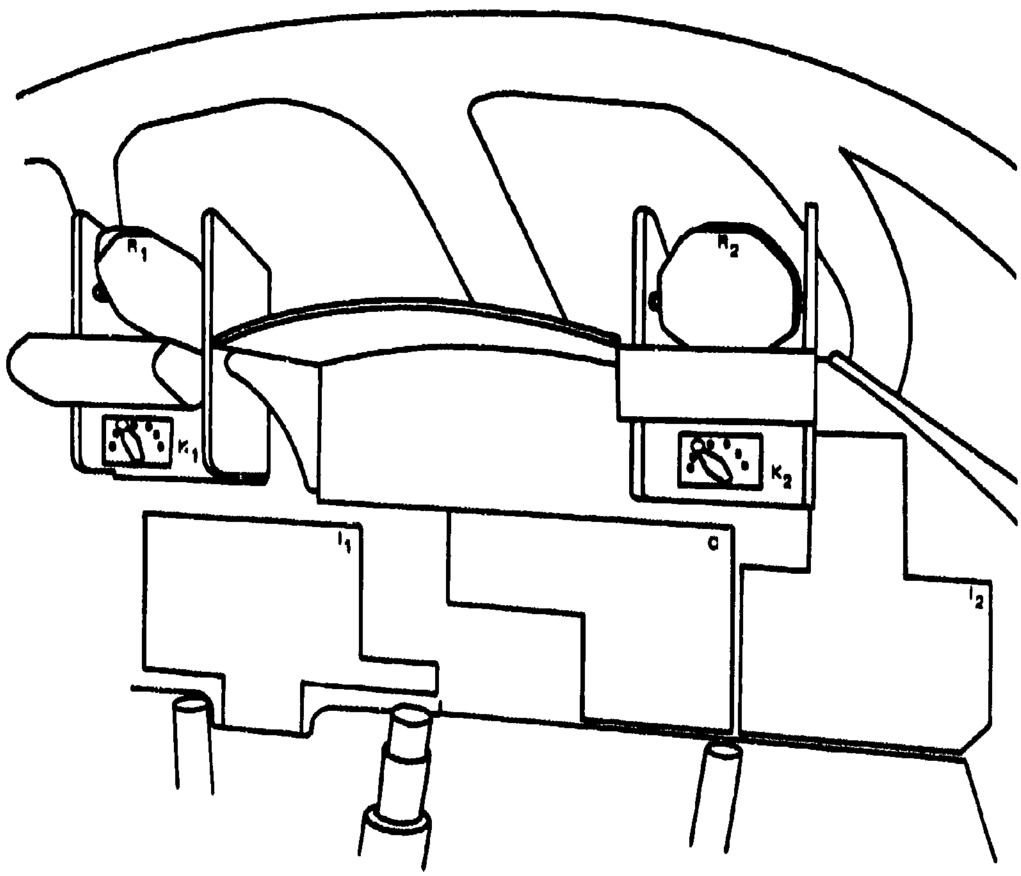
Thirteen (out of fourteen) subjects, all pilots, succeeded in reaching the approach position, at which it was to be determined whether or not they would continue to track the display with the same precision. If the tracking performance continued at the same level, leading to misalignment with the runway, there would be no objective evidence for critical observation in the external field. On the other hand, if runway misalignment were corrected, ignoring the displayed commands, it would be evident that subjects observed features in the external field with the same sort of care that typifies a visual approach, whilst completing a tracking task with measurable precision.

In fact, all subjects ignored the divergent command information and flew "visually" along the runway. In other words, when runways were crossed at large angles, there was insufficient cause to abandon the experimental requirements of following the display, but when the angle was small it was evidently assumed that the display was in error, that it was really "trying" to help fly along the runway, and that better performance could be achieved by visual flight methods. This result gave reason to believe that a head-up display might help eliminate or modify the transition in real flight, since the external field was observed critically while occupied (continuously) with the display field in a representative manner.

EXPERIMENT 4. CORRELATION WITH FLIGHT. CONTINUOUS TRANSITION BETWEEN INSTRUMENT AND VISUAL FLIGHT IN HEAD-UP MODE

Experiments 2 and 3 showed that a reflecting collimator display has sufficient information capacity for non-trivial guidance purposes, and allows concurrent, critical observation in superimposed visual fields. The system used for flight testing was accordingly built around a reflecting collimator, and a twin installation was provided so that two pilots could have the same display and forward view, Figure 6. A command input facility was available in the instrument panel so that the right-hand pilot could inject guidance signals as an alternative to the normal ILS coupling.

The object of flight testing was to confirm laboratory findings of information capacity and facility of observation in both visual fields. It was not necessary to develop specific methods proving an adequate information capacity, as the system was found to be usable for instrument flight in all phases of a sortie. It was, however, necessary to develop methods for studying observation of the external world, and two sufficiently objective experimental techniques were found for this purpose.



DISPLAY PRESENTED TO EACH PILOT THROUGH REFLECTOR PLATES R_1, R_2.
CONTROL PANEL C WITH COMMAND INPUT FACILITY, BETWEEN INSTRUMENT PANELS I_1, I_2.
POSITION OF REFLECTORS VARIED BY KNOBS K_1, K_2.

FIGURE 6. DUAL FLIGHT TEST INSTALLATION IN EXPERIMENT 4.

False "Fly-Down" Command

The training routine adopted for demonstrations started with a "directed takeoff," using computed information to generate an idealized rotation profile. Injected commands were then used for climbout and general flying at altitude, until the display could be used proficiently without overconcentration. At this stage, it was possible to undertake terrain following, or contour flying at low level, for which command signals were injected by the instructor, who effectively translated his local knowledge into visual instructions used by the trainee.

Having made certain that the trainee followed displayed commands continuously and efficiently, the instructor unexpectedly injected a false command signal, usually as a fly-down instruction when the external situation called for the opposite action. In the event of this command being accepted there would be no evidence of the trainee observing critically the forward view. (It would also probably be necessary for the instructor to take control.) On the other hand, if the command were to be ignored, it would be evidence of a correctly appraised external situation while continuously occupied with the display – all previous commands having been accepted. To conclude the routine, subjects made instrument approaches and, in some cases, completed the flare maneuver, by means of the head-up display.

Concurrent Recording for Both Visual Fields

Tracking errors were measured in flight by recording mean modulus command signals, using a low-inertia motor driven through a simple sign-reversing network, with the effect of measuring performance based on information gained from the display field. Information gained from the forward view, or external field, was estimated by recording the pilot's spoken description of the approaching terrain. Combination of these techniques during an instrument approach allowed an estimate to be made of the information gained concurrently in both fields.

Over 50 subjects took part in the flight program, completing more than 100 sorties of 1-1/2-hours average duration. The false command technique was not used in all cases because adequate experience could not always be assumed, but where the technique was used, the false command was ignored.[5]

The second technique was used by only one subject, who made an accurate approach to threshold (before overshooting), while giving a verbal description found to occupy more than 50 percent of the recording time. Limitations on the use of communication frequencies during the approach precluded further application of this technique, but 13 other subjects reported sighting air traffic, ground objects, and birds while using the head-up display.

These results do not prove continuous and complete awareness of both visual fields, but they show a reasonable division of attention between them, sufficient (for the first method) to allow observation of a potentially dangerous situation in the external field, while occupied continuously with the display (though this particular skill took about half an hour to learn). This experimental finding showed that the facility for critical observation found in the laboratory could be transferred to the real flight situation, allowing the "all or nothing" nature of the transition between instrument and visual flight to be replaced by a more continuous process. The flight tests also showed that the information capacity of the collimated display was adequate for all modes of flight, in agreement with the results of ground tests.

SUMMARY: INFLUENCE OF POSITION

It should be possible to improve information flow from separated visual fields by bringing them together, so as to eliminate acts of directing and focusing the eyes, and this can be done in three ways. Experiment 1 shows that the resulting relative positions of display and forward view can be regarded as equivalent, provided the information content is low. A common field position is preferable when the content is increased, and a complex field can be superimposed on the forward view by means of a reflecting collimator, the display being observed by normal visual methods. Experiment 2 shows that the tasks linked with the fields are then without effect on each other, being performed as well together as if by themselves, and eliminating large gaps of attention. Experiment 3, with a similar display position, shows that a complex external field can be observed critically, while occupied continuously with a complex display in a realistic manner. The flight trial, Experiment 4, shows correlation of real and simulated flight results; viz, fields superimposed in the same position allow adequate information capacity for practical purposes, and critical observation in the forward view while using the display, a process of "continuous transition." The influence of a common display position is thus essentially in avoiding abnormal visual methods and in allowing an information capacity adequate for instrument flight, while improving the total flow of information. The abrupt and mutually exclusive nature of the transition from instrument to visual flight is eliminated, while reducing associated gaps of attention and attendant risks, e.g., of mid-air collision. In other words, an efficient combination can be achieved by superimposing the display in the same position as the forward view.

DISPLAY PATTERN

The pilot's instrument panel and forward view are fields of visual information which generally cannot be interpreted by the same rules, e.g., the apparent movement of an external object does not have the same meaning as the movement of an instrument pointer. A difference of interpretative method may conceivably hinder the overall flow of information from both fields, especially when they are superimposed in the same position. If this is true, it should be possible to promote information flow by eliminating the difference, to the extent that a display may be designed to be understood by rules applicable to the forward view.

The method of coding information in the conventional instrument panel is one which depends heavily on the position, movement and shape of display elements. The method of decoding, or obtaining information from the forward view, although different, is also essentially geometric in that the position, motion and attitude of the vehicle may be judged from the apparent shape, motion and position of external objects. A suitable basis for designing a conformable display may, therefore, be sought in its visible pattern. At the same time, other visual characteristics of the display, such as brightness and color, should not be allowed to interfere with conditions promoting the overall flow of information from the fields to be combined.

It is known that an even distribution of brightness is beneficial to viewing,[6] so it is assumed that display brightness is made just sufficient to distinguish this field from the forward view when they are superimposed, and that all parts of the display are equally bright. It is also known that equidistant objects of different color appear at unequal distances (chromatic relief)[7], so it is assumed that color is uniform in a superimposed display and is made to lie near the middle of the visible spectrum. These conditions of brightness and color should cause least interference with the visual conditions desirable in superimposed fields; they may also be used to give identity to displayed information.

The choice of pattern as a basis for conformity implies a need for greater flexibility in generating displays than conventional methods allow, and this may be sought in cathode ray tube technology. Also, it will need to be shown that sufficient and necessary information can be represented conformably, to allow appropriate tasks to be performed. After meeting these needs, the effect of reducing differences of interpretation should be felt, if at all, in the ease with which display and forward view are used, and since a pilot can already interpret the forward view in flight, he may conceivably learn to use the display by transferring this skill to a display understood by similar rules. The influence of display pattern on information flow is thus to be sought in reducing interpretative differences between display and forward view, by investigating the learning process for a conformable display of suitable information.

CONFORMABLE DISPLAY OF ATTITUDE AND COMMAND INFORMATION

Information selected for a conformable head-up display should not only allow a pattern to be found which agrees at all times with the appropriate aspects of the forward view but should also be such that the pattern can be readily contained within the limited display field of a reflecting collimator. In the case of an aircraft display, some of the information normally supplied by flight instruments does not meet these two requirements. Thus, height and speed information may be difficult to extract from the forward view,[8] so a strictly matched pattern would not permit transfer of this information at a useful level, without some kind of pattern exaggeration and corresponding loss of conformity. Also, heading information is derived from the forward view by observing objects lying mostly outside the area usable as a head-up display. On the other hand, attitude and command information can be represented conformably in a limited area, as will now be shown.

The pattern used in the experimental display of attitude and command information is shown in Figure 7. The component parts of the display are a reference symbol, an artificial horizon and a flight director symbol. The appearance, movement conventions and conformity aspects of the display elements are presented in the following paragraphs.

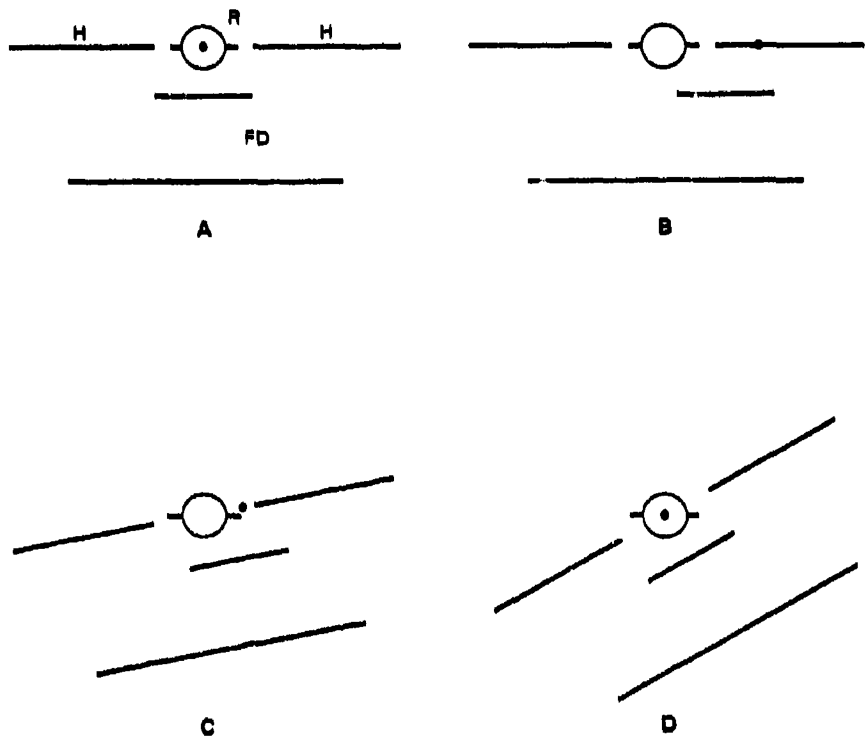


FIGURE 7. EXPERIMENTAL ATTITUDE AND COMMAND DISPLAY CONFORMING WITH FORWARD VIEW. (A) Aircraft reference R, Artificial Horizon HH, Flight Director FD. Azimuth command (B) partially satisfied (C) fully satisfied (D). Note movement of director index dot along horizon.

AIRCRAFT REFERENCE SYMBOL

The aircraft reference symbol is a small circle with lateral "wings." It is intended to remain fixed in the display field, and can thus be fixed in the aircraft framework without difficulty. The identity of the symbol is emphasized by its wings, which are used in estimating bank angle, and its circular shape allows a director index to be centered equally well from any direction. The symbol, being fixed, behaves in the same way as an object rigidly attached to the airframe, such as a windshield strut, so both display element and (external) object are interpreted by the same rule, viz a fixed position in the display field represents an aircraft axis.

ARTIFICIAL HORIZON SYMBOL

The artificial horizon is represented by a single bar having a central gap slightly wider than the reference symbol, to avoid interference. For special purposes, small vertical bars may be added to the underside of this gap, e.g., to show the downward direction in the absence of the flight director. The symbol is made to rotate in bank at the same rate as the visible horizon, and there is then no difficulty in understanding display and forward view by the same rule. In elevation, the situation is different because a single horizon symbol cannot be retained within the limited display field for all attitudes of elevation unless the presentation is scaled down. The artificial horizon will then move at a slower rate than the visible horizon, with only two coincidences per revolution. With this arrangement, forward view and display are interpreted by similar but not identical rules.

It is interesting to note an incidental advantage of scaled-down presentation in elevation, arising from the fact that the visible horizon seldom coincides with the true horizon. The difference clearly depends on height, visibility and terrain, and the artificial horizon, representing a truly horizontal direction, should not be made coincident with the visible horizon unless the chance of presenting false information is accepted. This difficulty is avoided by scaled-down presentation.

FLIGHT DIRECTOR SYMBOL

The flight director symbol, Figure 7(A), is a set of lines which are always parallel to the horizon and lie within a triangular envelope. The apex of the triangle, a single dot, is the flight director index.

Command information is shown by the position of the index in relation to the reference symbol. The index is moved along the horizon for azimuthal commands, Figure 7(B), and at right angles to the horizon for commands in elevation. When it moves, the triangular envelope distorts, while the baseline remains at fixed distance from the reference. As the command is satisfied, e.g., Figures 7(C) and 7(D), the index returns to the reference symbol in the usual way. If demands remain grossly unsatisfied, it may be necessary to "park" the index at the edge of the field in order to keep it visible.

By an extension of the rule already applied to the reference symbol, a *movable* display index represents a direction varying with respect to the longitudinal aircraft axis, such as a command direction. Conformity of movement is then secured simply by displacing the index in the direction of the command, so that it moves upward for a climb command or to the right for a command to turn right, and so on. In other words, both display and forward view are interpreted by similar rules if the aircraft reference is flown toward the flight director index.

If the flight director symbol is taken to represent a path from the baseline to the index, its perspective form heightens the sense of "from here-to-there," a feature which is also useful in distinguishing between up and down. It is not, and cannot be, a runway symbol. The total form of the symbol also leads the eye to the index, which should be useful if local variations in external brightness make the index difficult to find, and should help avoid overconcentration on the tracking task.

The complete experimental display is thus of information which can be represented within a limited optical field, as a pattern understood by rules similar to, but not always identical with, those applied in the forward view. The content should be sufficient for maneuvers requiring only attitude and guidance information, and by investigating the learning process in these conditions, it may be possible to estimate the influence of a conformable display pattern, which could allow a transfer of visual flight skill.

EXPERIMENT 5. INFLUENCE ON LEARNING OF PATTERN CONFORMABLE WITH FORWARD VIEW

Case (1) Instruction of Experienced but Skeptical Subjects by Diagram. Use of Display in Simulated Flight without Forward View

The object of the experiment was to investigate the influence of a conformable display pattern on ease of learning. The subjects were seven pilots, each having a minimum experience of 50 hours instrument flying. All subjects were known to be skeptical about head-up instrument flight.

Diagrams such as Figure 7 were used in explaining the experimental display of attitude and director information, with a view to performing a two-dimensional tracking task in simulated flight. For this purpose, the display was presented against an empty external field.

It was found that all subjects were unable to use the display. Although they would ordinarily be efficient in relating control actions to situations perceived in the external field of flight, they evidently could not behave in a similar way with a conformable display. The reason for this failure to transfer a known skill could have been that the pattern conformity principle was useless, but it was also possible that subjects had not been properly conditioned.

Case (2) Demonstration to Same Skeptical Subjects by Autopilot. Use of Display in Simulated Flight with Forward View

The same subjects, and a further group of six similar subjects, took part in the second phase of the experiment, where precautions were taken to avoid the possibility that subjects might be prevented from understanding the display by their own attitude. Operation of the display was demonstrated in an aircraft simulator against a forward view similar to that of flight (as in Experiment 3). In other words, pattern conformity was demonstrated in a dynamic situation, and subjects could see how the display was intended to look against the appropriate background.

To make the display work correctly, an autopilot was used to satisfy director demands so that subjects were relieved of almost all workload. However, the autopilot was adjusted to leave a small residual error, perceptible as a small displacement of the flight director, which subjects could reduce by using the control column to override and improve on the autopilot responses. Subjects were told they could switch out the autopilot entirely and assume manual control at any time.

Only one subject failed to use the display under these learning conditions. The remaining 12 disengaged the autopilot after an average time of 4-1/4 minutes and completed a tracking task, similar to that of Experiment 2, with mean modulus errors less than 1 deg.

The display could therefore be learned rapidly under the correct conditions, and most subjects were evidently able to transfer skills normally used in the external field to the conformable display. Perhaps the most striking feature of this result is the extent of the change in performance levels for Cases (1) and (2), from complete failure to almost complete success. New questions were to be answered: How important was the personal attitude of subjects? Could success be achieved by more highly motivated subjects with a less elaborate method of instruction?

Case (3) Instruction of Experienced and Motivated Subjects by Diagram. Use of Display in Simulated Flight without Forward View or Autopilot.

The subjects in this case were nine instrument flying instructors, all highly motivated about head-up presentation. Display usage was explained by diagram, after which simple attitude changes were demonstrated for a period of one minute, without steering commands. The presentation was made in the simulator against a blank external field, and the autopilot was not used. Immediately after this brief demonstration, subjects were given a typical tracking task.

It was found that all subjects performed satisfactorily under these conditions. Mean modulus heading errors were recorded, with an average for all subjects of 0.84 deg, and a standard deviation of 0.41 deg.

The display could thus be learned very rapidly indeed, without assistance by autopilot or forward view, and it was evidently possible for the customary skills of visual flight to be transferred to the display after receiving very simple instruction. Whether or not this possibility would be realized appeared to depend quite dramatically on the attitude of the user; on factors affecting the ability to start performing rather than the ability to perform, which was about the same for motivated and unmotivated subjects having a high level of flying skill. Then the question arose: Would the transfer of skill be less if subjects had less skill to transfer?

Case (4) Instruction of Inexperienced Pilots by Diagram and Simulator Demonstration, without Forward View or Autopilot.

No satisfactory learning curve could be plotted from the brief learning times of Cases (2) and (3). For this purpose, it would be desirable to have an expanded time scale, as might occur with inexperienced pilots using a conformable display. These pilots would have less skill in transforming the information derived from the external field into control actions and therefore less skill for transfer to the conformable display, which should thus take longer to learn.

Eight glider pilots acted as subjects in this case. Instruction was again by diagram, and then progressive maneuvers were practiced for five minutes without autopilot or forward view. Subjects next completed three 5-minute runs of a two-dimensional tracking task before resting. The series was continued for each subject until the standard deviation of the mean modulus tracking error was less than 0.12 deg of heading and 20 feet of height, over a group of five consecutive runs, when the display was considered to have been learned. Means and standard deviations for five qualifying runs are shown with learning times for six successful subjects in Table III. Two subjects failed to qualify.

The results show that glider pilots could learn the display in 20 to 30 minutes, which is reasonably small although longer than the time taken by an experienced pilot. It confirms the hypothesis that conformable fields are readily understood, but to an extent depending on the skill available for transfer. Further confirmation might be provided by showing that the display could be learned more readily than instruments having less conformity with the forward view, such as are found in the conventional flight panel. Before investigating this issue, however, it would be necessary to increase the information content of the experimental display to that of the conventional flight instrument system, with a view, also, to examining the learning process in real flight.

TABLE III
LEARNING TIMES FOR 6 SUBJECTS
WITH MEANS AND STANDARD DEVIATIONS OF MEANS
FOR TRACKING ERRORS IN 5 CONSECUTIVE QUALIFYING RUNS

SUBJECT	LEARNING TIME (MINUTES)	HEADING ERROR (DEGREES)		HEIGHT ERROR (FEET)	
		MEAN (OF 5 RUNS)	S.D.	MEAN (OF 5 RUNS)	S.D.
1	20	0.86	0.088	54.7	11.7
2	20	0.46	0.064	35.3	16.3
3	15	0.54	0.070	63.0	17.9
4	30	0.82	0.080	72.1	19.3
5	10	0.46	0.021	45.2	6.2
6	35	0.62	0.112	51.2	16.1

LEARNING TIMES ARE TOTALS FOR FAMILIARIZATION AND PREQUALIFYING RUNS.
QUALIFYING CRITERIA ARE S.D.'s LESS THAN 0.12 DEG AND 20 FEET.

Case (5) Inexperienced Pilots Learning Display in Real Flight. Comparison with Conventional System.

If a conformable display is understood by interpretative techniques similar to those in which the user is already skilled, learning should be possible under any conditions conducive to transfer, as the conditions of real flight may well be, either through the reinforcing influence of acceleration effects or through increased motivation. The investigation could thus be continued in real flight, with the precaution of using a control group of experienced subjects similar to those of previous cases.

The pupils were four inexperienced pilots (300 hours jet time), and a control group of four experienced pilots (1,400 hours or more). The arrangement shown in Figure 6 was used to provide instructor and pupil with the same display, forward view and controls. The previously described display of attitude and command information was augmented with symbolic, or nonpictorial, elements showing speed error and digital height, Figure 8, so that the complete presentation would be sufficient for instrument flight. Subjects were shown a movie and expected to use the display without prior training by simulator for takeoff, general flying, low-level flight and approach (a routine similar to that described under Experiment 4, Case (1)). The supervising instructor assessed the learning process in flights of about 1-1/2 hours duration.

It was found that all subjects were able to use the display *ab initio*. No differences were observed in the way each group learned to use the display, but inexperienced pilots were slower in learning to divide attention between display and forward view, i.e., in learning to use both fields efficiently.

The experimental display was thus learned in something between zero and 1-1/2 hours (clearly, it could not be considered fully learned until several maneuvers had been completed), and this is smaller by an order of magnitude than the learning time for a conventional flight instrument system. So a conformable display can evidently be learned more readily than a display showing little similarity to the forward view.

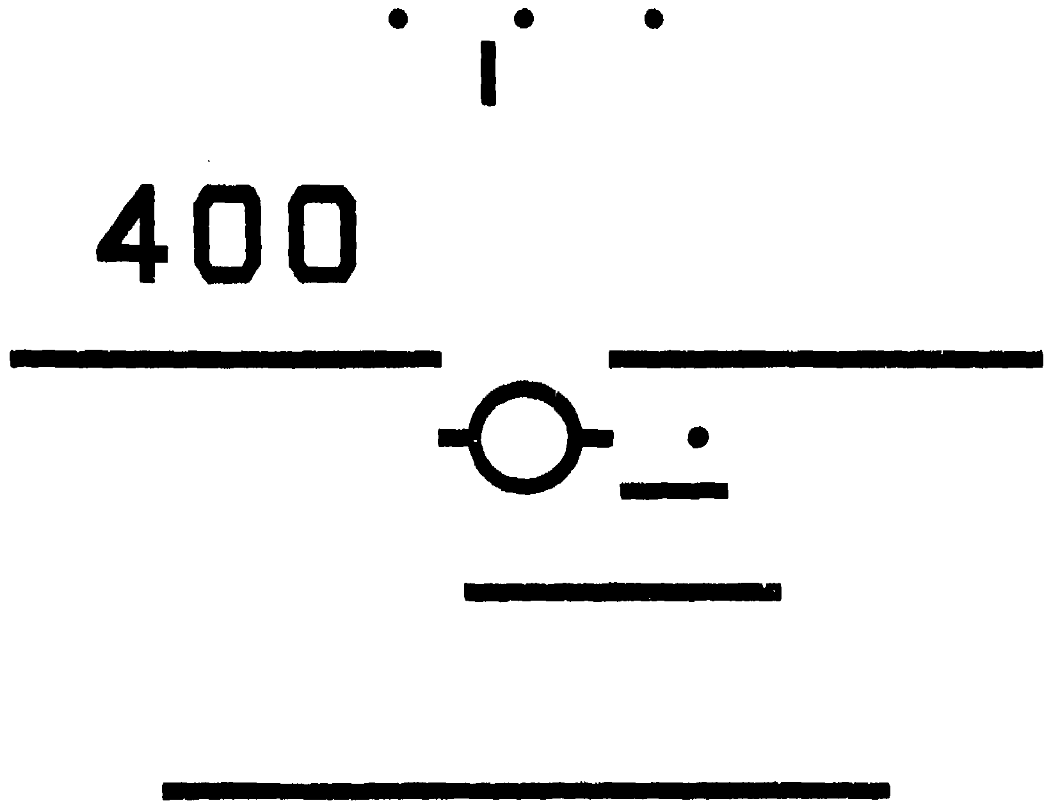


FIGURE 8. EXPERIMENTAL DISPLAY OF ATTITUDE, COMMAND, SPEED ERROR, AND DIGITAL HEIGHT INFORMATION USED IN FLIGHT TESTS.

The main usefulness of the control group was in showing that when greater skill can be transferred to the display, it is easier to draw information from both fields, presumably because the display field then needs less interpretative effort. This result emphasizes that head-up presentation cannot be evaluated on display usage alone. The significance of *ab initio* use by inexperienced pilots is that a little skill can be transferred quite rapidly in learning the display, suggesting that perhaps even less skill need be available in the subject.

Case (6) Non-Pilots Learning in Real Flight

As a final test of the influence of pattern conformity, two non-pilots were trained to use the experimental display in real flight, using the same cockpit arrangement, Figure 6, and display, Figure 8. In this case, experience in interpreting the forward view was limited to that gained from the mainly two-dimensional (dynamic) environment of ordinary life, and therefore comparatively little skill would be available for transfer to the display. It was thus to be expected that learning times would be greater than those for subjects in the previous cases.

The training procedure was similar to that of Case (5), but with more extensive practice in general flying before attempting low-level flight. After this extended learning period, subjects were able to use the display for terrain following and for the approach, although there was less evidence of critical observation in the forward view. It was thus possible to learn with only a modest level of skill available for transfer to the conformable display but, as expected, greater time was needed.

To sum up: The results of Experiment 5, collected in Table IV, were obtained with a display of attitude and command information designed to be understood by rules similar to, but not identical with, those applied to the forward view, and which could be accommodated within a limited optical field. The display could only be learned by unmotivated subjects with the help of autopilot and forward view, Cases (1) and (2), but motivated subjects of similar experience learned rapidly without these aids, Case (3), showing the significance of motivation in the learning process. With less flying experience, and therefore less visual flight skill available for transfer to the display, learning was slower, Case (4). With less conformity, learning was inferred to be slower, since greater times are needed to learn a conventional panel, in real flight, than the (augmented) display, Case (5). At the lowest level of skill, learning was still possible at reduced rate, Case (6). These results showed that the experimental display could be learned, given adequate motivation, at a rate depending on experience in using the forward view for visual flight and on the extent of conformity, with a smallest possible learning time in the region of zero.

The results are consistent with the concept of transferring skill between conformable fields, although it was not necessary for both fields to be present at the same time, Cases (3) and (4). With both fields present and conformable, there was little difficulty in interpreting them, Case (5), although more time was needed to learn how to observe in both fields. It seems reasonable to believe that the flow of information is better when the same skill can be used in each field than in the situation when skill cannot be transferred between fields.

TABLE IV

RESULTS OF EXPERIMENT 5 ON PATTERN CONFORMITY AND LEARNING

CASE	SUBJECTS	FLIGHT ENVIRONMENT	INSTRUCTION METHOD	INSTRUCTION AIDS	LEARNING CRITERION	LEARNING TIME
1	7 EXPERIENCED PILOTS, UNMOTIVATED	SIMULATED	DIAGRAM	NONE	GENERAL HANDLING ABILITY	INFINITE
2	7 EXPERIENCED PILOTS, UNMOTIVATED	SIMULATED	NONE	AUTOPILOT AND FORWARD VIEW	TRACKING ERROR LESS THAN 1°	4-1/4 MIN
	+6					
3	9 EXPERIENCED PILOTS, MOTIVATED	SIMULATED	DIAGRAM AND ATTITUDE DEMONSTRATION	NONE	TRACKING ERROR LESS THAN 1°	1 MIN
4	8 INEXPERIENCED PILOTS	SIMULATED	DIAGRAM AND MANEUVER PRACTICE	NONE	S.D.'s LESS THAN 0.12°, 20 FT	20-30 MIN
5	4 INEXPERIENCED PILOTS 4 EXPERIENCED PILOTS	REAL	USE IN FLIGHT	MOVIE	INSTRUMENT FLIGHT AND EXTERNAL OBSERVATION TO INSTRUCTOR'S SATISFACTION	LESS THAN 1-1/2 HR, POSSIBLY ZERO
6	2 NON-PILOTS	REAL	USE IN FLIGHT	MOVIE	LIMITED USE TO INSTRUCTOR'S SATISFACTION	LESS THAN 1-1/2 HR, BUT GREATER THAN FOR (5)

EXPERIMENT 6. INFLUENCE OF PATTERN CONFORMITY WITHIN DISPLAY

Case (1) Simulated Flight

It has been shown that a conformable display is easy to learn and is easy to use with the forward view, but the influence of conformity in improving the total flow of information has only been inferred. A more direct approach can be made by measuring performance of tasks associated with the display field, comparing a display having a single scheme of interpretation with an equivalent display having more than one scheme. Then, if better performance results with the single-scheme display, conformity within the display must improve the flow of information. In this way, it should be possible to measure the effect of eliminating differences of interpretation, by confining attention to the display field.

The experimental display provides command information in two dimensions, which is supported by attitude information showing the nature of the maneuver performed. The additional attitude information should improve performance, because Poulton[9] has shown that better tracking is possible when displaying both the error to be corrected and the direct effect produced by control actions. Beyond this, there may be a further improvement due to the method of presentation, insofar as the display is interpreted by one set of rules.

The experiment was designed to investigate, by change of display pattern, the progressive effects of adding information and of using a single framework. Three displays were used, each presenting the same command information, according to the same convention of movement (fly-to), Figure 9. A zero-reader display showed only command information. A so-called roller-blind display showed command and attitude but with different coordinate axes for each type of information. The experimental display showed both command and attitude information within the same framework. Any difference between performance with zero-reader and roller-blind displays would reflect the influence of added information; differences between roller-blind and experimental displays would reflect the influence of framework or interpretative scheme.

Twelve pilots of differing skill acted as subjects, performing a tracking task of six level 90-deg turns at a prescribed rate of 3 deg per second, in simulated flight. Subjects performed the task twice with each display, in balanced order, the conventional displays being presented head-down and the experimental display head-up (a difference of display position producing no measurable effect). Mean modulus errors in azimuth and elevation were measured to an accuracy of ±2 percent.

Analysis of variance showed that error differences for displays were highly significant in the heading channel ($P = 0.001$) and less significant in elevation ($P = 0.05$). Subject differences were also significant, as was reasonable, but all other sources of variance gave insignificant effects. These results are summarized in Table V.

It was clearly permissible to compare mean values for the three displays, and these are shown in Table VI. In azimuth, the mean value (of the mean modulus error) for the experimental display was 0.51 deg, for the roller-blind display it was 0.98 deg, and for the zero-reader it was 1.44 deg. These values are very nearly in the ratio of 1:2:3, and each is clearly separated by a 5-percent critical difference of 0.36 deg. In other words, tracking errors were distinctly and progressively reduced in the ratio 3:2:1 in the demand channel as the display changed from simple command, through command and attitude in mixed coordinates, to command and attitude in the same framework. Mean values were not so clearly separated in the height channel, where differences between displays were only just significant.

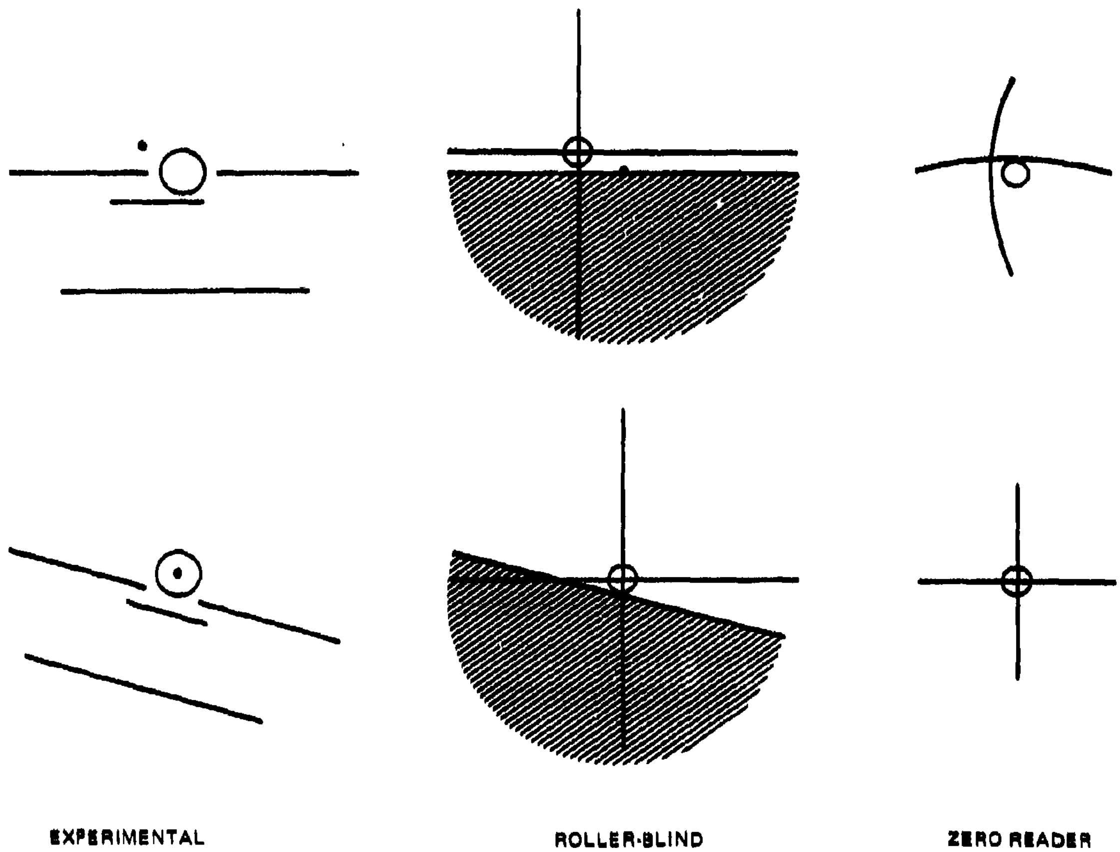


FIGURE 9. DISPLAYS OF COMMAND AND ATTITUDE USED IN EXPERIMENT 6. Commands for climbing turn to left shown above, satisfied commands shown below. Experimental display has one, and Roller-Blind two frameworks; Zero Reader only shows commands.

The experimental results show the expected improvement in tracking due to increase of information content and a further improvement due to reduction of interpretative complexity, these effects being especially clear in the demand channel. They confirm that an attitude-augmented flight director is better than a simple flight director, and show clearly the beneficial effect of eliminating differences of interpretation. It is concluded that conformity within the display improves information flow to an extent justifying application in display design.

Case (2) Real Flight

The results obtained in simulated flight suggest that it may be possible to improve the standard of instrument flying appreciably by using a display having a single interpretative scheme. For, if similar results could be obtained during real flight, it should be possible to fly much further down the approach path than is possible with zero-reader or roller-blind types of flight director, because departures from the ideal path would be smaller.

This possibility was investigated by observing tracking errors in real flight using the experimental display of Figure 8 and the disposition of Figure 6. Four pilots experienced in using head-up

TABLE V
RESULTS OF ANALYSIS OF VARIANCE FOR TRACKING ERRORS
OF 12 SUBJECTS USING 3 DISPLAYS FOR 2 RUNS

SOURCE OF VARIANCE	HEADING ERROR DIFFERENCES	HEIGHT ERROR DIFFERENCES
SUBJECTS (S)	P = 0.01	P = 0.05
DISPLAYS (D)	P = 0.001	P = 0.05
RUNS (R)	NOT SIGNIFICANT	NOT SIGNIFICANT
SD	NOT SIGNIFICANT	NOT SIGNIFICANT
SR	NOT SIGNIFICANT	NOT SIGNIFICANT
DR	NOT SIGNIFICANT	NOT SIGNIFICANT

TABLE VI
MEAN TRACKING ERRORS FOR 3 DISPLAYS

	HEAD-UP	ROLLER-BLIND	ZERO-READER
HEADING* (DEGREES)	0.51	0.98	1.44
HEIGHT (FEET)	29.8	51.1	66.7

*5 PERCENT CRITICAL DIFFERENCE = 0.36 DEG

presentation flew 33 runs, while recording mean modulus errors with respect to an ILS approach path. It was found that performance in elevation was such as to keep the director index within the aircraft reference circle, corresponding to a height error of 4 feet at an arbitrary height of 100 feet, for the "gearing" used in display. (Performance in azimuth was less accurate because of Dutch Roll.)

It is usually considered difficult to place an aircraft within 12 feet of the glide slope at a height of 100 feet when conventional instruments are used. The experimental display allowed this figure to be reduced by a substantial margin, thus confirming the simulated flight results and showing that a single framework display permits worthwhile improvement in the standard of instrument flying. Furthermore, since an error less than 12 feet at a height of 100 feet is considered acceptable for Category III approaches, this type of display should allow manual touchdown in all weather. A similar result was obtained independently by Morrall.[10]

To sum up Experiment 6: It should be possible to obtain direct evidence of the effect of removing interpretative differences by unifying the framework of a display presentation and measuring any change in performance. Simulated flight tests with a single-scheme display showed, in comparison with a two-scheme display, an almost 2-to-1 reduction in tracking errors, and real flight tests showed a marked improvement on conventional standards of instrument flying, allowing an aircraft to be placed well within the Category III window at 100 feet, and suggesting the possibility of all-weather manual landing.

These results show the effect of conformity in improving information flow, by allowing different parts of a display to be understood by similar rules, and to an extent justifying application in display design. In the case examined, conformity was internal to the display, but this display could be regarded as two fields of information superimposed in a common framework, which otherwise would be presented in two frameworks. It follows that a similar improvement should occur on reducing interpretative differences between display and forward view when these fields are superimposed, and such a mechanism is consistent with the ease of use experienced with the conformable display in flight, Experiment 5, Cases (5) and (6).

SUMMARY: INFLUENCE OF PATTERN

In a conformable display, the pattern is designed to reduce differences of interpretation, e.g., between display and forward view, and this should allow a transfer of skill between fields and an improvement in the flow of information. Experiment 5 shows that a flight display of this kind can be learned at a rate depending on piloting experience and extent of conformity, provided subjects are sufficiently motivated, with a limiting learning time of zero. This result suggests a transfer of skill between conformable fields either with or without the forward view present, the display being used readily in either condition, but with more time (up to 1-1/2 hours) needed to learn the concurrent use of display and forward view.

Experiment 6 shows that conformity within the display field improves performance and information flow, in real and simulated flight, to an extent justifying application to display design. By analogy, conformity of display and forward view should also improve information flow, which is consistent with the ease of use found in Experiment 5.

The influence of pattern (which is assumed to be viewed under uniform, matched conditions of brightness and color) is thus shown in the effect of designing a display to be understood by rules similar to, but not necessarily identical with, those applied to the forward view. Success in applying this concept of conformity without overflowing the limited optical field available for head-up presentation depends on the symbols chosen, which may include flight director and artificial horizon. Pattern conformity can be used to allow ease of learning and high tracking accuracy, and the significance of its influence lies in the possibility of achieving manual landings in all weather.

DISPLAY ERRORS AND LIMITATIONS AFFECTING SYMBOLS

It is clear from the preceding work that the characteristic advantages of head-up presentation depend on an identity of position and a similarity of form (pattern) for display and forward view. There appears to be only one way of achieving identity of position, i.e., by reflecting collimation, but there may be several ways of achieving similarity of form, e.g., by using flight vector and runway symbols instead of a flight director symbol. However, there may be risks in using other symbols, such as the ground object type. Besides the field limitation effect, noted briefly in connection with pattern requirements (page 15), there may be effects due to other characteristics of the system, such as errors. The object in this section is to discover the significance of display errors and limitations, in relation to symbols available for, but not necessarily suitable to, head-up presentation.

Since head-up presentation depends on choice of display position and form, small departures from an ideal configuration may have adverse effects and it is conceivable that these errors may affect different symbols in different ways. Errors of position occur when a symbol is placed incorrectly in the display field, whether through misalignment of a reflecting collimator, or through an incorrect or a nonlinear deflecting voltage applied to a cathode ray tube, and the influence of position error on a given symbol should depend on the significance of position in conveying the symbol's meaning. Similarly, if a pattern is generated by an electronic method (to achieve design flexibility and freedom from inertial effects), there may be errors of form due to circuit faults, and their influence should depend on the way shape is used to convey the meaning of a symbol. It is therefore to be asked how position and form errors affect symbols; e.g., whether a runway symbol is more affected by false position than alphamerics, and whether the additional information latent in a complex symbol form is wasted through increased chance of form errors.

Position or form errors which vary rapidly may be regarded as display noise. An electronic display is not necessarily subject to form noise because the pattern may be generated by time-sharing methods but position noise is distinctly possible because a cathode ray tube is highly susceptible to signal noise, affecting some or all of the symbols; moreover, the whole display field may be affected by mechanical vibrations, or the display aperture may be disturbed, though the latter effect should matter only if the field becomes partially masked. Display noise is thus perceived as partial- or whole-field noise, with or without aperture motion, and these noise types will be considered in their effect on symbols, using the results for position error but giving particular attention to flight vector and runway symbols, which are subject to special noise effects. (Flicker effects are ignored because they can be eliminated in practice by raising the frame rate above about 50 cycles per second.)

The display field in head-up presentation is frequently smaller than the observer's natural field of view, as a result of limiting the space used to install a reflecting collimator in the instrument panel. This may cause symbols to move out of the display field if they have the same angular displacements as objects in the external field, and it may cause an apparent enhancement of angular velocity within the reduced visual framework. Moreover, as symbols are added the visual field will become cluttered, so that symbols may need to be disposed according to their importance and so as to reduce interference. It may also be necessary to restrict the size and complexity of symbols, without destroying their identities. Field limitation effects should thus be important in deciding the types of symbol to be shown and how they should be controlled. Of less importance is the influence of display brightness, because sufficient operational visibility can be obtained with high brightness tubes, operating at about 15 kV, or by the use of narrow-band color filters (with some loss of information in the external field), so that brightness is not a limitation.

It will be shown that errors and limitations affect symbols differently, to an extent affecting the choice of symbols and with results which can be used to design displays. These results should also be used to compare displays, for it can be misleading to evaluate in terms of a particular attribute, such as display content,[11] since the aim of head-up presentation is to transfer information from both display and forward view, therefore other attributes, such as clutter, are relevant.

INFLUENCE OF POSITION ERROR ON SYMBOLS

Alphameric Symbol

The meaning of an alphameric symbol is independent of its position. For example, the meaning of the character A, or the numeral 8, is the same wherever the symbol is found. Alphameric symbols should therefore be immune to position error, and flight experience with a digital presentation of height, Figure 8, shows that no particular care is needed in maintaining an exact position for this type of symbol. It would, nevertheless, be possible for misorientation at a given field position to hinder access to the symbol's meaning, as when a symbol is presented upside down, but this is only remotely possible after once setting up an electronic display. Position errors are thus unlikely to affect alphameric symbols, and similar reasoning may be applied to a nonpictorial symbol, such as the speed error symbol in Figure 8. This result is shown in Table VII, together with results for other symbols.

TABLE VII
INFLUENCE OF POSITION ERROR ON SYMBOLS

SYMBOL	SIGNIFICANCE OF POSITION	INFLUENCE OF POSITION ERROR	REMARKS
ALPHAMERIC	NONE	NEGLIGIBLE	
REFERENCE	ARBITRARY	NEGLIGIBLE	
ARTIFICIAL HORIZON	RELATIVE	ONLY IN BANK	
FLIGHT VECTOR	ABSOLUTE	NOT NEGLIGIBLE	
GROUND OBJECT	ABSOLUTE	NOT NEGLIGIBLE	WHEN USED WITH FLIGHT VECTOR SYMBOL
FLIGHT DIRECTOR	RELATIVE	NEGLIGIBLE	DOES NOT DELAY RUNWAY ACQUISITION WHEN SYMBOL IS DISTRIBUTED

Reference Symbol

The aircraft reference symbol serves to show the direction of an arbitrarily chosen aircraft axis in relation to the forward view. The effect of position error is to cause the symbol to present a different axis, which will only be significant when the pilot needs a specific alignment with the external world. There appear to be few cases outside the realm of weapon-aiming where this type of alignment is mandatory, even during the ground run, and the influence of position error on the reference symbol is therefore small.

Artificial Horizon Symbol

The artificial horizon represents a truly horizontal direction, which is an abstract concept only approximated in rare cases by natural features, such as a cloud layer or the sea horizon. (The dip of the sea horizon in minutes of arc is approximately the square root of the height in feet.) A position error in the plane of elevation is therefore almost always undetectable, whatever the scale of elevation may be, and is thus insignificant. An error in bank angle, however, is detectable as a lack of parallelism; e.g., with a cloud layer, and flight experience shows that the tolerable misalignment is of the order of 5 degrees.

Flight Vector Symbol

The direction in which an aircraft moves, as distinct from the direction in which it points, can be shown by a flight vector symbol. If the symbol is misplaced from the absolute position of the flight vector in the external field, the aircraft will move sideways with respect to the direction shown by the symbol, causing apparent drift between flight vector and any adjacent ground object. If external visibility is good, or if an accurately positioned ground object symbol is displayed, the error may be detected and corrected, probably without serious effect on performance, but if the error remains undetected, the aircraft will proceed in the wrong direction. Position error of the flight vector symbol can thus exert an influence on performance.

Ground Object Symbol

It is generally assumed that the apparent position of a ground object symbol should represent the absolute position of the corresponding object in the external field. Since this position varies with aircraft attitude and position, it cannot be used by itself as a single source of information. When it is used in conjunction with a flight vector symbol (e.g., to show where the aircraft will meet the ground plane), both symbols may be subject to position error. If these errors are undetected and additive, the flight path will be doubly affected, so the influence of position error on a ground object symbol cannot generally be neglected.

Flight Director Symbol

Information is conveyed essentially by the relative position of elements within a flight director symbol, and it is therefore possible for the whole symbol to experience position error without affecting information content. This conclusion is amply confirmed by extensive flight experience of accurate touchdowns in crosswind conditions, without drift compensation of the display. Information is degraded, however, if elements suffer different position errors (an effect equivalent to signal error) but this possibility is reduced in electronic displays if time-sharing methods are used to generate the symbol, and the influence of position error on the flight director symbol can then be considered small.

While position error does not greatly affect information gained from a flight director symbol in the display field, it is conceivable that it may nevertheless affect the visual situation in the external field. For if there is any tendency for the user to fixate the center of the (misaligned) display, there may be delay in acquiring external ground objects thrown off-axis by misalignment. However, the flight director symbol used in the experimental display, Figure 7, should enable commands to be followed without fixating, because of what may be called the "distributed" form of the symbol. So it may be possible to show freedom from delay in acquiring off-axis ground objects when this type of flight director symbol is in use, and position error will then be almost entirely without effect.

EXPERIMENT 7. EFFECT ON RUNWAY ACQUISITION OF MISALIGNED DIRECTOR SYMBOL HAVING DISTRIBUTED FORM

The object of the experiment was to find out whether misalignment of a distributed form of flight director symbol delayed visual acquisition of a runway, in simulated flight conditions. The experimental display of command and attitude information, Figure 7, was presented by reflecting collimation against an initially blank forward view, and was used to track a series of shallow turns, of 2 to 5 degrees amplitude. The pilot's forward view of a runway appearing through cloud was simulated with 6 degrees of freedom. Starting conditions were prescribed by the experimenter to give unpredictable misalignments of display and emergent runway. Subjects were to use the display with given accuracy (1 degree error), to establish information flow from the display, and they were to press a switch on first sighting the runway. At this point, the angle of misalignment and the acquisition range would be determined.

Subjects were 4 non-pilots who each completed at least 15 runs with misalignments in the range 2 to 10 degrees, which is sufficient to cover a large proportion of the values likely to be experienced in practice. The results, Figure 10, showed no correlation between acquisition range and misalignment, there being no significant difference in range for all positions of the sighted runway.

Since the runway was acquired without change of acquisition range, for all angles of misalignment, there was no tendency to observe only the central region and ignore visual objects appearing at the edge of the visual field. The experimental method did not show whether or not subjects fixated centrally but the result could be explained on either basis. If subjects fixated the middle of the display field, off-axis effects tending to degrade vision were evidently balanced by factors acting in the opposite sense, such as changes of position or brightness. If there was no central fixation, the index position being inferred from the overall form of the director symbol, subjects were able to conduct rapid small-angle searches without loss of tracking performance.

A distributed form of director symbol can thus be immune to position error, as regards tracking information gained from the display and information concerning ground objects in the external field. Because of this immunity, the same display could be used according to the gun-sighting convention, in which the director index becomes a ground stabilized symbol and the aircraft reference a floating symbol, without change in the relative position of the two elements. The self-evident nature of the display, and consequent ease of learning, would then no longer be guaranteed, because of the moving reference symbol. It is also interesting to note that because position is not critical for this form of symbol it may be altered to suit the users' convenience (e.g., by means of movable reflector plates, Figure 6), and flight tests have shown a dispersion of about 2 to 4 degrees in preferred positions for given modes of flight.

The influence of position error on symbols is summarized in Table VII, using the analytical and experimental results. Symbols with meanings which depend on absolute position are more affected by position error than those having meanings independent of position, or dependent on arbitrary, or relative positions. Ground object and flight vector symbols are thus less suitable for head-up presentation than flight director, reference, and alphameric symbols.

INFLUENCE OF FORM ERROR ON SYMBOLS

Alphameric Symbol

The meaning of an alphameric symbol is conveyed by its characteristic shape, and it does not matter whether the symbol is large or small, or whether there are small changes of form, as are found in different styles of writing and printing. Alphamerics are thus not critically affected by form error.

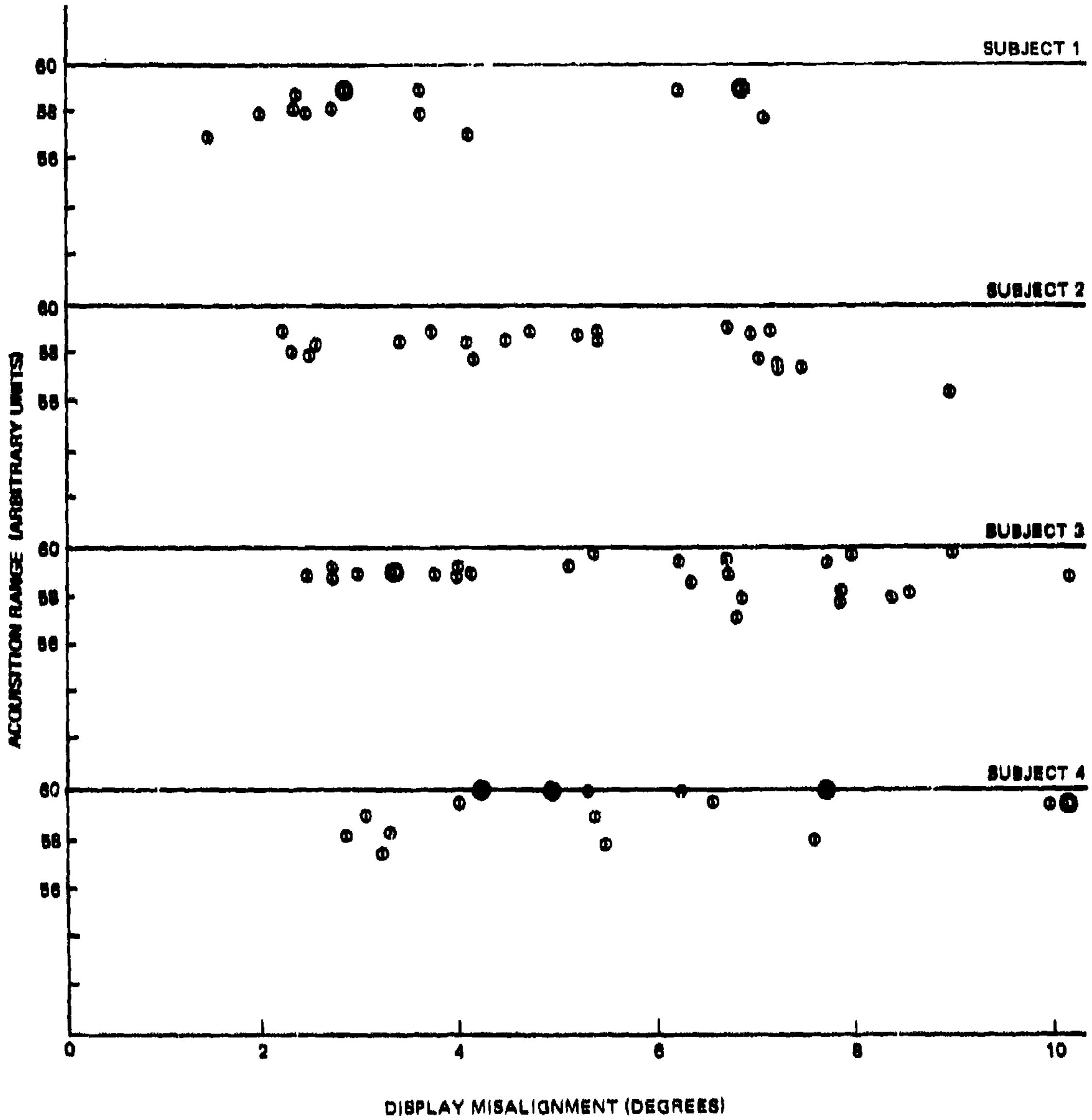


FIGURE 10. RUNWAY RANGE AND DISPLAY MISALIGNMENT FOR 4 SUBJECTS IN EXPERIMENT 7.

Reference, Artificial Horizon and Flight Vector Symbols

When symbols are used to show a position -- such as a fixed reference position, the angular position of a horizon, or the position of a flight vector -- their form must allow each symbol (assumed to be used only once) to be identified, and its intended position to be shown. If characteristic geometrical shapes, such as circle, line or cross, are used it should be possible to deform symbols without loss of identity as long as the characteristic shapes can be distinguished. It may even be possible to degrade forms beyond this point if symbols can be recognized in other ways, e.g., by movement characteristics. It should also be possible to deform the same type of symbol without losing the ability to show a position which might, for example, still be recognized as the center of an ellipse.

the mean position of a wavy line or the intersection of skew lines. When these simple and distinctive geometrical forms (circle, line, and cross) are used as reference, artificial horizon, and flight vector symbols, the arguments given here indicate that none of them will be affected critically by form error.

Ground Object Symbol (Runway)

A ground object may be shown in self-evident manner as a simple perspective transform of its ground plan outline. The symbol may then be relatively complex; e.g., a runway may be shown as a quadrilateral, and there will be a correspondingly small chance of destroying identity through form error. On the other hand, the form of a ground object symbol may be used to judge aircraft position, by perspective interpretation, and in this respect form error may be less tolerable.

It is generally agreed that position in the vertical plane through runway centerline cannot be judged with any accuracy from the apparent shape of the runway but lateral position with respect to the centerline can be judged from the angle at which centerline and horizon intersect. This angle can be observed as a departure from perpendicularity, which should be capable of estimation to about 1 deg,[12] corresponding to an accuracy of about H/60 in estimating lateral offset, where H is the height of the observer. In other words, lateral position can be judged accurately if the linear form of the symbol is generated with a directional accuracy of about 1 deg, and the symbol's usefulness thus depends critically on form error, a small change causing loss of information.

Flight Director Symbol

Arguments based on the powers of identification and location of simple geometrical shapes have been used to suggest that a reference symbol; e.g., of circular form, need not be affected critically by form error. The same arguments could be used for a display element in the form of a single dot, which should also be easily distinguished and located. It would then be possible to conclude that a director symbol, of dot-and-circle type, should be insensitive to form error.

The addition of other elements to support the director index, as in the experimental display, should improve distinctiveness and perhaps increase the amount of deformation needed to confuse symbols At the same time, there might be no loss of the power to indicate position through deforming the supporting elements, a deformed pathway still having the power to lead from here-to-there. In this case, an augmented dot-and-circle type of director display would also be insensitive to form error.

EXPERIMENT 8. INFLUENCE OF FORM ERROR IN COMMAND AND ATTITUDE DISPLAY

The object of the experiment was to investigate symbols having functions chiefly of identification and location, such as the reference and flight director symbols of the experimental display, which are expected to be insentive to form error. Minor circuit changes were used to make deformations in selected components of the command and attitude display, as shown in Figure 11, D1 to D8, where D9 is the standard form. The reference symbol was deformed into an ellipse, and an enlarged circle, in D1 and D2. The envelope of the director symbol was changed to give a funnel-shaped, and a truncated symbol, in D3 and D4. The envelope was separated into halves, laterally and vertically, in D5 and D6. Vertical spacing was altered in D7, and in D10 (not shown). All components, including the horizon, were grossly deformed in D8.

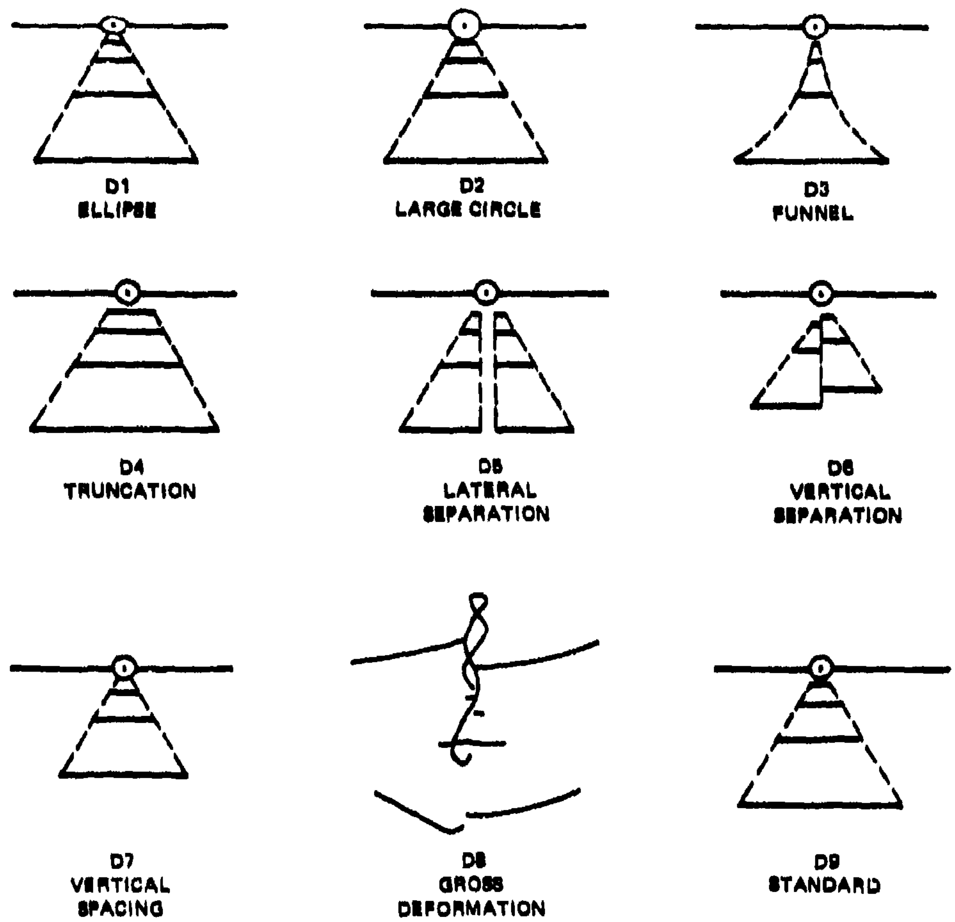


FIGURE 11. FORM ERRORS IN EXPERIMENT 8

The display was again presented by reflecting collimator in an aircraft simulator. Each form of the display was used once by twelve experienced pilots, in balanced order, for a tracking task of 6 level turns through 90 deg, at 3 deg per second. Familiarization was allowed with the standard form, D9, for longer than the known learning time, and the experimental runs were completed in two groups, separated by a rest period, while recording error scores in azimuth and elevation.

Because of its preponderant effect, the score for D8 (gross deformation) was excluded from the analysis of variance, which was used to show that display differences were highly significant in heading ($P = 0.001$): subject differences were also highly significant, in both channels. Means for the different display forms are compared in Table VIII, where it is seen that D5 (lateral separation) is the only mean besides D8 to be separated from the rest by more than a critical difference at the 0.1 percent level (0.216 deg). The mean for D8 (gross deformation) was just greater than four times the mean for all displays.

The results showed that several small changes of form could be made in reference and flight director symbols without impairing distinction between symbols, or estimation of the position represented by an element. The only form change affecting the estimation of position was lateral separation of the director symbol into halves, with consequent ambiguity of azimuth command and corresponding

TABLE VIII
MEAN TRACKING ERRORS FOR DEFORMED DISPLAYS

DISPLAY FORM		HEADING ERROR* (OVERALL MEAN, IN DEGREES)
D1	ELLIPTICAL REFERENCE	0.62
D2	LARGE CIRCLE	0.65
D3	FUNNEL ENVELOPE	0.63
D4	TRUNCATED ENVELOPE	0.69
D5	LATERALLY SEPARATED	0.93
D6	VERTICALLY SEPARATED	0.66
D7	VERTICALLY COMPRESSED	0.65
D8	GROSSLY DEFORMED	4.27
D9	STANDARD	0.62
D10	VERTICALLY COMPRESSED	0.61

*CRITICAL DIFFERENCE AT 0.1 PERCENT LEVEL = 0.216 DEG

drop in performance. Gross deformation, and therefore gross uncertainty of position, caused an appreciable loss of performance but without complete loss of control, indicating that symbols could still be distinguished, presumably by velocity characteristics, and their approximate positions inferred. The deformations found to be effective in degrading performance were quite complex, and thus unlikely to occur frequently. It could therefore be concluded that symbols having functions chiefly of identification and location, such as the experimental forms of reference and director symbols, are largely insensitive to form error.

The influence on symbols of form error is summarized in Table IX, where symbols are classified according to their information function. The evidence for considering alphamerics to be insenitive to form error is based on the common acceptability of alternate forms of the same character or numeral. The general immunity of symbols having powers of identification and of showing position is assumed from the experimental result for reference and director symbols. The evidence for taking a runway symbol to be critically sensitive to form error is based on its function of allowing aircraft position to be inferred from judgment of perpendicularity. In brief, form error appears to be chiefly important in the ground object symbol, of runway type, which is evidently the least suitable symbol for head-up presentation.

INFLUENCE OF NOISE ON SYMBOLS

It is unnecessary to consider the detailed effects of noise on all symbols because results have already been obtained for position error, of which noise may be regarded as a variation in time, variations of form error being relatively unlikely. On this basis, Table VII can be used to show that the influence of noise on flight vector and runway symbols should not be ignored because they are strongly influenced by position error. They are also subject to the special data source noise effects discussed below. On the other hand, alphamerics, reference, horizon and director symbols may be relatively insensitive to noise because they are less affected by position error. Whole-field noise, affecting the position of all symbols, should have little effect in this case, but partial-field noise may affect such of these symbols as have meanings dependent on the relative position of display elements, viz. horizon and director symbols.

TABLE IX
INFLUENCE OF FORM ERROR ON SYMBOLS

SYMBOL	INFORMATION FUNCTION OF SYMBOL FORM	INFLUENCE OF FORM ERROR
ALPHAMERIC	ENCODING	NOT CRITICAL
REFERENCE HORIZON FLIGHT VECTOR FLIGHT DIRECTOR	IDENTIFICATION AND SHOWING POSITION	NOT CRITICAL
GROUND OBJECT (RUNWAY)	IDENTIFICATION AND ALLOWING OBSERVER'S POSITION TO BE INFERRED	CRITICAL

EXPERIMENT 9. INFLUENCE OF NOISE ON EXPERIMENTAL DISPLAY

The object of the experiment was to investigate the influence of different kinds of noise on a command and attitude display, containing symbols which should be sensitive only to partial-field noise. The experimental display was presented against a dark ground by a reflecting collimator in the aircraft simulator. For whole-field motion, the entire cockpit and display installation was disturbed as an angular movement in elevation. For whole-field motion relative to the collimator aperture, a step voltage was applied to the Y-plates of the display-generating cathode ray tube at irregular intervals. Partial-field motion was introduced by applying a noise signal to the director symbol, causing relative movement of index and reference in a vertical direction. In all, seven alternative states of the display were available, including the standard form, partial-field motion at four different levels and whole-field noise with and without aperture motion.

The experiment was carried out with four pilots qualified in instrument flight each performing a tracking task of 6 level turns through 90 deg at 3 deg per second, using the display in each of the 7 alternative noise states, in balanced order. Familiarization was allowed for 5 minutes with the standard form, after which the experimental runs were completed without break in a period of about 40 minutes, while error scores were recorded.

Analysis of variance showed highly significant score differences for display states and for subjects ($P = 0.001$), and means for each state of the display are shown in Table X. It is seen that values for the standard display, 54.7 feet, and for both cases of whole-field motion, 52.4 feet and 41.4 feet (D2 and D7), are not separated by a 5 percent critical difference of 17.8 feet. But values for each state of partial-field motion, D3, D4, D5, and D6, exceed a mean value of 49.5 feet, for standard and whole-field states, D1, D2, and D7, by more than the critical difference at the 0.1 percent level, 27.3 feet. There is also a successive increase in score for each increased noise level, with values which can be shown to be approximately half the scores accumulating in the absence of any tracking action by subjects. In other words, subjects attempted to follow disturbances from a steady height, during level turns, to an extent which appeared to depend on noise level. Less pronounced effects were observed in the heading channel, where noise was not applied.

TABLE X
MEAN SCORES FOR NOISE STATES OF DISPLAY

NOISE STATE (VERTICAL DISTURBANCE)		OVERALL MEAN ERROR IN HEIGHT* (FEET)
D1	STANDARD FORM	54.7
D2	WHOLE-FIELD MOTION RELATIVE TO APERTURE, AS 0.8 DEG STEP FUNCTION TWICE PER TURN	52.4
D3	PARTIAL-FIELD MOTION OF RMS AMPLITUDE 0.93 DEG	99.6
D4	PARTIAL-FIELD MOTION OF RMS AMPLITUDE 1.07 DEG	110.0
D5	PARTIAL-FIELD MOTION OF RMS AMPLITUDE 1.22 DEG	119.8
D6	PARTIAL-FIELD MOTION OF RMS AMPLITUDE 1.35 DEG	144.8
D7	WHOLE FIELD MOTION OF RMS AMPLITUDE 0.56 DEG	41.4

*CRITICAL DIFFERENCE AT 5 PERCENT LEVEL 17.8 FEET
AT 0.1 PERCENT LEVEL 27.3 FEET
(CORRECTED FOR 4 SOURCES OF VARIANCE)

The experimental results show that whole-field noise, with or without aperature motion, had no measurable effect on the transfer of information from a display comprising reference, artificial horizon and flight director symbols. On the other hand partial-field noise applied to the flight director caused loss of performance through following spurious information. These results are reasonable for symbols having meanings dependent on the relative position of display elements.

SPECIAL DATA SOURCE NOISE EFFECTS

Flight Vector Symbol

The flight vector symbol is particularly susceptible to data source noise when its computation is based on measurement of the angle of attack, since turbulence may cause signal variations as great as the quantity measured. These variations may be smoothed out but information is then lost through the influence of the time constant, tending to delay changes in the position of the flight vector. Flight tests have shown this indirect effect of noise to be unacceptable to pilots.

Ground Object Symbol

The influence of data source noise on a ground object symbol depends on the method used to generate the symbol. If the symbol is formed by positioning distinctive features, such as corners of a runway, with respect to a datum determined by the data source signal, the effect of source noise will be to disturb the symbol as a whole. On the other hand, if the position of each feature is determined by an independent data source signal, it will be possible for the symbol to change shape in a random manner. The influence of this type of form noise could be felt when the shape of the symbol is used to estimate aircraft position.

Table XI summarizes the influence of noise on symbols. In the case of alphamerics, freedom from noise influence is assumed from their immunity to position error, with the further assumption that no visual blurring arises through high-frequency noise (which can usually be filtered without affecting the dynamic aspects of an information display of this kind). Symbols of the relative position type; i.e., horizon and director, used in conjunction with a reference symbol, are known from Experiment 9 to be affected only by partial-field noise, which can be ignored because flight experience shows no difficulty in filtering this kind of noise without loss of information. In the case of flight vector and ground object symbols, noise effects cannot be ignored because these symbols are of the absolute position type, which are sensitive to position error, and they may be subject to ineradicable effects of data source noise. The latter symbols are thus unsuitable for head-up presentation.

TABLE XI
INFLUENCE OF NOISE ON SYMBOLS

SYMBOL	INFLUENCE OF NOISE
ALPHAMERICS	NEGLIGIBLE
REFERENCE ARITFICIAL HORIZON FLIGHT DIRECTOR	NEGLIGIBLE
FLIGHT VECTOR GROUND OBJECT	NOT NEGLIGIBLE

INFLUENCE OF LIMITED DISPLAY FIELD ON SYMBOLS

Displacement Effect

Symbols which represent flight vector and ground object as absolute positions will have the same angular displacements as corresponding objects, imaginary or real, in the external world. They may therefore reach the edge of the display field after quite small changes of attitude, especially if the symbol itself covers a relatively large area of the display. A similar effect may occur through change of height, leading to a change of symbol size. The influence on these symbols of a limited display field is to cause, mainly through the former (displacement) effect, a loss of information which cannot be considered negligible.

On the other hand, a director symbol need not have the same angular displacements as an object in the external field since it is only required to show the direction and amount of a tracking command, to some convenient scale. It may reach the edge of the field but it can then be "parked" without loss of information and its position may be found rapidly with the help of supporting elements, such as those used in the experimental display. The influence of field limitation on the flight director symbol can therefore be ignored.

As previously discussed, the artificial horizon need not, and possibly should not, have the same angular displacement in elevation as the visible horizon. This symbol may be retained within the display field by elevation scaling, until zenith or nadir symbols appear, and it is not driven outside the field by changes of bank angle. Even less difficulty is found in retaining reference and alphameric symbols since they are not required to bear any relation to positions in the external field. It is thus permissible to ignore also the influence of field limitation on artificial horizon, reference and alphameric symbols. These results are summarized in Table XII, which shows that field limitation renders flight vector and ground object symbols less suitable for head-up presentation than the symbols used in the experimental display.

TABLE XII
INFLUENCE OF LIMITED FIELD ON SYMBOLS

SYMBOL	DISPLACEMENT EFFECT	VELOCITY EFFECT	INTERFERENCE
ALPHAMERICS REFERENCE HORIZON DIRECTOR	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
FLIGHT VECTOR GROUND OBJECT	NOT NEGLIGIBLE	NOT NEGLIGIBLE	NOT NEGLIGIBLE

Velocity Effect

Symbols having the angular displacement of objects in the external field will also move with their angular velocity, and they will cross a limited display field more rapidly than they cross the full extent of the forward view. This should cause an increase of apparent angular velocity, when displacement is expressed as a fraction of the field, an effect similar to what is experienced when the sea horizon is seen through a distant aperture in the side of a rolling ship. The symbols subject to this effect, which may attract more attention than the user wishes to give, will clearly be the symbols subject to displacement effect; conversely, those immune to displacement will also be immune to velocity effect. Symbols in the latter class include those which may be presented at a reduced angular scale, and flight tests have shown a 2-to-1 reduction to be suitable for flight director commands, a device which is also useful in reducing the risk of picture break-up (due to repetition rate). Velocity effect is included in summarizing the influence of field limitation, Table XII, and serves to strengthen the case against ground object and flight vector symbols.

Interference

When two symbols occupy the same position in a display they are generally more difficult to distinguish than if they are separate, and this may hinder access to information. When the separation is small but symbols remain overlapping, there may still be an effect on the transfer of information; e.g., the form of one symbol may conceal the position of the other, or both forms may combine into a total form which is difficult to interpret. Interference of symbols is the encroachment of one upon the space properly occupied by another, with consequent impairment of the information process.

In a limited display field, interference may arise either through failure to restrict the size of symbols or failure to avoid crossover due to symbol movement. It is usually possible to find an equitable basis for restricting symbol size; e.g., the length of line used to form a symbol may be made proportional to its information content, to a scale sufficient to preserve the identity of the smallest symbol. Table XIII shows how line lengths would be allocated on this basis to symbols used in head-up presentation, but it is understood that the rule can be applied to a runway symbol (assumed to be continuous) only at a particular height, since symbol size varies with height.

TABLE XIII
LINE LENGTHS OF SYMBOLS ACCORDING TO INFORMATION CONTENT

SYMBOL	INFORMATION DIMENSIONS	ALLOWABLE LINE LENGTH (ARBITRARY UNITS)
SPEED	SPEED	1
HEIGHT	HEIGHT	1
ARTIFICIAL HORIZON	BANK AND ELEVATION ANGLES	2
RUNWAY* AND FLIGHT VECTOR	LATERAL AND VERTICAL ERRORS	2
FLIGHT DIRECTOR	LATERAL AND VERTICAL ERRORS (AND RATES)	2, (4)

*SYMBOL SIZE VARIES WITH HEIGHT

It is more difficult to avoid crossover due to symbol movement. Symbols showing absolute positions cannot be restricted in their movements without misrepresentation; e.g., a runway symbol should be able to take any position in the display as attitude changes, and the flight vector symbol to move appreciably with change of angle of attack, or wind shear. On the other hand, symbols showing relative positions can be more easily handled, allowing other symbols, with fixed positions, to be kept outside their range of normal movement, at distances increasing as symbol importance diminishes (so that the more important information is more accessible). Interference thus depends on whether or not symbols show absolute position and this result, which is included in Table XII, shows a further disadvantage for flight vector and ground object symbols in head-up presentation.

SUMMARY: INFLUENCE OF ERRORS AND LIMITATIONS

It is shown, by considering how position is used to convey the meaning of symbols, that the influence of position error on flight vector and ground object symbols cannot be neglected. This influence is, however, negligible for symbols that do not show absolute positions, such as the flight director symbol, which can also be misaligned without causing delay in first seeing an emergent runway, when the symbol is given a distributed form, as in Experiment 7. The horizon symbol shows absolute position in bank and is subject to position error in this axis, but alphameric and reference symbols have arbitrary positions and are immune.

By considering how form, or pattern, is used to convey a symbol's meaning, it is shown that symbols having a form used to encode information, as alphamerics, are not critically affected by form error. Further, Experiment 8 allows the inference that symbols with a form used to identify and show position; viz, reference, horizon, director, and flight vector symbols, are also not critically affected. The only symbol in which form error cannot be assumed negligible is the runway symbol. (It is assumed that each symbol is used only once in the display.)

The position error results are used to show that the influence of noise on alphamerics may be neglected. Symbols with meanings dependent on relative position, such as horizon and director symbols (used with the reference symbol), are only affected by partial-field noise, as Experiment 9 shows for command information, but this effect can be neglected in practice. The influence of noise cannot be neglected in the case of flight vector and runway symbols, especially because of data source noise.

Consideration of the angular displacement of symbols in a limited display field shows that serious loss of information can occur with symbols showing absolute position, viz. flight vector and ground object symbols. The same symbols may also appear to move too rapidly across a limited field. Interference, due to static overlap in a limited field, may be avoided by conventions for restricting symbol size but dynamic overlap, due to symbol movement, cannot be avoided when symbols show absolute position. Symbols of the relative position type have movements which can be controlled and so need not cause interference or other field limitation effects. Thus, symbols with fixed position can be placed outside the range of movement of director and horizon symbols under most conditions of use, and at distances corresponding to their significance. (Interference of horizon and reference can be avoided by making a central gap in the horizon bar.)

These results are summarized in Table XIV, where it is seen that the runway symbol is less satisfactory than any other symbol, and the flight vector symbol almost equally unsatisfactory for head-up presentation. It may be argued that wide-angle, head-up systems will one day gain acceptance with the user, even at the risk of having optical equipment close to the face, and field limitation effects would then be less important. Even so, the runway symbol would still be worse than most others on at least three counts, and the flight vector symbol on two. (The runway symbol may also need comparatively elaborate methods of generation.)

TABLE XIV
SUMMARY OF EFFECTS OF ERRORS
AND LIMITATIONS IN HEAD-UP PRESENTATION

SYMBOL	POSITION ERROR	FORM ERROR	NOISE	FIELD LIMITATION EFFECTS		
				DISPLACEMENT	VELOCITY	INTERFERENCE
ALPHAMERIC	0	0	0	0	0	0
REFERENCE	0	0	0	0	0	0
HORIZON	X (BANK)	0	0	0	0	0
DIRECTOR	0	0	0	0	0	0
FLIGHT VECTOR	X	0	X	X	X	X
RUNWAY	X	X	X	X	X	X

0 SIGNIFIES NEGLIGIBLE OR NOT CRITICAL (FORM ERROR)
X SIGNIFIES NOT NEGLIGIBLE, OR CRITICAL (FORM ERROR)

It can also be argued, despite these defects, that ground object and flight vector symbols could be *included* in a display based on the more satisfactory flight director symbol. This argument ignores at least three sources of danger. First, the user would have more information presented in his line of sight than has been shown to be safe in flight. Second, velocity effect would cause the less reliable symbols to achieve greater visual prominence. Third, interference would reduce the usefulness of the flight director and supporting symbols.

Runway and flight vector symbols are thus almost entirely unsatisfactory for head-up presentation, and can only be justified on the rather inadequate grounds that the pilot is accustomed to seeing the runway during the approach. On the other hand, Table XIV shows that a basic flight instrument display can be presented in the head-up mode, without exceeding the constraints imposed by the system. This could consist of a flight director of distributed form supported by a horizon (at reduced elevation scale) with alphameric or nonpictorial speed and height symbols, these symbols (assumed to be uniquely identifiable) being almost entirely free of the effects discussed.

SUMMARY

The HUD is a particular kind of presentation designed to eliminate the physical acts necessary in transferring attention between visual fields in different positions, and to avoid the complexity of interpretation arising when the fields are understood by different rules. It is also intended to withstand the influence of errors and limitations to which the system is subject.

The display is presented at large or infinite distance along the line of sight, allowing it to be seen as part of the forward view without change of focus or line of regard. This arrangement permits an information capacity sufficient for instrument flight, which can be performed efficiently while observing critically the forward view. It virtually eliminates the transition and reduces risks arising through inadequate external observation, including the risk of collision. These results may be expected to have an effect on flying procedures based on a rigid distinction between visual and instrument flight rules.

The visible form or pattern of the display is viewed under uniform, matched conditions of brightness and of color, to eliminate possible sources of interference between fields. The pattern represents information which can be shown continuously in a limited display field. It is understood by rules similar to those applied in the forward view and has thus a self-evident quality which allows a transfer of skill between fields, reducing learning time and workload. By applying a similar conformity principle within the display field itself, a high level of tracking accuracy may be achieved, sufficient for the purpose of manual touchdown in all weather conditions.

The display is presented by means of a reflecting collimator, and the pattern is generated on a cathode ray tube for flexibility and freedom from inertial effects. Symbols may be subject to errors of position and form; noise may be experienced; and field limitation may cause symbols to be lost by displacement, to move too fast, and to interfere with each other. These effects vary considerably among symbols: the runway symbol is subject to all of them and the flight vector symbol to all but one; on the other hand, alphameric, reference, horizon, and director symbols need only be influenced to a negligible or non-critical extent, except for the effect of position error, in bank, on the artificial horizon. Experimental results of particular importance include the non-critical effect of misalignment of the director symbol; the influence of partial-field noise on the same symbol; and its freedom from form error effects.

It is possible to provide sufficient information for instrument flight with symbols free of these effects if care is taken to limit bank error and signal noise affecting the director. Runway and flight vector symbols are ruled out, even as auxiliaries or as components of a wide-angle display. Symbols are each used only once; they are restricted in line length according to information content and are placed at radial distances consonant with their importance. Interference is reduced by parking the director symbol and scaling down horizon symbol movements in elevation.

In brief, HUD is a cathode ray tube display presented by reflecting collimator and comprising sufficient information for all modes of instrument flight. It is a fly-to, distributed director and attitude display, shown in a single coordinate system conforming with the forward view, and supported by alphameric or nonpictorial height and speed components, each being uniquely identifiable, proportionately disposed, and spatially isolated. In this form HUD is capable of implementation in the present state of the art; it virtually eliminates the transition; is learned rapidly and may be used without over-concentration to fly a very accurate flight path. These leading particulars are summarized in Table XV.

TABLE XV
HUD LEADING PARTICULARS

PICTURE GENERATION	CATHODE RAY TUBE
OPTICAL PRESENTATION	REFLECTING COLLIMATOR
INFORMATION CONTENT	SUFFICIENT FOR ALL INSTRUMENT FLIGHT MODES
SYMBOLS	FIXED AIRCRAFT REFERENCE SCALED-DOWN HORIZON DISTRIBUTED FLY-TO ELASTIC DIRECTOR ALPHAMERIC/NON-PICTORIAL HEIGHT AND SPEED
SYMBOL DESIGN FEATURES	COMMON FRAMEWORK FOR SYMBOLS JUSTIFYING CONFORMITY WITH FORWARD VIEW UNIQUE IDENTIFICATION LENGTH PROPORTIONAL TO CONTENT LOCATION ACCORDING TO SIGNIFICANCE MUTUAL ISOLATION VELOCITY ACCORDING TO SIGNIFICANCE SUBJECT TO OVERALL SAFE LIMITING CONTENT
PROPERTIES	ELIMINATING TRANSITION RAPID LEARNING, OR SELF-EVIDENCE ACCURATE FLIGHT WITHOUT OVERCONCENTRATION

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