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HUMAN FACTORS ENGINEERING FOR HEAD-UP DISPLAYS: A REVIEW OF MILITARY SPECIFICATIONS AND RECOMMENDATIONS FOR RESEARCH.

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HUMAN FACTORS ENGINEERING FOR HEAD–UP DISPLAYS: A REVIEW OF MILITARY SPECIFICATIONS AND RECOMMENDATIONS FOR RESEARCH

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ABSTRACT

This report is a review of Human Factors literature and military specifications concerning Head-up Displays (HUDs). The objective is to identify important categories of Human Factors research concerning virtual-image displays. These research categories are questions that must be answered before specifications can be written for the optimal design of HUDs.

The review encompassed an exhaustive list of references available through the Defense Documentation Center (DDC) as well as other pertinent sources not given in the DDC listing. Each requirement in the General Specification for Head-up Displays, MIL-D-81641(AS), was compared with the available data. The data base for requirements and the importance of further research concerning each requirement were qualitatively rated. Categories of necessary research were established.

Human Factors knowledge has not kept pace with the proliferating uses of HUDs and the expansion of HUD technology. Consequently, the majority of existing Human Factors specifications for HUDs are based on expert opinion rather than empirical data. Several categories of research are required to provide an adequate data base for future specifications, and to understand how specific issues in the design of HUDs affect performance.

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I. INTRODUCTION

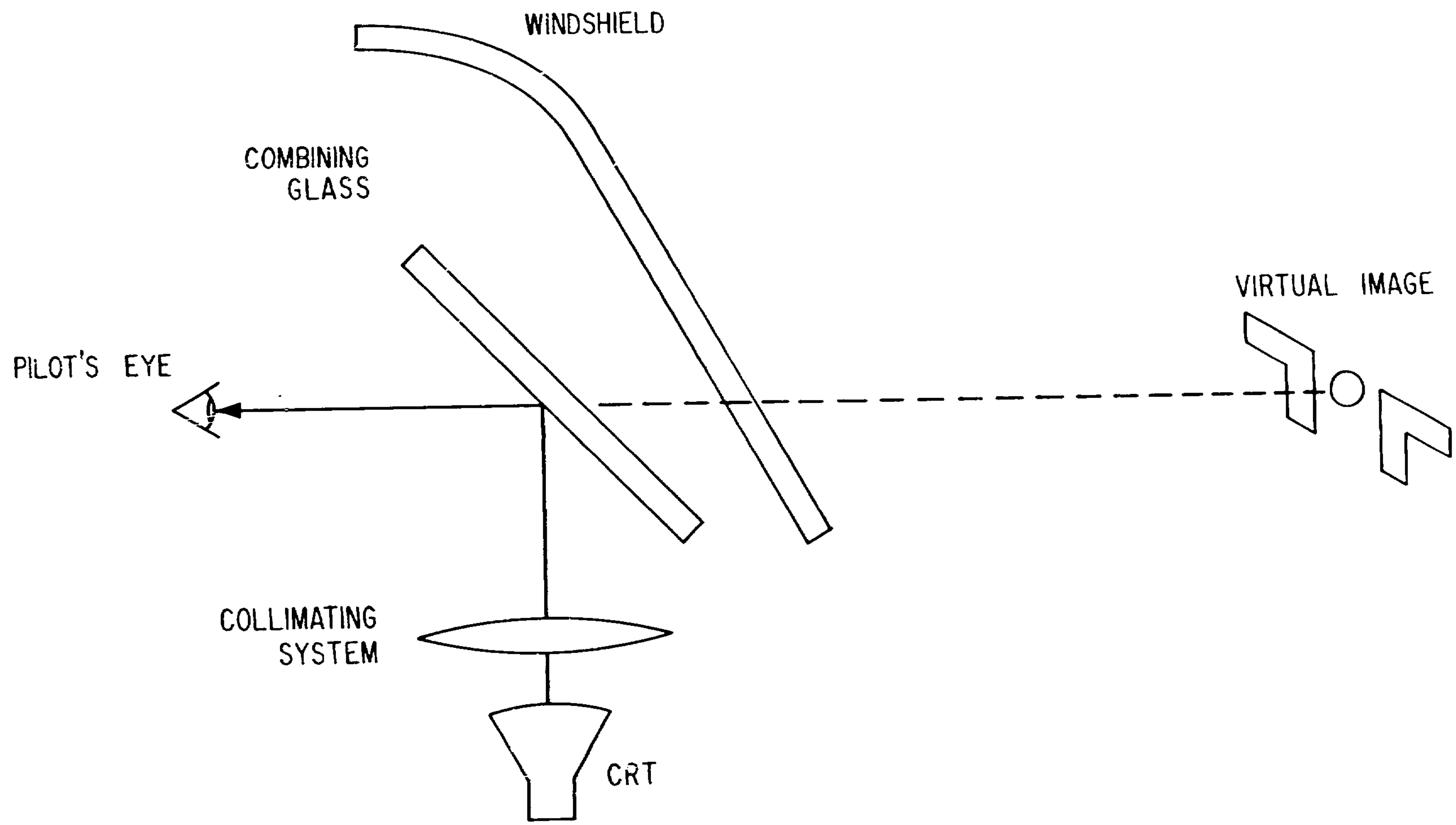
OBJECTIVES

The objectives of this report are as follows: (i) Review the Human Factors specifications in MIL-D-81641(AS) dated 26 June 1972, entitled "General Specification for Head-up Display." Human Factors are considered in Section 3.5 of MIL-D-81641(AS). (ii) Compare the specifications for Head-up Displays (HUDs) with available data from the Human Factors Engineering literature. Where possible, document the sources of specific requirements. (iii) For each specification, assign a qualitative rating of the available, pertinent Human Factors data. (iv) Recommend research to provide additional data necessary to establish optimal specifications for HUDs.

BACKGROUND

Walchli (1967) gave a historical review of the development of HUDs to that date. To summarize his review, HUDs were first explored in the 1950's as a landing aid for pilots flying new, high-performance aircraft under VFR conditions. A recurrent problem was that pilots were unable to make rapid and accurate attitude and position judgements on high-speed approaches. The HUD was developed to eliminate the head movement, eye movement, and reaccommodation required when changing view from ground objects outside the cockpit to panel-mounted instruments. The first HUDs superimposed flight-control information on the external field of view by using a device similar to a gunsight. Symbols were collimated and projected on a combining glass so that pilots could view distant, external objects and the projected symbols simultaneously. A schematic illustration of a HUD is given in Figure 1.

Since the initial concern was the VFR undershoot/overshoot problem during landing, early work attempted to project a flight path symbol indicating the point of the intersection of the plane's velocity vector with the Earth. However, HUDs were quickly seen to have potential applications in many more phases of a mission, including IFR-VFR transition, total IFR landing, takeoff, climb, terrain following, and weapon delivery. In all of these situations an advantage is presumed to result if a pilot is not required to shift his visual attention from the external field to the instrument panel. Human Factors studies and studies of information requirements for diverse missions led to a proliferation of HUD designs, formats, and uses.



Firgue 1. Schematic drawing showing components of a Head–Up Display.

In 1967 Matrix Corp. was awarded a contract to study standardization requirements for electronic and optically generated aircraft displays. This resulted in a report (Ketchel and Jenney, 1968) prepared for JANAIR. The requirements listed in Section 3.5 of MIL-D-81641(AS) are based on the recommended guidelines found in Ketchel and Jenney (1968), as well as some subsequent research and test results.

Since the time of the Ketchel and Jenney report, research relevant to HUD requirements has expanded in several directions. Three other major surveys of literature pertinent to the development of HUD specifications have been published (Meister and Sullivan, 1969; Semple et al., 1971; Jenney et al., 1971). New technology utilizing holography and plasma displays may soon make possible HUDs with greater brightness and larger fields of view. Formal surveys of A-7 pilots are available giving valuable feedback about HUDs from that group of users. Many reports of HUD tests and evaluations have been completed. This report will consider these new developments when comparing current HUD requirements with available literature.

ORGANIZATION AND METHOD OF REVIEW

In order to document the sources of specifications in MIL-D-81641(AS), Human Factors literature concerning visual displays was reviewed. The review encompassed an exhaustive list of references available through the Defense Documentation Center (DDC) as well as other pertinent sources not given in the DDC listing. Included are reports of experiments and flight tests, surveys of pilots, Human Factors reference volumes, applicable military standards, and HUD technical analyses.

The report will be presented in four sections. First, an overview of the HUD specifications will be given. Second, specific comparisons of research findings and HUD specifications will be listed. Third, the state of Human Factors knowledge underlying each specification will be qualitatively rated. Finally, based on the foregoing analysis, several programs of necessary research will be outlined.

II. OVERVIEW OF HUMAN FACTORS SPECIFICATIONS FOR HUDS

GENERAL

Section 3.5 of MIL-D-81641(AS) includes five subsections. Subsection 3.5.3 lists hardware specifications for the Electronics Unit, and subsection 3.5.5 concerns Display Unit Mounting hardware. These sections are not directly pertinent to the stated objectives, and will not be discussed further. The remaining subsections, 3.5.1 Symbology, 3.5.2 Pilot's Display Unit, and 3.5.4 Manual Controls, will be reviewed and compared with available Human Factors data.

One observation pertains to the whole of Section 3.5. It is that some of the presumed advantages of HUDs have not been adequately documented. It is known that head-up presentation of flight-control symbols results in better performance than head-down presentation in certain dual-task situations where one task involves monitoring the field of view outside the cockpit (Naish, 1961). It has also been established that compact, head-up presentation of contact-analogue and flight-control symbols are advantageous during simulated, low-altitude, terrain-avoidance missions (Gold and Deutschle, 1968; Soliday and Milligan, 1967). Surprisingly, however, the presumed advantage of HUDs under VFR conditions has not been documented. The advantage of collimating symbols has not been established independently of the position and format of the display. Furthermore, work is needed to justify those aspects of HUDs required by Section 3.5 that are neither real-world overlays nor are involved in directing the aircraft. In particular, the advantages of having instrument scales on the periphery of the HUD ought to be documented, and ought to be related to the viewing angle at which the scales are displayed and the resulting increase in display clutter. Finally, the effectiveness of projected scales ought to be compared against identically designed panel-mounted versions of the same display (Soliday and Milligan, 1967). Without such data the majority of the HUD specification may be addressing details about symbols that cannot be used, or that produce no advantage over conventional display systems.

SYMBOLOGY

The specifications dealing with symbology are a major concern of this report. As shown by Orrick and York (1975), a different set of symbology has been developed for each type of aircraft equipped with a HUD. However, MIL-D-81641 (AS) defines the symbol modes, general symbol characteristics, and individual symbol characteristics to be required on all future HUDs. These requirements are not well based in Human Factors data. In a few cases, data exist that appear to run contrary to the proposed specifications. Much more frequently it is the case that few or no data are available to compare against specifications. The result is a series of specifications that serves a purpose in setting standards for symbology, but may not set the standards at optimal points.

Since so few Human Factors data directly pertinent to virtual-image HUDs exist, the requirements in subsection 3.5.1 appear to be derived from three indirect sources. First, some well-known conventions of Human Factors Engineering have been applied in the specification. This is certainly valid and useful. There is little reason to suspect that stereotypic population preferences (e.g., heading scale aligned horizontally, altitude vertically) would change during use of HUDs.

A more questionable source of specifications is the extrapolation of findings from other types of visual displays. For example, Semple et al. (1971) noted they were unable to find any work on scale legibility performed on electronic or virtual-image displays. They also termed as a "data void" some issues concerning the electronic display of alphanumeric symbols. Furthermore, the authors advised against direct application of findings from research on electromechanical or trans-illuminated displays. Many symbol and scale characteristics (height, aspect ratio, spacing, etc.) were recommended as candidates for systematic study. Definite values for these same parameters appear as requirements in subsection 3.5.1. The required values are often within the range of values recommended for study, but there are no data to indicate that they are optimal values.

Finally, some specifications concerning symbology appear to be based solely on the technology available when the specification was written. The alphanumeric font specified can be easily displayed by random-scan devices, but there has been no study of its legibility. The prescribed arrangement of symbols fits into a 28° x 20° field of view, but there is a great likelihood that display clutter in some modes will be overwhelming. These and other characteristics of HUDs should be investigated to determine optimal requirements. It may happen that the cost of new technology is not worth the increase in performance. However, the data must be in hand to make that judgment.

PILOT'S DISPLAY UNIT

Subsection 3.5.2 of MIL-D-81641(AS) concerns the Pilot's Display Unit and specifies the minimum performance required of the HUD light source, circuitry, and associated optical equipment. Ideally such specifications should be based on Human Factors studies that have defined problem areas, and have tested different solutions. Since the data are typically lacking, the specifications convey only general requirements related to display parameters. These statements represent the current state of knowledge in Human Factors Engineering. However, they do not give definite guidelines to the manufacturer of the equipment.

At least four examples of this difficulty can be found in Subsection 3.5.2. One is the issue of the color of symbols to be generated on the combining glass. Specifications for a trichroic filter give the bandwidth, transmission and reflection requirements, but fail to specify where the "notch" filter should be located in the visible spectrum. A second example concerns symbol brightness and contrast. The specification requires only that the standby reticle (illuminated by a separate source) have a minimum brightness of 1600 foot-lamberts. The brightness and contrast required of all other symbols are not explicitly stated. Two further examples of this difficulty occur where the specification requires that glare and fatigue be "minimized." In all of these cases manufacturers for whom the specification is intended are not given clear equipment minimums.

To develop useful minimums, research must first identify causes of generic problems such as symbol clarity or fatigue, and then perform tradeoff studies manipulating parameters of the HUD in factorial fashion. An excellent example of this approach was demonstrated by Gold and Hyman (1970) and Gold and Perry (1972). Their work identified binocular disparity as one possible source of visual discomfort produced by HUDs. They established tolerances that are included in Subsection 3.5.2, and are meaningful to an engineer. The approach is not an easy one, but one that must be pursued if the objectives of the HUD specification are to be accomplished.

MANUAL CONTROLS

The final subsection to be reviewed and compared with Human Factors data is 3.5.4 specifying the design and function of manual controls for HUDs. Design of controls is required to be in accordance with MIL-C-6781 (Aircraft Control Panel Specification), MIL-STD-1472 (Human Engineering Design Criteria), and MIL-STD-203 (Aircrew Station Controls Standard). This report will focus on the prescribed functions of the controls. The functions were developed in accordance with survey findings (Ketchel and Jenney, 1968) that defined combinations of symbols required for each phase of a mission. Recent data from a survey of A-7 pilots (Opittek, 1973) suggest that the allocation of functions to controls might be better organized in some instances. In certain other cases symbol modes are desirable but are currently not required. The results of such surveys are difficult to anticipate before the HUD is in actual use. However, a HUD research program can now take these results into account.

SUMMARY

This overview has summarized some general characteristics of the specific comparisons listed in the following. The main finding is that the HUD specifications are necessarily dependent upon the current state of Human Factors knowledge for visual displays. Where the specification goes beyond current knowledge, it does accomplish the goal of uniformity. However, the requirements are arbitrary and may not specify optimal display parameters. Where the specification is conservative, little useful information is conveyed to the manufacturer, and requirements have little impact. Generally, the specification can benefit from user feedback. To develop a better set of HUD specifications, one cannot simply rewrite MIL-D-81641(AS). Rather, a research program must be undertaken to adequately define requirements.

III. COMPARISONS OF SPECIFICATIONS AND DATA

SYMBOLOGY DISPLAY MODES (3.5.1.1)

This subsection specifies how individual symbols are to be grouped into nine functional display modes (takeoff/navigation, landing, bombing, etc.). The optional and required modes for each type of naval aircraft are listed. Individual symbols are further grouped in various ways for the purpose of assigning their functions to manual display controls. Subsection 3.5.1.1 thus lists requirements concerning two issues: the information available for display during different phases of a mission, and the options a pilot has to display different parts of that information.

The most extensive survey of information requirements for HUDs if found in Ketchel and Jenney (1968), and the specifications are generally in accord with that survey. The method employed in the survey was to compare 16 studies of information requirements for various aircraft and missions with an analysis of the information displayed by 11 different HUDs and Vertical Situation Displays operational at the time of writing. On the basis of that comparison, types of information (e.g., pitch angle, altitude) were then listed as mandatory, desirable, optional, or not required for three general mission phases (takeoff, en route, landing). With few exceptions, the information requirements for takeoff and landing given by Ketchel and Jenney are specified in MIL-D-81641(AS). The specification goes beyond the survey to divide the "en route" category into a number of different modes (terrain following, bombing, boresight weapons, guided weapons, test, boresight, and standby).

The studies of information requirements surveyed by Ketchel and Jenney were carried out for diverse purposes and pertain to a wide range of Vertical Situation Displays. Only a fraction of the data is directly pertinent to virtual-image HUDs. For example, a study may indicate that a pilot must have information about altitude at the time of landing, but it does not necessarily imply that an altitude scale must be included in the landing mode of a virtual-image HUD.

An important study reviewed by Ketchel and Jenney (1968) that dealt specifically with HUDs was performed by Sperry Gyroscope Co. (1963). That report included an analysis of information required by pilots during different phases of a mission. The criteria for inclusion of the information on a HUD were that the information (i) enhanced instrument head-up flight, (ii) enhanced visual head-up flight, (iii) improved the ability to assess partial information from the external world, (iv) was sampled frequently, or (v) improved the IFR-VFR transition. Unfortunately, the study was not empirically based. This leads to the following difficulties. The frequency of sampling information was estimated and not measured. The above criteria were never demonstrated empirically for any information source. The analysis was performed without specifying the form of individual symbols, or the format of the entire display. Consequently, the tradeoff of supplying necessary information versus over-saturating with information (display clutter) cannot be assessed.

In fact, the information required specifically on a virtual-image HUD for various mission phases is a largely unresearched issue. It is also a complicated issue undoubtedly involving tradeoffs in performance. One example of such a tradeoff was discovered by Fogle et al. (1974). In their investigation of a HUD for Remotely Piloted Vehicles, fewer control reversals occurred if two display symbols (artificial horizon and aircraft symbol) were present on the same display rather than having only one or the other symbol present. However, the combined case also resulted in the longest latency of response. In other cases, the recommendation has been made that certain symbols be deleted due to display clutter (e.g., Sperry Rand Corp., 1968). This kind of finding may be true of several symbol combinations, particularly the scales specified for display on the periphery of the HUD. Several required display modes and the resulting display clutter are illustrated in Figures 2, 3, 4, and 5.

It should be noted that HUDs, particularly as they assist in the landing mode, have been evaluated in numerous flight tests (e.g., Ramsey and Momiyama, 1963; Johnson and Momiyama, 1964; Jones and Smith, 1966; Morrall, 1968; Harlow, 1971). Unfortunately, such tests usually rate total system capability in subjective reports. The advantage of HUDs, even in landing, has been rarely documented in controlled experiments using objective measures of performance (Egan, 1976). Moreover, no attempt has been made to empirically demonstrate the advantage of each kind of information required for display by MIL-D-81641(AS).

In addition to the lack of empirical studies, feedback from operational communities has not been used to determine information requirements. A common complaint of the A-7 pilots surveyed by Opittek (1973) was the presence of too much symbology during critical phases of missions when an object had to be acquired and maintained visually. On the other hand, results showed that an indicator of the exact angle of bank, and a scale of UHF radio frequencies, might be more useful than some other HUD symbols currently required.

Very little evidence is available concerning the other issue in subsection 3.5.1.1, that of organizing display functions so that pilots can manually determine the combination of symbols to be displayed. Here there are again tradeoffs involving the number of controls versus display flexibility. For example, both airspeed and vertical velocity were listed as mandatory or desirable for all flight phases by Ketchel and Jenney (1968). According to the specification, a pilot can display one or the other of these scales but not both simultaneously. There is also specified a "scales on" and a "scales off" submode so that the pilot has the choice of displaying all or none of the scale positions at any one time. This runs contrary to the comments of some A-7 pilots who preferred to turn off selected scales at certain times. Whether the type and flexibility of information displayed are optimal is presently an open question.

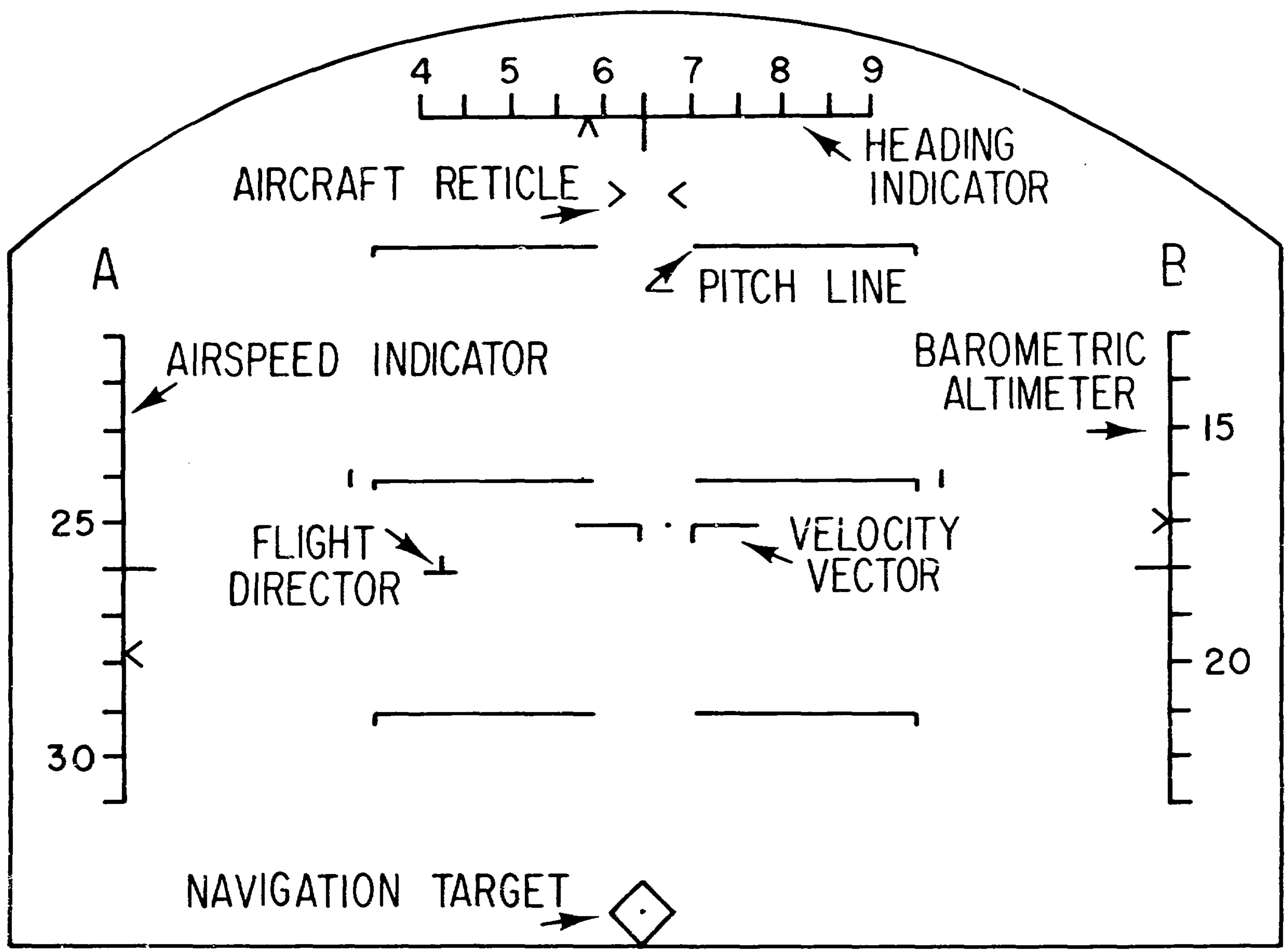


Figure 2. Symbology specified for the navigation mode.

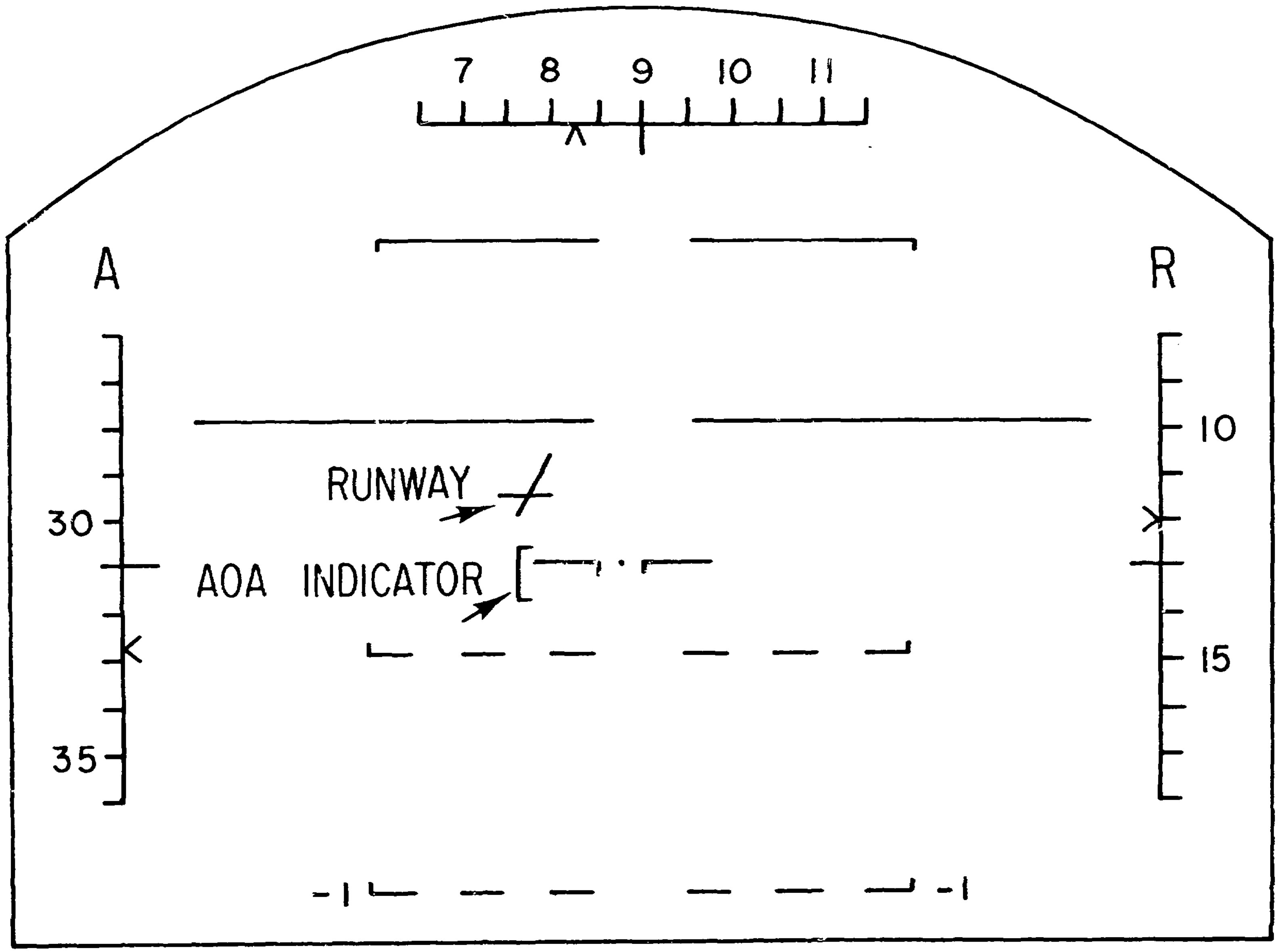


Figure 3. Symbology specified for the landing mode.

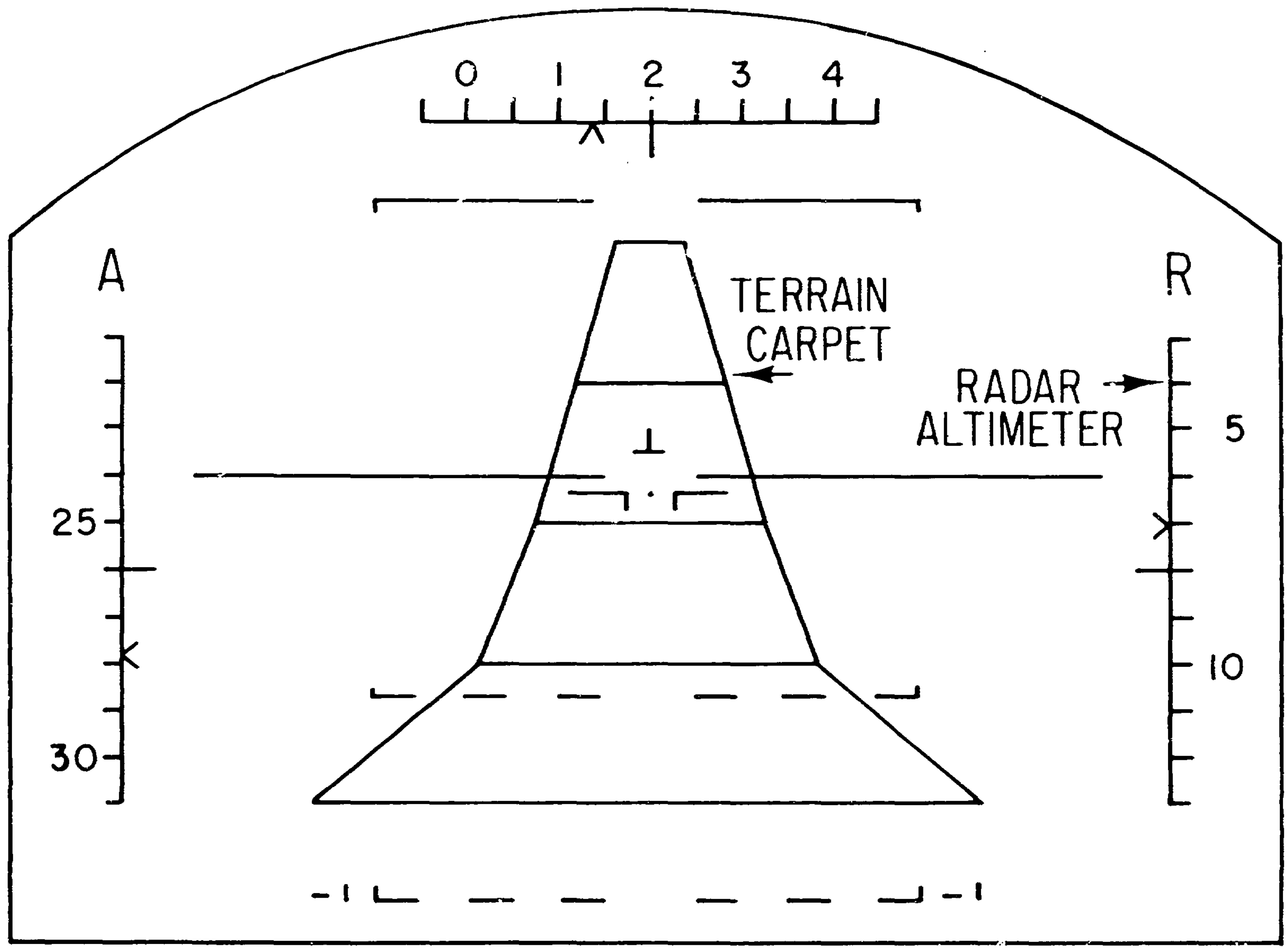


Figure 4. Symbology specified for the terrain-following mode.

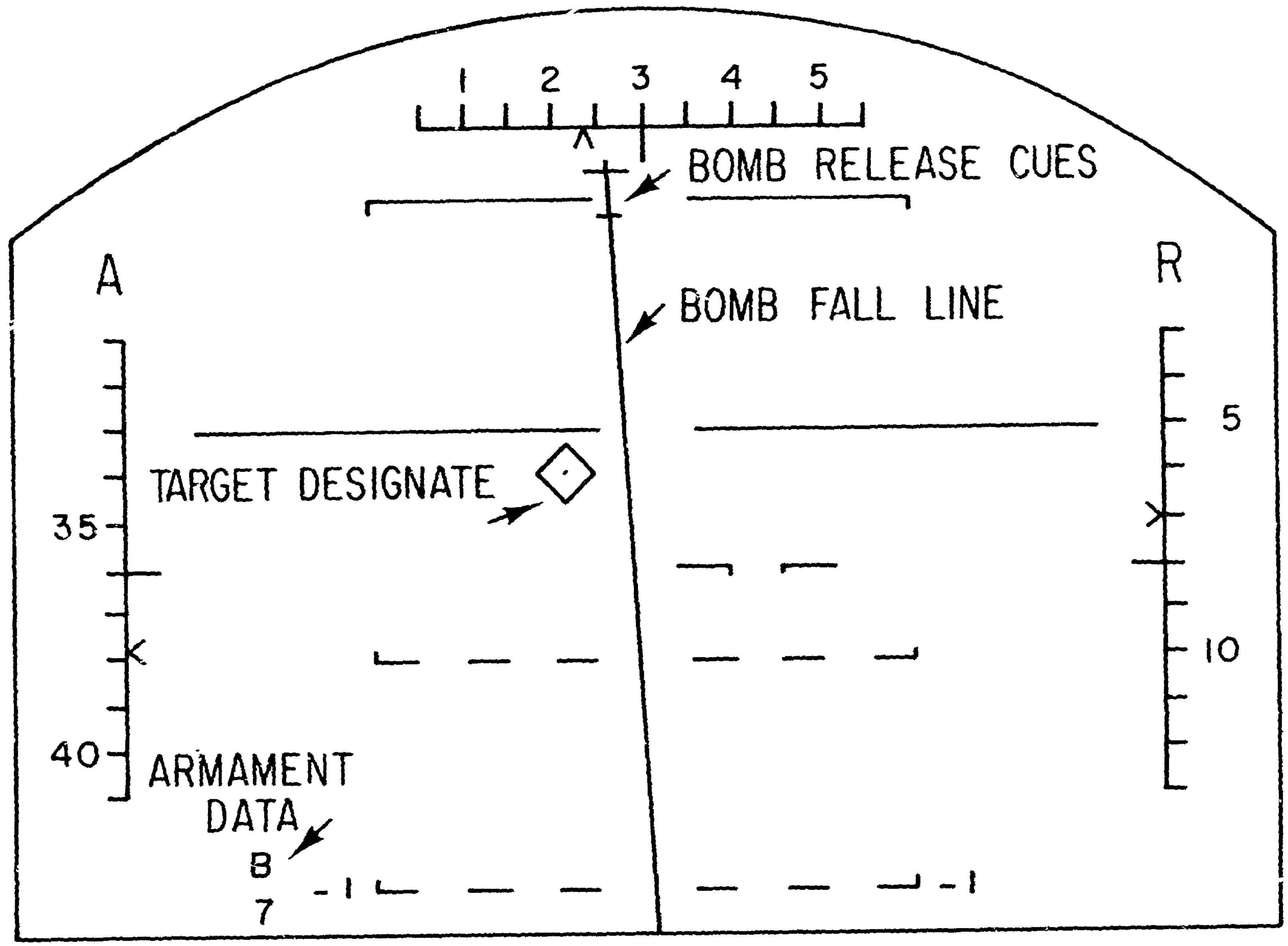


Figure 5. Symbology specified for the bombing mode.

SYMBOL SIZE AND SHAPE, GENERAL REQUIREMENTS (3.5.1.2)

The two major specifications in this section concern the linewidth of symbols and the alphanumeric characters to be used. Linewidth is specified to be 1.0 ± 0.2 milliradians on a black background. This value is in the range recommended by several surveys of the display literature. Ketchel and Jenney (1968) recommended linewidths of 3.0 to 5.0 minutes of arc (approximately 0.9 to 1.5 milliradians). Meister and Sullivan (1969) recommend linewidths of 1/10 to 1/6 of the symbol height, which yield the same range for the size of the symbols specified. The document concerning transilluminated displays, MIL-M-18012, specifies linewidths of 1.7 to 3.0 minutes (approximately 0.5 to 0.9 milliradians), but that specification was not intended for use on electronic displays. Semple et al. (1971) recommend linewidths of 5 to 30 percent of symbol height or approximately 0.45 to 2.7 milliradians for the specified character size. These values were recommended as a range in which to experimentally determine optimal linewidth. As noted above, Semple et al. (1971) could find no systematic study of linewidths for electronic or optically generated displays, and cited reasons why a simple extrapolation of results from other types of displays is undesirable.

Stated simply, symbol linewidth for HUDs has not been studied and the specified values are based on an educated guess of what the optimal values might be. However, there is evidence to suggest that the one milliradian standard may result in excessively wide lines, especially for night viewing. Sheehan's (1972) survey indicated that over 70 percent of the A-7 pilots found that symbols interfered with night vision of the real world. Pilots' comments further suggest that excessive linewidth was a major cause of this problem. This issue is important, because it leads many pilots to turn off the HUD. Ripley and Dobry (1971) tested a HUD and found that 4 mil and 2 mil lines interfered with vision. They recommended narrowing linewidth to 1 mil. While these figures cannot be converted into angular subtense without the specifications of the optical system, for a typical HUD focal length the recommendation suggests that thinner linewidths may be desirable.

In the case of all the surveys cited previously, linewidth in cast in terms of symbol legibility. With linewidths of 1 milliradian there may be no legibility problem, but rather a problem of looking around the symbols to see real-world objects. This may be especially critical at night when HUD symbols and real-world objects all have positive contrast. The electronic generation of virtual-image symbols and the superpositioning of symbols on a real-world background are two problems peculiar to HUDs that must be studied before optimal symbol linewidth can be specified.

The alphanumeric characters required by the HUD specification are not written in the standard Leroy font, and do not correspond to the character set specified by MIL-M-18012. Both Ketchel and Jenney (1968) and Semple et al. (1971) recommended those two sets of characters. The reason for the departure from the recommendations is that the CRTs generating HUD symbology are random-scan devices. Such devices generally have character sets consisting of a connected sequence of strokes. These character sets have not been experimentally tested for legibility or common confusions. On the other hand, alphanumeric font has not been a major complaint in any of the surveys or tests reviewed. Ketchel and Jenney (1968) concluded that it is not yet feasible to standardize a font for HUDs, and that MIL-M-18012 be taken as a guide for future designs.

Data concerning symbol height, width, and spacing for HUDs are also lacking. As in the case of linewidth and font, the HUD specification lists definite values for each of these parameters. The comparison of data with specifications in subsection 3.5.1.2 is summarized in Table I. The tabled values had to be modified in some cases to make for a consistent format (e.g., substituting milliradians for minutes of arc). Note that only MIL-D-81641 (AS) pertains directly to HUDs, and the recommendations of Semple et al. are values proposed for experimental investigation.

Table I

Recommended Values for HUD Symbol Characteristics

Source	Symbol Linewidth (milirad)	Alphanumeric Font (type)	Letter Height (min.)	Letter Width (% Height)	Letter Spacing (% Height)
Ketchel and Jenney (1968)	0.9 - 1.5	a	≤ 30	...	...
Meister and Sullivan (1969)	0.9 - 1.5	...	12-15	67-73	...
Semple et al. (1971)	0.45 - 2.7	a,b	10-30	30-100	5-100
MIL-M-18012	0.5 - 0.9	a	15-21	40-110	8-20
HUD Specification	1.0 ± 0.2	c	30	67	33

[a]Font specified by MIL-M-18012

[b]Standard Leroy font

[c]Line-written font in MIL-D-81641(AS)

SYMBOLS, INDIVIDUAL REQUIREMENTS (3.5.1.3)

The specifications in this section will be analyzed from three points of view. Data pertinent to selected individual symbols will be reviewed first. A discussion of the specified tape symbols will follow. Third, the issue of designing symbols for a coherent format will be discussed.

Individual Symbols

Velocity Vector and Flight Director. The velocity vector and flight director symbols represent respectively the airplane's actual and command direction. When the steering command is satisfied, the flight director symbol resides in the aperture of the velocity vector forming a complete "wings and wheels" symbol. Ketchel and Jenney (1968) actually recommended using two different symbols to serve the function of the velocity vector. In their formulation, an "aircraft symbol" had the same shape as the velocity vector specified in MIL-D-81641(AS), but it always remained in the center of the display serving as a fixed reference point. The vector velocity of the airplane was recommended to be symbolized as a circled dot indicating the actual path of the aircraft. Sperry Rand Corp. (1968) tested a third version of these symbols in which the dot at the center of a flight path marker moved to give the pilot information about flight path angle in high "g" maneuvers. That configuration was disconcerting to pilots flying terrain following missions in the simulator; so, it was abandoned.

Ryan (1969) reported comments of 11 pilots who used an F-14 HUD in simulated landings and bombing runs. In those tests the velocity vector was either fixed at the center of the display, or indicated the flight path relative to the real-world. Pilots' comments were contradictory and performance data were not reported. Thus, the necessity of a fixed, center reference has not been established. Concerning symbol size, Ripley and Dobry (1971) suggested that the overall width of the velocity vector be reduced from 5° to its currently specified 4° width. The recommendation was based on test results of a HUD in which the wider velocity vector was found to mask other symbols.

Gold and Deutschle (1968) measured performance in a flight simulator programmed for high speed, low altitude missions. The presence of a flight director on the HUD resulted in better performance for that situation. The flight director symbol specified in MIL-D-81641(AS) has the shape of a cross (Ketchel and Jenney, 1968) rather than the circle used by Gold and Deutschle. There is no evidence to indicate that the shape of the flight director symbol is critical, but the necessity of having one appears well founded.

Warning Indicators. The breakaway and warning indicators appear to be well-designed symbols. Sheehan (1972) tested several variables relevant to warning signals and also surveyed 87 A-7 pilots regarding HUD warning indicators. When compared to Sheehan's recommendations, the warning symbols are of sufficient size, occur in the optimal area of the display, and have flash rates corresponding to known principles for emergency indicators (4 cps, equal on/off durations).

Only two comments will be offered concerning the specified warning signals. One is that a single warning indicator for a large set of malfunctions may not be an optimal design. Sheehan's data indicated that pilots strongly preferred a short word identifying the type of emergency rather than a single symbol showing only that some emergency exists. Tradeoffs between responding immediately to the emergency and identifying its exact cause are bound to occur. Sheehan gives rank-ordered lists of emergency indicators, and it seems reasonable to identify at least the more important emergency situations. Additionally, the flash rate for the emergency situations (breakaway, pull-up, warning, master arms switch) is the same for the far less serious situations when a "Group A" symbol (velocity vector, flight director, aiming reticle, angle of attack error, runway) drifts to the boundary of the display region. This similarity may have the effect of reducing the impact of a warning during a critical time, or causing an overreaction in normal situations.

Pitch and Horizon Lines. The pitch and horizon lines in MIL-D-81641 (AS) incorporate the following desirable features: 5° increments, labeled positive and negative values, dashed versus solid lines as a redundant positive/negative pitch attitude cue, lines having center gaps to prevent obscuration of important areas, and full $\pm$ 90° pitch scales. These characteristics when combined with the horizon line seem to fill the information requirements for pitch angle and vertical orientation. The specified pitch and horizon lines are similar to those in the A-7, and the A-7 HUD has been well received (Opittek, 1973) with few complaints noted regarding the pitch ladder. Furthermore, when A-7 pilots flew with two versions of the pitch ladder in an F-14 simulator (Ryan, 1969), they much preferred the version similar to the specification. That result may have been biased by their previous experience with one set of symbols. However, the pitch scale proposed for the F-14 lacked several of the features listed above, and the pilots indicated that it should either be changed to include the features or be removed entirely. Similarly, Ripley and Dobry (1971) noted deficiencies in a HUD under test because it lacked several features of the pitch scale listed above.

Bombing Symbols. Concerning the symbology involved in bombing, much less is known. Generally, A-7 pilots have reported favorably on these symbols. Reports from the F-14 simulator study were fragmentary. Bombing symbols were not reviewed by Ketchel and Jenney (1968). Ripley and Dobry (1971) did recommend a circular target-designate symbol that changed size once radar lock-up was achieved. That symbol has not been tested against the one specified by MIL-D-81641 (AS). The design of the bombing symbols ought to be closely tied with the perceptual and motor functions required of the pilot in a bombing run. This task involves target tracking, designating, and flying the aircraft to the bomb fall line. The details of the manual controls required to slew the bombing symbols on the HUD are not included in the HUD specification. Without more evidence, this group of symbols is difficult to evaluate.

Terrain Carpet. Gold and Deutschle (1968) experimentally tested a terrain carpet in a simulation of terrain avoidance under full IFR conditions. The results showed that the terrain carpet significantly reduced the number of hazardous maneuvers attempted by pilots. The dimensions of the terrain carpet were developed by Sperry Rand Corp. (1968). Two suggestions for further testing were proposed by Gold and Deutschle: enhancing the visual distinctiveness of the first critical element in the terrain carpet, and possibly reducing the number of terrain elements in the carpet. Since their study was performed under full IFR conditions, it may also be beneficial to test the terrain carpet under conditions where the symbols overlay visual input from the real world. Finally, Soliday and Milligan (1967) suggested that the effects of widening the carpet and putting gaps in the center of the terrain elements ought to be evaluated as a way to reduce display clutter.

Angle of Attack Error. Of the remaining individual symbols, the angle of attack error and the runway symbol have received some study. The angle of attack symbol is specified to be a bracket placed perpendicular to and left of the velocity vector. It operates in a fly-to fashion. This operation is consistent with other HUD symbols, but opposite that of the panel mounted angle of attack indicator. Johnson and Momiyama (1964) noted the advantage in having the angle of attack on the left side of the display during carrier landings since a pilot's visual attention is focused toward the "meatball" on the port side of the carrier. However, a tradeoff is that the angle of attack bracket sometimes obscures the meatball. It is of some interest that the A-7 HUD has an angle of attack symbol that differs in two important respects from MIL-D-81641(AS). It is a fixed symbol in the center of the field of view and operates in a fly-from fashion. When A-7 pilots flew the F-14 simulator (Ryan, 1969), almost all experienced difficulty with the angle of attack indicator that operated like the one in MIL-D-81641(AS). This problem may disappear with training, but it underscores the necessity of standardization, and the need for research to determine the best symbolic representation.

Runway. The runway symbol does not correspond to the one proposed by Ketchel and Jenney (1968). The shape of the specified symbol tended to be confused with the cross of the flight director during simulated landings (Ryan, 1969). Some pilots also felt that the change in the symbol's perspective was not great enough to provide useful information while the airplane was making heading changes during an approach. This finding is consistent with the fact that the runway symbol specified does not include several natural cues that pilots use in VFR approaches (Walchli, 1967). It is also consistent with Naish and Shiel's (1965) report that pilots preferred an "elastic" symbol that conveyed perspective during landing.

Summary. The comparison of specifications and research concerning individual symbols permits two conclusions. First, in cases where experiments have been conducted, useful information has resulted. Designs for the velocity vector, pitch scale, and terrain carpet are examples. Experimental studies are especially useful when high-fidelity simulation is used and performance data as well as subjective reports are collected. Under these conditions the positive contributions of the new information contained in a symbol can be weighted against the negative contribution of increased display clutter. Second, further study of specified and novel symbology ought to be carried out. Symbols involved in carrier landings (angle of attack error, runway) ought to be given special attention so that confusions and clutter are at a minimum and visual cues are at a maximum during the time of intense visual tracking and stress.

Tape Symbology

Indicators of vertical velocity, airspeed, mach number, heading, barometric altitude, radar altitude, and closure are all displayed by tape symbology described in the HUD specification. Each tape has three components: a moving numerical scale, a fixed line pointing to the center of the scale indicating the actual flight parameter, and a moving pointer indicating the command parameter. Scale dimensions proposed in MIL-D-81641(AS) are similar to those used on the Sperry Rand Corp. (1968) altitude scale, though that scale operated in a different fashion.

Several characteristics of these scales compare favorably with a summary of data concerning scale legibility (Semple et al., 1971). The scales have only a single marker instead of multiple pointers indicating actual values. The scales are linear. An effective way to enumerate scale intervals has been employed. These principles are well founded in Human Factors research with electromechanical and transilluminated displays, and they should apply to HUDs as well. Currently there exist no relevant data developed on electronic or optically generated displays.

Data concerning at least four issues are necessary to the development of optimal tape symbology for HUDs. The first issue is the type of scale to use. Several different types of scales seem to be reasonable candidates for use. These include simplified circular dials, moving pointer displays, numerical readouts, moving tape displays, and thermometer-type scales (DeBellis, 1973).

As an example of an alternate scale design, the range and rate of closure scales in the air-to-air mode could be combined as a simple moving arc giving rough range and rate information like the time-till-weapons-release cues on the F-14 and F-111A HUDs. Other kinds of scales can be evaluated as candidates for each kind of information required. This is not a simple task since several dependent variables as well as task demands must be considered to obtain proper evaluation (Roscoe, 1956).

The second issue is scale position. Currently, the scales have been assigned to the peripheral regions of the HUD, 7^{o} - 10^{o} away from the center. It is known that tracking under conditions of parafoveal viewing rapidly deteriorates especially for certain types of displays (Clement et al., 1971). If scales are to be on the periphery, any savings over having them mounted on the instrument panel ought to be documented and weighed against their contribution to display clutter. A study of the effects of moving the scales systematically out on the periphery ought to be available for use with new HUDs having increased fields of view. Finally, alternatives to peripheral display ought to be examined. For example, Sperry Rand Corp. (1968) considered peripheral display of altitude undesirable for terrain avoidance missions. They proposed a moving altitude scale that maintained a constant position with respect to the velocity vector. That proposal was not adopted, since the altitude scale was lost when the velocity vector traveled to the edge of the HUD (Soliday and Milligan, 1967).

Another important alternative to peripheral display of scales is the integrated, panel-mounted display. A tenable hypothesis is that a direct-view display presenting altitude, airspeed, and heading in a well-integrated format is as effective as a virtual-image display of those scales on the periphery of the HUD field of view. Displaying scales on the instrument panel instead of the HUD could greatly reduce the clutter of symbols on the HUD, but increased head movement and changes in fixation required may outweigh that advantage. The available evidence (Soliday and Milligan, 1967) shows that a HUD with a heading indicator resulted in smaller heading error than a panel-mounted display, which in turn resulted in smaller error than a HUD without a heading indicator. Those results are not conclusive since scale placement and format were confounded. The effectiveness of panel-mounted displays should be studied in controlled experiments.

The third and fourth issues to be considered in developing optimal scales have been mentioned previously. The analysis of symbol characteristics presented above applies to tape symbology as well. In addition to choosing physical parameters for symbols, there are also questions concerning symbol selection. For example, the heading indicator proposed for the Sperry Rand Corp. (1968) HUD did not have numeric values, but only an indication of "heading error." While pilots flying a simulator with this HUD complained of having no numeric values, steering was better with this HUD than it was using a panel-mounted display. The fourth issue is the pilot's option to display different scales. Pilots have indicated (Opittek, 1973) a desire for more options than those available with the specified scales on/off switch.

To summarize the section on tape symbology, the specified indicators are designed in accord with some known principles. However, certain questions raised by the tape symbology ought to be addressed. These questions include the type of scale, scale position, the symbols used, and the display options available to the pilot.

Display Format

Individual symbols and tape symbology specified in subsection 3.5.1.3 have been reviewed and compared with available literature. There remains the analysis of the format to present all elements in a coherent display. The situation regarding format is much the same as with other display parameters. The HUD specification corresponds to some general principles derived from work with electromechanical displays, but there are other questions about format for which no data currently exist. The heading scale is aligned horizontally and airspeed and altitude scales are set vertically on the left and right of the display. This format preserves compatibility among HUD and control-panel instruments and between instruments and population preferences. An attempt has been made to keep the center $14^{o} \times 21^{o}$ field clear for the more important flight-control and weapons symbology. To reduce clutter, individual symbols are not allowed to overlay the tape symbology at the periphery. These aspects of the HUD format seem to be well founded.

Other format problems appear to have been arbitrarily "solved" in the specification. One general problem is how to design and place a number of indicators so that attention can be allocated optimally. Senders (1964) developed a method for formally determining how often an instrument required monitoring and found that experienced operators distributed their attention accordingly. If these data can be obtained for HUD indicators, it may be possible to group the indicators requiring the most monitoring. A specific problem in MIL-D-81641(AS) concerns the vertical velocity, angle of attack, and altitude indicators located at the far left, center, and far right of the display. These indicators are all used in landing. A better way to group them may be possible.

A second problem is display clutter. This is a complaint in every survey of pilots using HUDs. Presently the concept of clutter is so poorly defined that it is not very useful. Perhaps analyses along the lines of Poole's (1966) formulation will aid in defining clutter. Until that is done, the HUD will continue to interfere with some tasks, or be turned off by the pilot.

Display formats involve interactions among visual inputs. For virtual-image HUDs, interactions among display symbols occur as do interactions between symbols and input from the real world. Since a poor format can negate the effect of several different visual inputs, the format problem is as important as any problem bearing on a single symbol. It is also a pervasive problem. In Opittek's (1973) survey, 11 of 17 pilots indicated that they turned the HUD off at critical phases of a mission because it interfered with their performance. Since virtual-image formats have not been thoroughly studied, the format problem has not been solved in MIL-D-81641(AS).

PILOT'S DISPLAY UNIT (3.5.2.1)

Included in this subsection are the specifications for the combining glass, a component whose characteristics interact with several other display parameters. The combining glass is a partial mirror allowing the pilot to view light transmitted from the far side and reflected from the near side (see Fig. 1). Its specified trichroic color separation coating must reflect 55 percent of the incident light within a spectral band or "notch" while transmitting 80 percent or more of the incident light falling outside the notch. The result is that a less powerful light source is needed to achieve acceptable symbol to background contrast, while outside viewing remains at an acceptable level.

Kelley et al. (1965) studied several different combining glasses with a constant 10,000 foot-lambert background to determine contrast thresholds. Subjects had to identify orientations of a horizon line and angle of attack indicator representing a coarse and a fine discrimination respectively. The trichroic coating allowed subjects to achieve 90 percent accuracy with the least amount of luminance from the symbol light source. Since this seems to be the only study of the impact of trichroic filters on performance, the adequacy of requirements in MIL-D-81641(AS) depends on the generality of these results.

The results found by Kelley et al. (1965) cannot be simply generalized. One trichroic coating, one symbol color, one combining glass orientation, and one constant background light source were used. Stimuli were not dynamic, nor was there a dynamic real-world background against which to view them. Trichroic coatings were not tested in combination with night filters. The procedures were to expose a display for three seconds, and measure accuracy alone. In short, the study of Human Factors for trichroic filters on HUDs has not reached an advanced level. On the other hand, the results of Kelley et al. (1965) together with the advantages of less power required by the light source suggest that trichroic filters ought to be studied in depth. Other filter types and filter combinations ought to be tested also (see Semple et al., 1971).

Two final observations about the combining glass are (i) the optimal mounting orientation ought to be specified, and (ii) alternatives to a single, rigid combining glass ought to be investigated. Regarding the orientation, there is a critical angle between the combiner and canopy which determines whether reflections and secondary images will be observed. It should be possible to determine the angles in a simulator. Additionally, there are alternatives to the specified combiner. The canopy may serve as the combiner, there may be a set of parallel combiners to increase vertical field of view, or the combiner mount may be movable to give over-the-nose visibility during an approach. The effectiveness of these and other alternatives can be evaluated.

ACOUSTIC NOISE GENERATION (3.5.2.4)

The maximum allowable noise level is 85 decibels. This appears to be a reasonable figure since the Occupational Safety and Health Act specifies that the limit of exposure to sound levels of 90 decibels (A-weighted) can be as much as 8 hours per day. Only if dealing with pure tones does there seem to be any risk of hearing loss at sound levels of 85 decibels (see Hodge and Garinther, 1973).

FIELD OF VIEW (3.5.2.8)

The HUD specification requires an instantaneous monocular field of view (FOV) of $20^{\circ} \times 28^{\circ}$ measured from the design eye position of the cockpit. The position at which the measurement is made is critical as shown by Ripley and Dobry (1971). They found the total monocular FOV for an experimental HUD to be $24^{\circ} \times 31^{\circ}$. However, in the airplane those figures were decreased to the range of $9.5^{\circ} \times 23^{\circ}$, depending on how the pilot was seated with respect to the HUD exit pupil. A typical seat position reduced the FOV by one-third, and changing seat positions to increase the FOV was hazardous. Requiring the FOV to be measured at the design eye position of the cockpit assures HUD-cockpit compatibility.

The selection of a $20^{\circ} \times 28^{\circ}$ FOV appears arbitrary. Shown in the top row of Table II (adapted from Opittek, 1973) are the dimensions of FOV for five operational HUDs and two under development. Only those under development meet the specifications of MIL-D-81641(AS). Not shown in Table II are three additional HUDs previously developed by Spectocom, Sperry Rand Corp., and General Electric Corp. Test data from those HUDs indicated that they would not meet the FOV requirements.

One approach to the issue of FOV size is to maximize it. For example, Walchli (1967) noted several restrictions incurred with small HUD FOV. Preservation of 1-to-1 display to real-world correspondence is difficult to maintain; important symbology may be driven out of view (e.g., a runway symbol in conditions of high crosswinds); symbols will move out of view as the distance between airplane and ground decreases. In Opittek's (1973) survey, 4 of 17 A-7 pilots thought the HUD FOV was not adequate. Eleven of 17 thought a larger FOV would be advantageous in weapon delivery. Consequently, there seems to be cause for maximizing HUD FOV.

However, there are material and performance tradeoffs to consider. The technology of wide-angle optics presently leads to large costs in terms of weight, size, and accuracy (Ketchel and Jenney, 1968). Holographic lenses may one day reduce those costs, but they are still under development. More importantly, the performance tradeoffs accompanying a maximum FOV HUD have yet to be determined. No study has systematically varied HUD FOV, but this variable may be critical. It is known that peripheral visual acuity decreases rapidly from its maximum for central viewing (Wulfeck et al., 1958). As mentioned previously,

TABLE II

HEAD-UP DISPLAY TRADEOFF SUMMARY (Adapted from Opittek, 1973)

Parameters	A-7E Elliott	F-111D Norden	F-14A Kaiser	F-15 McDonnell-Douglas	Wide Angle HUD Farrand	A 4M Elliott	Hughes Advanced HUD Design Goals	MIL SPEC MIL D 81641 (AS)
Type	CRT/Refractive optics	CRT/Reflective optics	CRT/Refractive optics	CRT/Refractive optics	CRT Reflective optics	CRT/Refractive optics	Advanced Techniques	NA
Field of View instantaneous (V x H)	$10.8^\circ \times 16.1^\circ$ $11.2^\circ \times 16.4^\circ$ (Binocular)	$14^\circ \times 16^\circ$ (Binocular)	$14.1 \times 18.2^\circ$ (Binocular)	$12^\circ \times 17^\circ$ (Binocular)				$20^\circ \times 28^\circ$
Total (V x H)	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$35^\circ \times 25^\circ$	$11^\circ \times 16^\circ$	$45^\circ \times 60^\circ$	
Viewing Distance, in.	29	25	22	33	15	20		
Display Accuracies	1.1 mr in center 10° 1.6 mr within 10° to 20°	NA	NA	1.5 mr in center 3° 3.0 mr within 3° to 20°	2 mr	1 mrad center 3 mr edge	1 mrad over FOV	1 mrad (central 12°)
Brightness (max.) Ft.L.	1500	1500	1600	1500	1500	1000	Full resolution symbols in 10K Ft.L ambient 1.6 contrast ratio.	
Combining Glass Transmissibility %	76	73	70	75	NA	85	Maximize	80

tracking performance deteriorates under parafoveal viewing (Clement et al., 1971). Furthermore, if head movements are required to view tape symbology on the periphery of a wide FOV HUD, response times to those indicators will be greatly increased. This issue should receive high priority in future HUD research programs.

COMBINING GLASS (REAL WORLD TO OBSERVER) DISPLACEMENT ERROR (3.5.3.9)

The specification lists maximum allowable displacements of real-world objects when transmitted through the combining glass. A previous section (3.4.1.1) listed display accuracy required for CRT symbols. These accuracy requirements appear to be somewhat arbitrary, and possibly too stringent. Again, the systematic studies performed on this issue are scarce. Walchli (1967) reviewed studies by Naish (1965) in which the effects of sybmol misalignment and display system noise were investigated in an aircraft simulator. While the generality of the studies can be questioned, there was no effect on visual acquisition of a runway due to misalignment of superimposed symbols. Only system noise that caused relative motion of symbols adversely affected performance. In a test of a wide-angle HUD, Hussey (1970) reported displacement errors somewhat larger than those in the HUD specification. The reported values were not considered objectionable, at least in the central field. Moreover, the contract in that test listed as goals displacements in some cases twice as large as MIL-D-81641(AS) now requires.

Referring to Table II, it can be seen that the operational HUDs come reasonably close to meeting the accuracy requirement. However, in the opinion of Opittek (1973), larger FOVs with the required degree of accuracy are not possible with conventional optical systems. There appears to be a lack of systematic study of display and combining glass accuracy, and the accuracy requirements appear technologically difficult to achieve in large FOV HUDs. Further study may suggest that the requirement be made less stringent, or at least given less importance relative to other parts of MIL-D-81641(AS). This issue should be considered when determining optimal FOV.

BINOCULAR DISPARITY (3.5.2.10)

If the pilot's eyes are focused on some distant object, then binocular disparity of the HUD images will result. This is caused by differences in the distortion of the images presented to the two eyes. Symbols on the combining glass will lack detail or will split apart into two images. The problem may be severe. For example, Riply and Dobry (1971) listed binocular disparity as one deficiency that precluded use of a HUD being tested as a primary integrated display system for the all-weather attack mission.

In a series of studies (Gold and Hyman (1970), Gold and Perry (1972)) binocular disparity tolerances were established under several experimental conditions. For sustained viewing in a HUD simulator, Gold and Hyman (1970) established the tolerances listed in the HUD specification. Further results included: (i) greater disparity tolerated for images viewed against homogeneous background as compared to a static, real-world background, (ii) greater disparity tolerated for static as compared to moving images, (iii) thicker image lines, low image brightness, and dual overlapping monocular fields did not significantly change binocular disparity tolerances. Gold and Perry (1972) confirmed the tolerances established earlier. Furthermore, they found no change in tolerance due to viewing images against a dynamic rather than static real-world background. The HUD specifications related to binocular disparity are both important and well substantiated by data. Comments by Ripley and Dobry (1971) indicate that in-flight testing expecially using the night filter may serve to further validate these tolerance limits.

The HUD specification lists the range of eye positions at which disparities ought to be measured. Those requirements are related to Gold and Hyman's (1970) study of exit pupil size. In that study, large effects of latency of response were due to exit pupil size, distance of head from exit pupil, and the interaction of those two variables. The recommended 3" x 5" viewing rectangle was the largest exit pupil tested. Larger sizes and different shapes ought to be tested before the 3" x 5" size is considered optimal. Ripley and Dobry (1971) pointed out that the horizontal dimension of the exit pupil they tested remained roughly constant for a variety of fore-aft head positions. This resulted in satisfactory viewing even though the vertical dimension decreased.

GLARE (3.5.2.12)

The HUD specification states simply that glare should be minimized. As noted previously, this is a fine goal, but conveys little useful information to a manufacturer. Studies of factors such as surround and display brightness, combiner characteristics, and type of filter, should be performed to identify common causes of glare. Horning et al. (1971) reported a preliminary study describing measurement techniques and suggesting that a glare criterion be set at ten times the adaptation luminance. Jainski (1971) used psychophysical techniques to establish relationships among the luminance and angle of glare sources and the corresponding threshold of a test stimulus. Further work concerning glare must be accomplished before data can be used to specify characteristics of equipment.

FATIGUE (3.5.2.14)

As in the section on glare, this section simply states that the HUD should be oriented to minimize personnel fatigue. The intent is apparently to eliminate the necessity of straining forward or raising up to see the entire HUD FOV (Ripley and Dobry, 1971). Requiring the FOV to be measured at the cockpit design eye position is one answer to that problem. Enlarging the exit pupil may be another solution. However, there are certainly other sources of fatigue. Soliday and Milligan (1967) found that pilots' performance in an aircraft simulator deteriorated over time if they were using a HUD. Fatigue is commonly reported by pilots transitioning from the real world to HUD symbology and back (Johnson and Momiyama, 1964; Sheehan, 1972). Both the effort to adjust accommodation and the development of "HUD myopia" (attending to symbols to the exclusion of scanning environment) ought to be documented. As further data concerning fatigue become available, they can be related to display parameters.

NIGHT FILTER (3.5.2.16)

The HUD specification lists some general characteristics of a filter to be placed over the CRT during night operations. It is puzzling that a night filter can be specified at all since neither the color of the CRT symbols nor their range of brightness or contrast is specified. The importance of properly illuminating the symbols for night operations cannot be denied, but the problem may not be solved by simply adopting the convention of red-lighted displays for night viewing. In Opittek's (1973) survey, 15 of 17 A-7E pilots indicated that CRT symbols interfered to some extent with their night vision. Five of the pilots said they preferred the unfiltered symbology at night because they could achieve better symbol, real-world contrast without it. In a study of HUD symbol color for low levels of ambient light, Gabriel, Uyeda, and Burrows (1965) found that, of the conditions studied, red symbology actually produced the worst performance. The subject of filters is complicated because the resulting luminance and color of symbols interact with other display and environmental factors. In addition, there are subjective reports that a night filter may cause greater binocular disparity (Ripley and Dobry, 1971). Symbol illumination is one of the most significant parameters of a HUD, and a great need exists to establish optimal specifications.

STANDBY RETICLE (3.5.2.17)

The standby symbology can be displayed when desired by the pilot and has its own light source. Previous comments about symbol linewidth apply to the standby symbol linewidth as well. Ripley and Dobry (1971) recommended that the reticle be visible against a 10,000 foot-lambert background so that boresighting could be accomplished in normal daylight, and the standby reticle could serve as a back-up gunsight. Requiring brightness of 1600 foot-lamberts insures a 20 percent contrast against such a background viewed through the combining glass. Of greatest interest is the fact that the only exact specifications for symbol brightness and contrast are found in the subsection concerning the standby reticle.

MANUAL CONTROLS (3.5.4)

The manual HUD controls have been reported as a source of difficulty in flight test and evaluation (Hubner and Blose, 1966). In addition to the obvious tradeoff between simplicity of controls and flexibility of display, an important goal for the design of manual controls was noted by Johnson and Momiyama (1964). It is that the pilot should not have to manually change mode during a critical phase of a mission (e.g., landing). Excessive time and head movements are required before a control can be activated because of poor design of knobs and readout windows. Knobs have not been functionally organized. Two further minor observations are noted. The brightness control may have to be redesigned to permit manual override and fine adjustment at low levels of intensity. For the scales control, no provision is made to display some but not all scales, or to shift scales from one side to another. The latter capability was deemed an "enhancing feature" of a system tested by Ripley and Dobry (1971).

ADDITIONAL REQUIREMENTS

At least two additional specifications ought to be researched and included in Section 3.5 of MIL-D-81641(AS). These concern the symbol brightness and symbol dynamics.

Symbol Brightness

As noted previously, the only exact specifications for symbol brightness and contrast are found in the subsection concerning the standby reticle. The reason that these have not been exactly specified is probably twofold. First, desired contrast levels are not clearly indicated in Human Factors literature. Certainly the most difficult levels to achieve will be those for the brightest background conditions. This background luminance has been commonly estimated to be 10,000 foot-lamberts, or the equivalent of sunlighted snow. Under these conditions, estimates of acceptable contrast ratios range from about 5 to 80 percent of the light transmitted through the combining glass. The 5 percent figure is from the Kelley et al. (1965) study using the 90 percent accuracy threshold with a trichroic color-coated combiner. The 80 percent contrast figure has been taken by Opittek (1973) as a design goal for comfortable vision.

The second difficulty in specifying minimum contrast levels has to do with state-of-the-art technology. For the purpose of comparison, the luminance required for 80 percent contrast will be computed as follows. Ignoring the effect of the canopy, the background will be at least 8,000 foot-lamberts when viewed through the combiner, since the trichroic coating will transmit at least 80 percent of the incident light. If 80 percent contrast is required, then symbols viewed through the combiner must have a luminance of 8,000 + .8 x 8,000 or

14,400 foot-lamberts. Consequently, CRT luminance at the eye must be 6,400 lamberts. As the combiner reflects only 55 percent of the light from the CRT (ignoring absorption by collimating optics), a source of more than 11,000 foot-lamberts is required to achieve 80 percent contrast. Table II lists the maximum luminance at the eye for state-of-the-art CRTs. These range from 1000 to 1600 foot-lamberts. Source luminance is typically only 2,000 foot-lamberts. It appears that 80 percent contrast in combination with high background luminance and the specified combiner characteristics may be beyond current technology (Opittek, 1973).

An additional technical point was raised by Grindle et al. (1967). They noted that automatic brightness controls available at that time could preserve constant contrast only within a limited range of background lighting. Technological advances have subsequently extended the limits of these controls, but no control operates in the full 0-10,000 foot-lambert range. A possible consequence is that even if a high luminance source were developed, the pilot would have to manually adjust brightness when flying in conditions of partial overcast.

The HUD specification does list conditions of background lighting for testing symbol contrast (subsection 4.8.2.1). Unfortunately, the criterion of the test (4.8.3) is only that "Symbols shall be easily detected and recognized." Whether this refers to something like the 90 percent accuracy threshold or the minimum contrast for comfortable vision is not specified.

Three points will be made to summarize the situation with respect to brightness and contrast. First, some attempt to specify minimum values ought to be included in MIL-D-81641 (AS). Second, to develop those specifications requires research probably using trichroic filters under a variety of lighting conditions (including use of night filter). Third, the desired source and automatic brightness controls may have to be developed to meet this specific need.

Symbol Dynamics

Two issues concerning the dynamics of symbols ought to be addressed in MIL-D-81641 (AS). First, the optimal damping or "quickening" of the flight director, velocity vector, and all ground-stabilized symbols ought to be specified. If this is not done, the symbols may be too sensitive to control inputs or there may be a large lag between input and symbol response (e.g., Hubner and Blose, 1966; Sperry Gyroscope Co., 1963). The result is that the symbols are difficult to track, and a smooth flight path cannot be maintained.

Second, when the input driving any symbol fails, there should be a requirement to alert the pilot to the failure. The symbol should not simply stop moving, as this might be interpreted as a command being satisfied by the current flight path. It may prove better to simply remove the faulty symbol from the display.

IV. ASSESSMENT OF DATA BASE FOR SPECIFICATIONS

ASSESSMENT PROCEDURE

In this section, two types of qualitative ratings will be described and applied to each specification previously reviewed. The first rating classifies the source of each specification. The second rating assesses the importance of remaining problems related to each specification.

CLASSIFICATION OF BASES FOR SPECIFICATIONS

The basis of each specification can be classified into one of four categories. The tables and brief descriptions of the categories follow.

1. Available Technology - the specification is based on current technological limits of display or optical components. More exacting requirements may be desirable but are not yet practical.

2. Expert Opinion - the specification results from an extrapolation of work on other kinds of displays, or is an "educated guess." No Human Factors data generated on virtual image displays are available.

3. Accepted Conventions - the specification is based on well known conventions for aviation.

4. Empirical Findings - the specification is based on results of laboratory experiments, simulator tests, or flight tests.

CLASSIFICATION OF PROBLEM AREAS

Problems requiring further research will be classified into three categories according to their impact on performance using HUDs.

1. Critical - research in this area should have high priority as a known problem with large effects on performance exists.

2. Intermediate - problems in this area either have less impact on performance, or unknown effects.

3. Solved - due to the specification, either no problem remains, or remaining problems have only small effects.

ASSESSMENT OF DATA BASE

Each specification with its relevant sources is listed on the left of Table III. The basis of the specificaton is classified, a brief description of necessary research is given, and the impact of remaining problems on performance is assessed.

Table III

ASSESSMENT OF DATA BASE FOR SPECIFICATIONS

SECTION	RELEVANT SOURCES	BASIS OF SPECIFICATION	NECESSARY RESEARCH	PROBLEM CLASSIFICATION
3.5.1.1 Symbology Display Modes	Ketchel and Jenney (1968) Sperry Gyroscope Co. (1963) Fogle et al. (1974) Sperry Rand Corp. (1968) Opittek (1973)	Expert Opinion	Study in controlled experiments: 1. Presumed advantages of specified Information. 2. Presumed advantages of HUD in VFR conditions 3. Presumed advantages of symbol collimation Obtain user feedback on required information	Critical
3.5.1.2 Symbol size and shape, general requirements	Semple et al. (1971) Ketchel and Jenney (1968) MIL-M-18012	Expert Opinion	Determine optimal linewidth, alphanumeric font; and symbol size, aspect ratio and spacing	Intermediate
3.5.1.3 Symbols, Individual Requirements a. Individual Symbols (i) Flight Director and Velocity Vector	Ketchel and Jenney (1968) Sperry Rand Corp. (1968) Ryan (1969) Ripley and Dobry (1971) Gold and Deutschle (1968)	Empirical Findings		Solved
(ii) Warning Indicators	Sheehan (1972)	Empirical Findings	Test single word warnings and effects of flash coding	Intermediate
(iii) Pitch and Horizon Lines	Ryan (1969) Ripley and Dobry (1971)	Empirical Findings		Solved
(iv) Bombing Symbols		Expert Opinion		Solved
(v) Terrain Carpet	Gold and Deutschle (1968) Sperry Rand Corp. (1968) Soliday and Milligan (1967)	Empirical Findings	Investigate ways to reduce clutter due to carpet	Intermediate
(vi) Angle of Attack Error	Johnson and Momiyama (1964) Ryan (1969)	Expert Opinion	Determine whether fly-to or fly-from symbol is best	Intermediate
(vii) Runway	Ketchel and Jenney (1968) Ryan (1969) Walchli (1967) Naish and Shiel (1965)	Expert Opinion	Test difference between specified symbol and one incorporating perspective cues	Critical
b. Tape Symbols	Semple et al. (1971) Sperry Rand Corp. (1968) Clement et al. (1971)	Expert Opinion	Test different types of scales, scale position, scale symbols, and scale options	Critical

Table III (Cont'd)

ASSESSMENT OF DATA BASE FOR SPECIFICATIONS

SECTION	RELEVANT SOURCES	BASIS OF SPECIFICATION	NECESSARY RESEARCH	PROBLEM CLASSIFICATION
3.5.1.3 (Continued)				
c. Format	Senders (1964) Poole (1966)	Expert Opinion	Relate effectiveness of scale to scale position; investigate "display clutter"	Critical
3.5.2.1 Pilot's Display Unit Components	Kelley et al. (1965) Semple (1971)	Empirical Findings	Test trichroic filters under a wide range of conditions; investigate other reflecting devices	Intermediate
3.5.2.4 Acoustic Noise Generation	Hodge and Garinther (1963)	Empirical Findings		Solved
3.5.2.8 Field of View	Opittek (1973) Ripley and Dobry (1971) Walchli (1967) Wulfeck et al. (1958)	Available Technology	Establish performance tradeoffs for viewing symbols in a wide FOV HUD	Critical
3.5.2.9 Combining Glass (real world to observer) displacement error	Hussey (1970)	Available Technology	Test effects of allowing greater error	Intermediate
3.5.1.10 Binocular Disparity	Gold and Hyman (1970) Gold and Perry (1972) Ripley and Dobry (1971)	Empirical Findings	Validate tolerances by in-flight testing, especially using night filter	Intermediate
3.5.2.12 Glare	Horning et al. (1971) Jainski (1971)	Expert Opinion	Identify glare sources and relate to display parameters	Critical
3.5.2.14 Fatigue	Johnson and Momiyama (1964) Soliday and Milligan (1967) Sheehan (1972)	Expert Opinion	Investigate "HUD Myopia" and reaccommodation problems	Critical
3.5.2.16 Night Filter	Opittek (1973) Gabriel et al. (1965)	Accepted Convention	Investigate filter characteristics as they interact with other display parameters	Intermediate
3.5.1.17 Standby Reticle	Ripley and Dobry (1971)	Expert Opinion		Solved
3.5.4 Manual Controls	Johnson and Momiyama (1964) Ripley and Dobry (1971)	Expert Opinion	Study functional organization of controls; investigate increases in display options available	Intermediate
ADDITIONAL REQUIREMENTS				
1. Symbol Brightness	Opittek (1973) Kelley et al. (1965)		Establish minimum symbol contrast	Intermediate
2. Symbol Dynamics	Hubner and Blose (1966) Sperry Gyroscope Co. (1963)		Establish optimal dynamic characteristics of symbols	Intermediate

V. CATEGORIES OF NECESSARY RESEARCH

Much of the required research shown in Table III can be organized into four general categories. Each will be briefly discussed.

A. TEST ASSUMPTIONS UNDERLYING HEAD-UP DISPLAYS

There are several critical questions to be answered that concern the rationale for employing virtual-image displays. Since HUDs are being required on many new aircraft, it is surprising that these questions have not been thoroughly researched. Instead, answers to these questions have been presumed so that technological advances in displays could be incorporated into new cockpit designs. The result is that there is very little hard evidence documenting the overall advantages of HUDs, and there is even less evidence concerning specific issues in the design of virtual-image displays. Consequently, it is impossible to assess the impact of each HUD component on performance, and, as shown above, it is difficult to write a HUD specification based on solid data. Research into several specific issues will help validate assumptions underlying HUDs.

The first issue concerns the contribution of each component of the instrument scanning process to the "visual comprehension lag." These components include head movement, eye movement, accommodation, and brightness adaptation. It is estimated that the transition from viewing the world outside the cockpit to viewing panel-mounted instruments takes about 0.8 seconds (Wulfeck et al., 1958; Hasselbring, 1970). It is critically important for design purposes to know how components of scanning contribute to the lag. For example, it may be true that one component accounts for most of the lag. In that case, when design tradeoffs are considered, that component ought to be eliminated with a higher priority than others. This is especially important if the elimination of other components introduces undesirable effects.

Second, conflicts among basic visual mechanisms that are caused by virtual-image displays ought to be researched. There may be a peculiar relationship, for example, between vergence and accommodation introduced by HUDs. These and other conflicts may partially negate the advantages of HUDs by increasing latency of response or causing visual fatigue. On the other hand, the effects of the conflicts may be reduced through training or experience.

Third, attention and workload in situations requiring the processing of several sources of visual information ought to be studied. As Senders (1983) indicated, it is not currently known whether the latency of "overt sampling" (i.e., redirection of gaze) is longer than the latency of "covert sampling" (i.e., redirection of attention). A presumption has been that eliminating components of "overt sampling" will significantly improve performance. The presumption is true only if the overt processes have much greater impact than covert processes, a fact that has yet to be demonstrated.

Neisser and Becklin (1976) observed subjects monitoring events on videot- ,es of two superimposed episodes. They found two effects pertinent to this discussion. Subjects' performance in monitoring one episode was slightly worse if the episode was superimposed on another, to-be-ignored episode rather than being presented alone. There was a large additional deterioration in performance if subjects were asked to monitor events on each of two superimposed episodes simultaneously. It is important to note that the effects found by Neisser and Becklin occurred despite the fact that the subjects did not have to adjust accommodation, move their heads, or adapt to new brightness levels to view the alternative episodes. These findings suggest that the effects of "covert sampling" can be sizeable.

Finally, the advantage of displaying each type of information specified for HUDs ought to be proved. This issue requires as a first step the kind of functional analyses performed by Ketchel and Jenney (1968), but that is only a beginning. As noted previously, tradeoffs must be documented between the ease of scanning information sources versus the penalty of increased display clutter. This research is probably most necessary for the tape symbology. However, as the results of Fogel et al. (1974) showed, even the addition of a horizon line caused increases in response latency. These kinds of performance tradeoffs must be known before decisions about adding information to HUDs can be made with confidence.

B. DEVELOP NECESSARY SYMBOLS

This category of research deals directly with utilizing the flexibility of the CRT display on HUDs. In the case of symbols designed to overlay real-world counterparts (e.g., runway, terrain carpet), studies must be made of the visual cues used by pilots viewing the real world under VFR conditions. Some of those cues may then be incorporated in symbols to be displayed under IFR conditions. Currently, the specified runway symbol may be problematic for the very reason that it does not incorporate visual cues ordinarily used by pilots judging the relationship to a runway. The terrain carpet, on the other hand, appears to provide sufficient height and depth cues to make it a good aid for low-level, terrain-avoidance missions.

Also included in this category of research should be the systematic study of physical stimulus parameters. A partial list would include symbol height, width, spacing, and linewidth. Parameters of the trichroic filter and the night filter ought to be systematically studied to find the best way to enhance contrast. Definite values for many such parameters appear in MIL-D-81641(AS), but these values are not usually based on data from electronic or optically generated displays. Those data are currently not available. New information is required in order to assure that specifications are set at optimal values.

Finally, certain parameters not mentioned in MIL-D-81641(AS) ought to be researched so they can be specified in the future. A list of the physical parameters of symbols would include brightness, color, and contrast. The dynamic properties of symbols ought to be researched as well so that control lag and sensitivity can be specified.

C. TEST DISPLAY FORMATS

Formats for display symbols ought to be studied with the goal of arranging symbols for efficient monitoring, while causing a minimum of interference with outside viewing. Research with individual indicators and scales must provide the data to make a choice among the many possible formats for displaying status information. In addition to facilitating the acquisition of information from a single indicator, the monitoring of several indicators ought to be made optimal. One approach to this task is to determine the typical frequency with which indicators are monitored, and then arrange the indicators so that efficient patterns of eye movements are possible. These aspects of format apply to all visual displays.

In the attempt to reduce interference among visual inputs, formats present Human Factors Engineering problems unique to HUDs. Since the presentation of virtual images is free of many constraints imposed by electromechanical devices, groups of symbols presented close together may be uninterpretable or interfere with outside viewing. As shown previously, current HUDs often present the pilot with a confusing array of information, and interfere with the visual acquisition and tracking of real-world objects at crucial times. Two distinct problems may be at work. One is display clutter, the simple problem of not being able to look "behind" symbols to see real-world objects. The other is "HUD myopia" -- the tendency to overconcentrate on HUD symbols to the exclusion of scanning the real world. When either of these happens, the common practice is to turn the HUD off, thereby negating its potential advantage.

D. STUDY OPTICAL PROPERTIES

Until optical systems permitting a large FOV can be developed without accompanying size and weight costs, the problem of establishing optimal FOV will remain. Even if new technology can maximize FOV, tradeoff experiments will have to be performed to establish the advantage of increasing FOV compared to the resulting increase in distortion of symbols and view of the outside world. Performance tradeoffs between scanning information on the periphery of a wide FOV HUD and presenting that information on the instrument panel ought to be determined. There is also work to be done for exit pupil size and head-to-exit-pupil distance. Some data are available for these parameters, but the studies to date have led to minimal rather than optimal guidelines.

Available evidence on glare and fatigue suggests that the optical components of the HUD may be responsible for those effects. The research in this area must first define suitable criteria for glare and fatigue, and then relate these effects to specific display parameters.

DISCUSSION

The categories of research required to develop HUD specifications are outlined in Table IV. Several important issues pertain to all of the categories and deserve mention. Above all, the dependent variables and experimental conditions used in this research must be chosen and interpreted with some care. In the studies reviewed, the following dependent variables were among those used: error rates generated by limiting time to view a single symbol, amount of "reserve control capacity" on a secondary task, error from desired flight path in an aircraft simulator, and written comments following actual flight test and evaluation. This range of experimental conditions makes it difficult to assess the relative importance of variables studied in different experiments.

In choosing experimental conditions and dependent variables, the Human Factors researcher faces a dilemma. Taken individually, effects found in well-controlled laboratory experiments may have a negligible impact in an operational environment. On the other hand, the laboratory experiment may be the only way possible to collect the data necessary to understand a basic phenomenon. Flight tests and subjective reports have a role in assessing the immediate application of a total system, but no understanding of any single issue is possible unless experimental variables and controls can be used. Furthermore, unless objective measures are used, performance tradeoffs may not be noted. No simple solution to this problem exists. The recommended approach is that the researcher be aware of this difficulty when experimental conditions and dependent variables are selected. Then, results should be generalized with great caution.

The second general issue pertains to possible technological advances in HUDs. Most of the necessary research identified here is relevant to but not restricted to operational HUD systems. There are special problems to be studied that are associated with (i) symbol sources other than CRTs, (ii) optical systems other than conventional lenses, and (iii) novel display-control designs. It is highly probable that technological advances will be made in one or more of these areas within the next decade. It is also likely that HUDs will be adopted for use in rotary wing and V/STOL aircraft (see, for example, Gold and Walchli, 1974). These technological advances should be anticipated by specific research programs to develop the necessary Human Factors specifications.

Third, while the analysis of manual controls does not appear as a separate category of research, that analysis is still important. It should be preceded by research on other issues, particularly those mentioned in the first two categories. Furthermore, many manual control problems are not peculiar to HUDs, and specific problems often arise for particular systems. Thus general issues in the study of controls may be best researched in other contexts. Problems specific to HUD systems can probably be handled on an _ad hoc_ basis.

Table IV

CATEGORIES OF RESEARCH REQUIREMENTS

ITEM	CATEGORY
I	Test Assumptions Underlying Head-up Displays.
	. How do scanning components contribute to the "visual comprehension lag?"
	. What is the impact of basic visual conflicts caused by HUDs?
	. What effect do virtual images have on visual attention in multitask situations?
	. Can an advantage be shown for each type of information required by MIL-D-81641(AS)?
II	Develop Necessary Symbols
	. Can overlay symbology incorporate natural visual cues?
	. What are the optimal physical characteristics of symbols?
	. What are the optimal dynamic characteristics of symbols?
III	Test Display Formats
	. Can symbols be arranged for optimal scanning of information?
	. What contributes to "display clutter" and "HUD myopia?"
IV	Study Optical Properties
	. What tradeoffs are incurred by increasing Field of View?
	. Which display parameters cause glare and fatigue?

Finally, the categories of research in Table IV are not intended to be distinct. In fact, overlap is desirable. Symbol development and format problems are clearly related. Formats are in turn related to the optical properties of HUDs, and all of these issues combine in determining the potential advantage of HUDs. The categories shown in Table IV represent one way to organize the research required to develop optimal Human Factors specifications for HUDs.

CONCLUSIONS

The technology of HUDs has advanced greatly from the first days of collimating flight-path information for VFR landing. Human Factors knowledge has not kept pace. Consequently, the majority of specifications found in Section 3.5 of MIL-D-81641(AS) are based upon expert opinion, rather than upon data utilizing electronic displays. Research is required to provide an adequate data base for future specifications, and to understand how specific issues in the design of HUDs affect performance.

REFERENCES

Clement, W. F., Allen, R. W., and Graham, D. Pilot experiments for a theory of integrated display format. JANAIR Report 71107, October, 1971, Systems Technology, Inc., Contract No. N00014-68-C-0443, Office of Naval Research.

DeBellis, W. B. Flight information scale test for head-up and panel mounted displays. Technical Memorandum 22-73. Aberdeen Proving Ground, Md.: U. S. Army Human Engineering Laboratory, October, 1973.

Egan, D. E. Research toward improving the performance of pilots using head-up displays. Paper presented at Carrier Landing Performance Conference, Naval Safety Center, Naval Air Station, Norfolk, Va., April 14, 1976.

Fogel, L. J., Englund, C. E., Mout, M. L., and Hertz, T. D. Principles of display and control design for strike RPVs. Report No. N00014-72-0196. Decision Science, Inc., June, 1974.

Gabriel, R. F., Uyeda, L. R., and Burrows, A. A. An investigation of lighting in displays with superimposed fields while at low levels of illumination. February, 1965, Douglas Aircraft Co., Inc., Aircraft Division, Contract No. Nonr 4348(00), Office of Naval Research.

Gold, T. and Deutschle, C. A. Flight simulation study of head-up displays for high-speed flight at low altitudes. Report No. SGD-4277-0190, December, 1968. Sperry Gyroscope Division, Sperry Rand Corp., Contract No. NOw63-0190d, Naval Air Systems Command.

Gold, T. and Hyman, A. Visual requirements study for head-up displays. Final Report-Phase I. JANAIR Report 680712, March, 1970. Sperry Gyroscope Division, Sperry Rand Corp., Contract No. N00014-66-C-0114, Office of Naval Research, Naval Air Systems Command, U. S. Army Electronics Command.

Gold, T. and Perry, E. F. Visual requrements study for head-up displays. Final Report. JANAIR Report 700407, March, 1972. Sperry Gyroscope Division, Sperry Rand Corp., Contract No. N00014-68-C-0465, Office of Naval Research.

Gold, T. and Walchli, R. M. Head-up display for all-weather approach and landing of tilt-wing V/STOL aircraft. Paper presented at AIAA 6th Aircraft Design, Flight Test and Operations Meeting, Los Angeles, California, August 12-14, 1974.

Grindle, B. D., Busch, D. S., and Ohnmacht, R. B. CRT display circuits. Technical Information Series No. 67APJ7. Binghamton, New York: Defense Electronics Division, Avionic Controls Department, General Electric Corp., April, 1967.

Harlow, R. A. Flight assessment of head-up display as a clear weather approach aid. Technical Report 71141. Farnborough, England: Royal Aircraft Establishment, July, 1971.

Hasselbring, H. H. A survey of sighting and aiming devices. Technical Report TR-1557. Indianapolis, Indiana: Naval Avionics Facility, July, 1970.

Hodge, D. C., and Garinther, G. R. Noise and blast. In Parker, J. F. and West, V. R. (Eds.) Bioastronautics Data Book, Washington, D.C.: National Aeronautics and Space Administration, 1973, Pp 693-750.

Horning, D. O., Finch, D. M., Mellander, K., and Miller, A. Head-up display study. FAA-RD-71-60, May, 1971, Institute of Transportation and Traffic Engineering, University of California, Berkeley, Contract ARDS-434, Department of Transportation, Federal Aviation Administration.

Hubner, J., and Blose, L. E. First interim report: preliminary flight evaluation of the F-111B primary flight displays. NATC Technical Report ST 46R-66. Patuxent River, Md.: Naval Air Test Center, June, 1966.

Hussey, C. L. Evaluation of a wide angle head-up display optical system. Report No. NADC-AM-7042. Warminster, Pennsylvania: Naval Air Development Center, December, 1970.

Jainski, P. The effect of dazzle on electronic display visibility in modern high-performance aircraft cockpits. A summary. German Federal Ministry of Defence Research Project TII3, with the designation number T-808-1-203. Farnborough, England: Royal Aircraft Establishment Library Translation Number 1545, March, 1971.

Jenney, L. L., Malone, T. B., and Schweickert, G. A. Head-up displays. A study of their applicability in civil aviation. January, 1971, Matrix Research Division, URS Systems Corp., Contract NASW-1940, National Aeronautics and Space Administration.

Johnson, R. K., and Momiyama, T. S. Flight test and evaluation of the Spectocom head-up display installed in an A-5A airplane. NATC Technical Report FT 2222-65R-64. Patuxent River, Md.: Naval Air Test Center, December, 1964.

Jones, R. W. and Smith, A. J. The head-up display of carrier approach information. Technical Report 66055. Farnborough, England: Royal Aircraft Establishment, February, 1966.

Kelley, C. R., Ketchel, J. M., and Strudwick, P. H. Experimental evaluation of head-up display high brightness requirements. Technical Report No. HFR 9765-1, November, 1965. Kaiser Aerospace & Electronics, Contract No. AF33(675)8260, United States Air Force.

Ketchel, J. M. and Jenney, L. L. Electronic and optically generated aircraft displays. A study of standardization requirements. JANAIR Report No. 680505, May, 1968, The Matrix Corporation, Contract No. N00014-67-C-0517, Office of Naval Research.

Meister, D., and Sullivan, D. J. Guide to human engineering design for visual displays. Canoga Park, Calif.: Bunker-Ramo Corp., August, 1969.

MIL-D-81641(AS): Display, head-up, general specification for. 26 June 1972.

MIL-M-18012B: Markings for aircraw station displays, design and configuration of. 20 July, 1964.

Morall, J. C. The pilot's safety problem in category II operations and the potential contribution of head-up display. Aeronautical Research Council Current Papers, C. F. No. 1001. London: Ministry of Technology, 1968.

Naish, J. M. A system for presenting steering information during visual flight (the head-up display). Part 1--the effect of location of the instrument display on combined instrument and visual flying. Technical Note I.A.P. 1132. Farnborough, England: Royal Aircraft Establishment, October, 1961.

Naish, J. M. A system for presenting steering information during visual flight (the head-up display). Part 2--the form of the presented information. Technical Note I.A.P. 1138. Farnborough, England: Royal Aircraft Establishment, February, 1962.

Naish, J. M., and Shiel, R. Flight trials of the head-up display (H.U.D.) in Meteor 7/8 and Hunter 12 aircraft. Technical Report No. 65254, Farnborough, England: Royal Aircraft Establishment, November, 1965.

Neisser, U. and Becklin, R. Selective looking; attending to visually specified events. Cognitive Psychology, 1976, 7, 480-494.

Opittek, E. W. Head-up display study. Technical Report AFAL-TR-73-215, July 1973, Hughes Aircraft Co., Contract F33515-72-C-2140, United States Air Force Avionics Laboratory.

Orrick, W. P. and York, P. E. Head-up display symbology. Technical Report No. NADC-75267-40. Warminster, Pennsylvania: Naval Air Development Center, December, 1975.

Poole, H. H. Fundamentals of display systems. Washington: Spartan Books, 1966.

Ramsey, W. E. and Momiyama, T. S. Final Report. Flight test and evaluation of the Sperry head-up display installed in an F-11A (F11F-1) airplane. NATC Technical Report No. FT2211-15R-63. Patuxent River, Md.: Naval Air Test Center, August, 1963.

Ripley, M. J., and Dobry, T. E. Flight evaluation of a wide field-of-view head-up display installed in an A6-A airplane. NATC Technical Report WST-134R-71. Patuxent River, Md.: Naval Air Test Center, August, 1971.

Roscoe, S. N. Development of integrated display panels at Hughes Aircraft Company. Paper presented to the Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October, 1956.

Ryan, J. G. Results of F-14A HUD symbology simulation. Final Report. NADC Report No. NADC-SD-6940. Warminster, Pennsylvania: Naval Air Development Center, June, 1969.

Semple, C. A., Jr., Heapy, R. J., Conway, E. J., Jr. and Burnett, K. T. Analysis of human factors data for electronic flight display systems. Technical Report AFFDL-TR-70-174, April, 1971, Manner Systems Sciences, Inc., Contract No. F33615-70-C-1132, United States Air Force.

Senders, J. W. The human operator as a monitor and controller of multi-degree of freedom systems. IEEE Transactions on Human Factors and Electronics, 1964, Vol. HFE-5, 2-5.

Senders, J. The automobile windshield as an extreme case of a "heads-up display." In M. J. Brooks (Chm.), Head-Up Displays, symposium presented at Human Factors Society, September 11, 1968.

Sheehan, D. J. Head-up display warning requirements research. Final Report. Report No. 1232 R 0006, August, 1972. Norden Division of United Aircraft Corporation, Contract No. N00014-71-C-0272, Office of Naval Research.

Soliday, S. M., and Milligan, J. R. Simulation of low altitude high speed mission performance, Volume II. Technical Report SEG-TR-66-67, February, 1967, North American Aviation, Columbus Division, Contract AF 33(657)-1378, United States Air Force.

Sperry Gyroscope Co., Progress report on human factors and analytical study for head-up display system development. Sperry Report No. AB-1210-0008, August, 1963, Sperry Rand Corp., Contract No. NOw 63-0190-d, Avionics Division, Bureau of Naval Weapons (CONFIDENTIAL Report), title UNCLASSIFIED.

Sperry Rand Corporation. Flight simulation investigation of head-up display for low altitude high-speed missions. Technical Report ASD-TR-68-5, March, 1968, Sperry Rand Corp., Contract No. AF33(657)-13544, United States Air Force.

Walchli, R. M. Head-up display review. Document No. F044-7U1, July, 1967, The Bunker-Ramo Corp., Contract No. AF 33(615)-3757, United States Air Force.

Wulfeck, J. W., Weisg, A., and Raben, M. Vision in military aviation. Technical Report WADC-TR-58-399. Wright-Patterson Air Force Base, Ohio: Wright Air Development Center, November, 1958.

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This report is a review of Human Factors literature and military specifications concerning Head-Up Displays (HUDs). The objective is to identify important categories of Human Factors research concerning virtual-image displays. These research categories are questions that must be answered before specifications can be written for the optimal design of HUDs.

The review encompassed an exhaustive list of references available through the Defense Documentation Center (DDC) as well as other pertinent sources not given in the DDC listing. Each requirement in the General Specification for Head-Up Displays, MIL-D-81641(AS), was compared with the available data. The data base for requirements and the importance of further research concerning each requirement were qualitatively rated. Categories of necessary research were established.

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Human Factors knowledge has not kept pace with the proliferating uses of HUDs and the expansion of HUD technology. Consequently, the majority of existing Human Factors specifications for HUDs are based on expert opinion rather than emperical data. Several categories of research are required to provide an adequate data base for future specifications, and to understand how specific issues in the design of HUDs affect performance.

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