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THE UTILITY OF ANALOG VERTICAL VELOCITY INFORMATION DURING INSTRUMENT FLIGHT WITH A HEAD-UP DISPLAY (HUD)

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The United States Air Force (USAF) is attempting to create a standard symbol set for use with the HUD as a primary flight reference. As part of that effort, eight HUD-experienced pilots and twelve non-HUD-experienced pilots participated in a study that examined the effects of variations in vertical velocity indicators (VVI) for use under instrument flight conditions in a simulator. Five configurations were assessed: digital readout, boxed digits with tape, dial, altimeter arc, and altimeter arc with digital readout. The results clearly indicated that the altimeter arc with digital readout, and the altimeter arc alone, resulted in significantly more accurate maintenance of flight parameters (i.e., vertical velocity and altitude) than did the digital readout alone, the boxed digits with tape, or the dial. Subjective data supported the objective findings, in that pilots preferred either configuration that included the altimeter arc. These findings suggest that analog vertical velocity information is useful on the HUD, particularly when it is located in close proximity to the altimeter.

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THE UTILITY OF ANALOG VERTICAL VELOCITY INFORMATION DURING INSTRUMENT FLIGHT WITH A HEAD-UP DISPLAY (HUD)

INTRODUCTION

Pilots have always had a need for vertical motion information. In fact, vertical velocity is arguably the most important basic flight parameter of aircraft motion. The vector addition of vertical velocity, forward velocity, and lateral velocity determines the displacement of the aircraft as a moving body. Accounts by early instrument flight researchers note that the Wright brothers were the first to recognize the need for vertical motion indications (Ocker, 1930). The Wright brothers solved the problem by attaching an 8- to 10-inch-long piece of string to one of the aircraft struts. An approximation of the aircraft vertical speed and direction could be obtained by referencing the vertical deflection of the string. The string was used until mechanical vertical velocity indicators (VVIs) were developed. Surprisingly, even after many years and technological advancements, the VVIs of today look very much like the early mechanical ones (Ocker & Crane, 1932).

The approach to landing an aircraft and the landing itself involve the skillful integration of vertical velocity with other flight parameters. In many flight situations, one of the first instruments visually scanned after rolling out on final and establishing an aimpoint is the VVI. The pilot is usually too high above the ground to accurately determine height and detect useful vertical motion information. Hence, a quick glance at the VVI, especially when outside visual cues are lacking, provides vital information for the remaining approach. Even though few pilots actually look at the VVI during the flare and landing, vertical velocity is assessed by reference to the rate of apparent motion of the surrounding terrain. Some flight manuals even require the vertical velocity to be checked prior to touchdown to ensure that the structural limits of the aircraft are not exceeded. Because of the importance of vertical velocity during all phases of flight, the VVI has remained an integral part of every head-down instrument panel.

Head-up displays (HUDs) have created an interesting change from the traditional manner in which vertical velocity information is displayed. The HUD provides the pilot with a display of the direction of the aircraft motion, and superimposes an aircraft symbol, representing the flight path, onto the real world. This resultant symbol has decreased the need for an independent VVI. The pilot no longer must mentally integrate the individual velocities; they are already combined and displayed as the flight path marker. Traditional panel instruments and "attitude" flying (i.e., pitch and vertical velocity flight control) are slowly becoming a thing of the past. "Vector" displays (HUDs, and in some cases, helmet mounted displays) are the new instrument displays beginning to replace the traditional head-down instrument indicators.

Unfortunately, a few unexpected problems were noticed as pilots began to rely more frequently on the HUD for aircraft control and performance indications. Aircraft were over-rotating on takeoff, causing the tail to drag; some other "difficult to understand" inflight accidents occurred, and the HUD was suspected to have been a contributing factor. Although these operational problems were identified early (Newman, 1980), it was not until the Aircraft Attitude Awareness Workshop in 1985 that researchers and pilots identified and agreed on the need for specific improvements. Symbol design and mechanization, fault detection and warning indications, symbology standardization, field of view limitations, and training were identified as weaknesses with current HUDs and recommendations were made to improve them (McNaughton, 1985). If the USAF was to adopt the HUD for use during instrument flight, then these apparent problems had to be addressed and improvements needed to be made.

The ensuing attempt to address these issues resulted in extensive research (Weinstein & Ercoline, 1991) and controversy (Iavecchia, Iavecchia & Roscoe, 1988; Roscoe, 1987; Newman, 1987). Even though the USAF never accepted the HUD as a primary flight display, technology and mission-essential information requirements rapidly caused a new cockpit instrument configuration to evolve with the HUD as the central theme (Fig. 1). If the HUD was going to replace the traditional panel instruments, then some type of standardization was required, and additional research was necessary to help define the standardization issues.

Unresolved Issues

Although extensive research efforts have helped resolve a number of the standardization issues, several aspects of the symbology have yet to be determined (Bitton & Evans, 1991). For example, the flight path and climb/dive marker symbols have not been defined. The flight path marker will represent the true velocity vector of the aircraft, while the climb/dive marker will show the climb/dive angle of the aircraft with respect to the climb/dive ladder. The flight path marker has traditionally been a circle with wings and a tail (-ȯ-), and was used as a control reference for the aircraft. However, since the climb/dive marker will now primarily be used to control the aircraft, while the flight path marker will be free to display the total velocity of the aircraft, the question arises as to which symbol should look like a traditional flight path marker: the symbol that moves like a traditional flight path marker, or the symbol used to control the aircraft. This issue is being explored by investigators at the Wright Laboratory at Wright-Patterson AFB.

Several other symbology representations have not been investigated yet. These include: 1) the presentation format for bearing information, 2) the utility of various global attitude references, 3) the optimal presentation format of energy management cues (i.e., airspeed deviation, angle-of-attack deviation, and acceleration), 4) the utility of display augmentation techniques (e.g., quickening, compression, and caging), and 5) the optimal configuration of positive failure indications. (It has been determined that removing faulty information from the HUD is not sufficient for failure indication.)

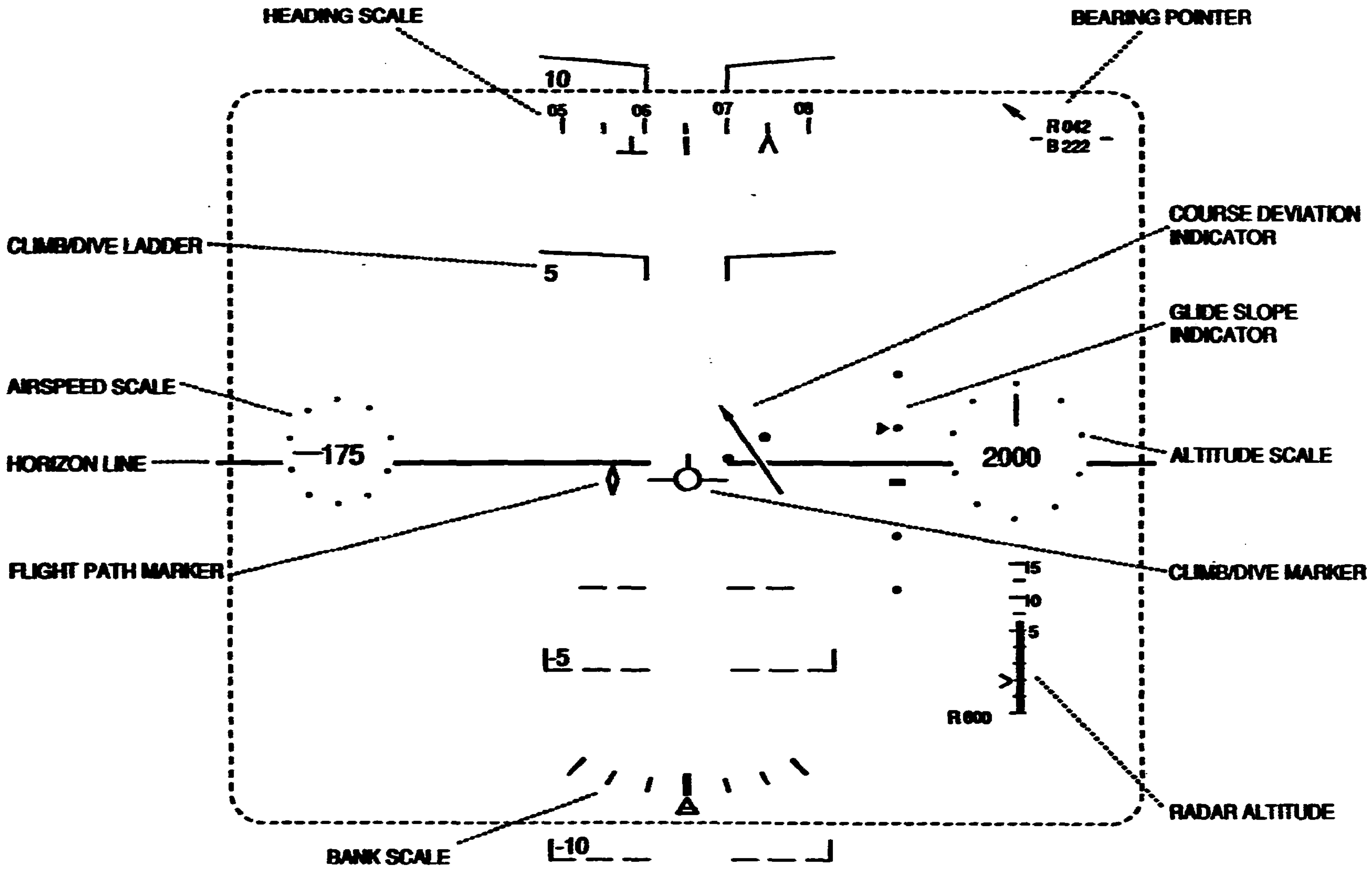

Figure 1
Typical composite candidate standard HUD symbology

Analog vertical velocity information. The current research effort examined an additional issue that remains unresolved in the development of a standard symbology set: the necessity of and the optimal configuration for analog vertical velocity information. The current draft standard states that a digital readout of vertical velocity on the HUD is sufficient in most phases of flight (Bitton & Evans, 1991). However, when flight path information is not available, then analog vertical velocity information may be beneficial, as described below.

The position of the flight path marker on the HUD is determined by a combination of the aircraft airspeed, pitch, bank, vertical velocity, G loading, and wind. Therefore, the pilot can control the flight path of the aircraft by essentially overlaying the flight path marker on the desired real-world destination. In this typical flight situation, the pilot does not need a constant analog representation of the vertical aircraft velocity since this information has already been integrated into the calculation of his flight path. However, in certain situations (e.g., high angle-of-attack, sinking) the actual flight path of the aircraft (and therefore the flight path marker) cannot be represented within the field of view of the HUD. When the flight path marker is not usable, the pilot must resort to using pitch and vertical velocity information to control the flight path. As part of an effort to improve the ability of the HUD to provide unambiguous, easily assimilable vertical velocity information, the USAF has been exploring various alternative configurations for the VVI.

The presentation of vertical velocity information by a digital readout is one possible format for use on the HUD. Digital readouts are generally superior to analog displays when precise numeric information is required to complete a task (Sinclair, 1971). In addition, a digital readout is desirable on the HUD to reduce clutter. However, with aircraft parameters such as vertical velocity, the values often change so rapidly that the digits may be difficult to read. Many flying maneuvers require a pilot to capture a particular vertical velocity or notice changes in vertical velocity. Therefore, the use of an analog vertical velocity indicator may be beneficial for these tasks.

The Current Experiment

There were two objectives in the current study: 1) Determine if an analog presentation format allows a pilot to perform flying tasks that require vertical velocity information more accurately than does a pure digital readout, and 2) Determine if the incorporation of analog vertical velocity information with a digital readout is beneficial during these same tasks. The design of this study allowed for the exploration of both of these issues. Subjects were required to perform several VVI-intensive flying tasks with the five VVIs shown in Figure 2: 1) a digital readout, 2) a circular moving-pointer dial, 3) boxed digits with a trend tape extending from the top or bottom to indicate positive or negative vertical velocities, respectively, 4) an arc around the altimeter beginning at the nine o'clock position and extending around the top or bottom of the altimeter to indicate positive or negative vertical velocities, respectively, and 5) a combination of the digital readout and the arc.

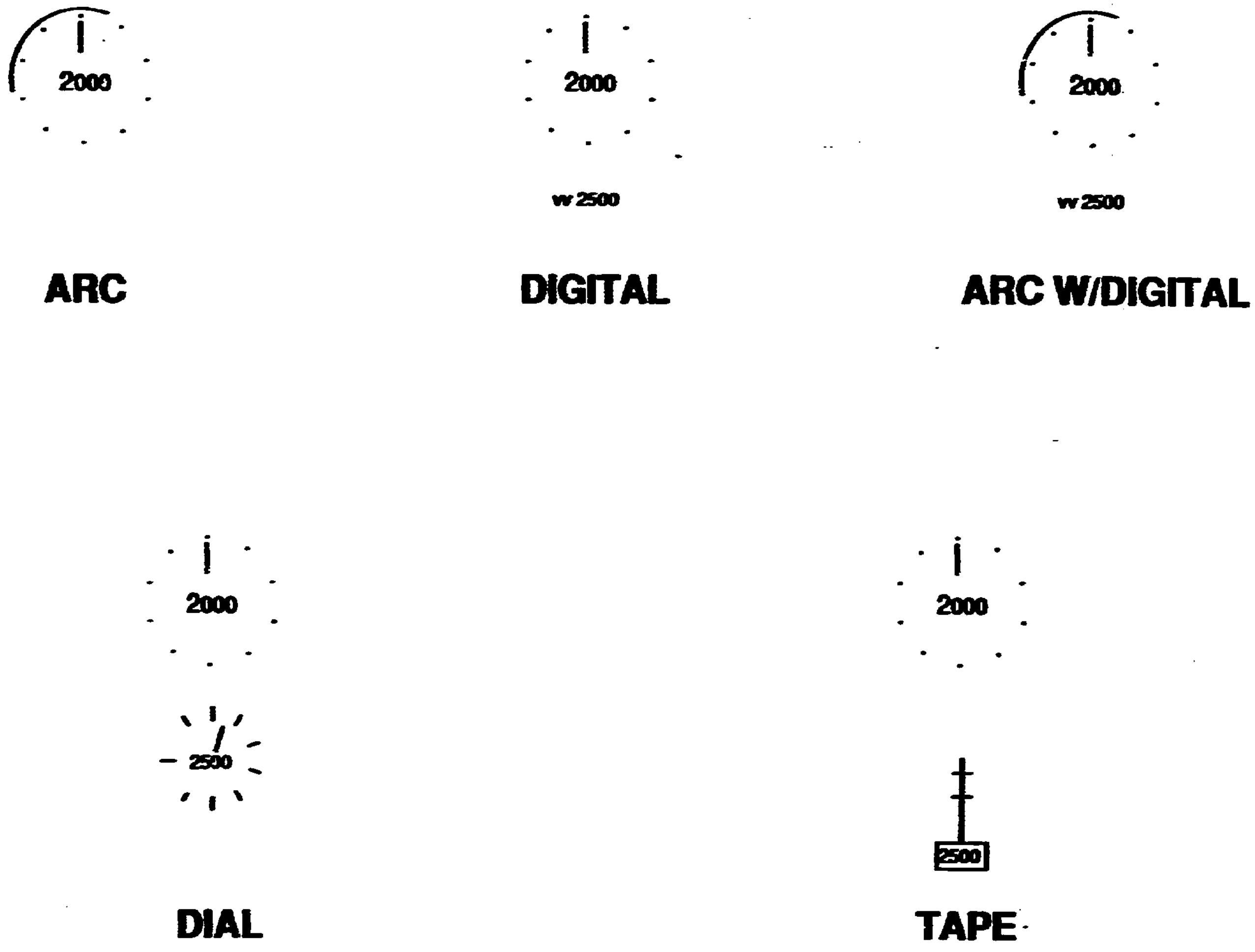

Figure 2
Five vertical velocity indicators tested in the current study.

Digital display. The digital readout was located directly below the altimeter, and the digits were preceded by the two-letter identifier, "vv". The digital format provided precise numeric vertical velocity data.

Dial display. The dial display was similar to a head-down analog dial with a digital readout in the center of the dial. The distance between the "0" and 1000 ft/min marks on the dial was twice the distances between the subsequent marks. This scaling was used on all of the analog indicators to allow for more precise control and ease of recognition of changes in vertical velocities less than ±304 m/min (1000 ft/min).

Tape display. The boxed digits with trend tape also allowed for the precision of a digital display with the addition of analog information. Both the dial and tape formats provided the benefits of analog presentation while conforming to several well established human factors design principles. First is Roscoe's (1981) principle of compatibility of motion. Roscoe proposes that the motion of display elements should be compatible with the pilot's mental representation of motion in the world. The tape VVI was designed so that when the tape was above the digital readout and moving up on the display, vertical velocity of the aircraft was positive and increasing; and when the tape was below the digital readout and moving down on the display, vertical velocity of the aircraft was negative and increasing. These physical indications on the display were compatible with the pilot's mental representation of the aircraft motion. A similar analysis can be applied to the dial display if the scale is simply transformed into a circular format. Compatibility with the pilot's mental representation should reduce the cognitive processing demands associated with use of that configuration, and as a result reduce the pilot's mental workload and the risk of display interpretation errors.

Second, the dial display conformed to the population stereotype of "clockwise to increase" that suggests that clockwise rotation on a dial should correspond to increasing values of the quantity displayed (Wickens, in press). The tape display also conforms to a population stereotype: up to increase, down to decrease. Since the tape and the dial configurations conformed to the principles of compatibility of motion, and population stereotypes, these configurations should have less potential for interpretation errors and the ensuing risk of spatial disorientation than would a pure digital readout.

Arc display. The arc display does not include the precise digital readout, but does provide the benefits of analog displays. As with the dial and tape displays, compatibility of motion and population stereotypes are preserved. The arc also reduces display clutter by consisting of a single stroked line around the altimeter instead of comprising a separate instrument.

The integration of the vertical velocity information with the altimeter suggests several other potential benefits. First, by placing the VVI in close proximity to the altimeter, the area subtended by the pilot's crosscheck of the instruments is reduced from the area subtended by the pilot's crosscheck with the other analog displays. Second, the location and size of the arc reduces display clutter. With reduction in display clutter, the pilot can view more of the outside world through the HUD maintaining a higher level of spatial orientation and overall situational awareness. Third, according to the principle of compatibility of proximity, information that must be integrated for decision making purposes is best arranged in close physical proximity on a display, and more specifically as several attributes of a single object display (Boles and Wickens, 1983). Since the pilot must mentally integrate vertical velocity information with altitude information to acquire an accurate mental representation of the vertical state of the aircraft, it is beneficial to have the two pieces of information located on the same display. In summary, the arc display adheres to the principle of compatibility of motion, population stereotypes, and the principle of compatibility of proximity. Therefore, we predict an advantage for the arc VVI over the other analog displays.

Arc with digital readout display. One objective of this current study was to determine if there was a significant advantage to including digital readouts with analog indicators. Therefore, a fifth configuration was added that combined the arc with a digital readout. The digital readout was located directly below the altimeter, in the same manner as the digital readout alone.

This paper describes a study that examined the effects of various configurations of VVIs on instrument flight performance during VVI-intensive maneuvers. Straight and level flight and vertical S maneuvers were used to assess pilots' abilities to use the different vertical velocity configurations.

METHOD

Subjects

Eight HUD-experienced, and twelve non-HUD-experienced male, military pilots volunteered to participate in the study. One subject was not able to complete the study; therefore, his objective data were not included in the statistical analysis. However, the subject did fill out the questionnaire and his subjective data was used in the analysis. The average total flight time for all of the subjects was 2,800 hours, and the HUD-experienced pilots had an average of 670 hours of HUD flying time. The pilots had experience in a number of HUD-equipped aircraft, including the F-15, F-16, and A-10.

Apparatus

The experiment was conducted in the Visual Orientation Laboratory (VOL) in the Crew Technology Division, Crew Systems Directorate of the USAF Armstrong Laboratory at Brooks AFB, Texas. The VOL includes (a) a Silicon

Graphics IRIS 3130 computer workstation, (b) a Sony VPH-1030Q1 color video projector, (c) a subject booth containing a Draper Cine-15 viewing screen, and (d) a simulated F-16 aircraft seat with a side-arm force-stick controller on the right and a throttle on the left. Both the video projector and the viewing screen have a vertical adjustment allowing the center of the projected image to be set at eye level for each subject sitting in the simulated aircraft seat.

Tasks

The subjects were asked to perform four instrument maneuvers with each HUD configuration. The only difference between the HUDs was the VVI (Fig. 2).

During Task 1, subjects were asked to maintain straight and level flight at an altitude of 8,500 ft, an airspeed of 360 knots and a heading of 010 degrees. Task 2 was a vertical S alpha, which is a climb and descent flown on a constant heading. Subjects were asked to climb from 8,500 feet to 9,500 feet and then descend to 8,500 feet with a constant vertical velocity of 1,000 feet/minute, an airspeed of 360 knots, and a heading of 010 degrees. Task 3 was a vertical S delta, which also involved a climb from 8,500 feet to 9,500 feet and a descent to 8,500 feet, at a vertical velocity of 1,000 feet/minute and an airspeed of 360 knots. In the vertical S delta, however, a 30 degree right bank is added during the climb and the direction of the bank is reversed at the top to 30 degrees left for the descent. In this case, heading is irrelevant. Random vertical motion perturbations, generated by a sum of sinusoids forcing function, were used to increase the difficulty of the vertical S tasks. When performed correctly the vertical S alpha and delta should take two minutes each to complete. Task 4 was another segment of straight and level flight at 8,500 feet, 360 knots, and a heading of 010 degrees, but this segment included the sum-of-sinusoids perturbation.

Procedure

The subjects were asked to perform the four instrument flight procedures with each of the five HUD configurations, which resulted in a total of 20 trials per subject. The HUDs were presented with a gray background scene simulating flight in instrument meteorological conditions. The flight path marker was not presented on the HUD; accordingly pilots were instructed to use the pitch reference and vertical velocity information to perform the tasks. Subjects were allowed to "free-fly" each HUD until they were comfortable with its operation and were ready to start the experimental trials. The "free-flight" for each HUD was flown immediately before the set of experimental trials for that display. Practice vertical S maneuvers were flown by each subject. All trials were run during a 2-hour session. Subjects were encouraged to rest whenever necessary. The HUD presentation order was balanced across subjects. The four flight manuevers were always flown in the order discussed above (Task 1, Task 2, Task 3, and Task 4).

The primary factors in evaluating the quality of a VVI are how well the pilot can maintain a predetermined vertical velocity, and how effectively he can detect and respond to deviations in vertical velocity with that display. Therefore, root mean squared errors (RMSE) from a set vertical velocity was the primary measure used to evaluate the five HUD configurations. The dependent variables analyzed in the straight and level portions were the altitude, airspeed, and heading RMSE. For the vertical S alpha, the vertical velocity, airspeed, and heading RMSEs were examined, and for the vertical S delta the vertical velocity, airspeed, and bank RMSEs were analyzed. However, a secondary measure of the quality of a VVI is the reduction in pilot workload associated with that configuration relative to other configurations. In the current scenario a decrease in workload was assumed to be associated with an increase in the pilot's ability to maintain other flight parameters (i.e., altitude, heading, airspeed, bank). This means that an improvement in the maintenance of these other flight parameters is expected with an increase in the quality of the VVI.

The nature of the straight and level tasks and the vertical S tasks required that attention be centered on different portions of the symbology, and therefore the VVI played a different role during the two types of tasks. The straight and level tasks required strict attention to the altimeter, and the VVI was used to detect changes in vertical velocity that would eventually result in changes in altitude if left unchecked. In addition, the pilot crosschecked airspeed and heading in order to maintain 360 knots and 010 degrees. The vertical S tasks required maintenance of a 1,000 ft/min vertical velocity, and thus the pilot focused attention primarily on the VVI while including the other symbology into his crosscheck to maintain 360 knots, the 010-degree heading (vertical S alpha) or the 30-degree bank (vertical S delta), and altitude within the restrictions.

At the completion of each task, subjects were asked to rate the effectiveness of each VVI in completing the task. Subjects responded with a numeric rating of "1" through "7" where "1" represented very ineffective and "7" very effective.

RESULTS

Of the 19 subjects who completed the objective data collection session, 8 had previous HUD experience and 11 had no prior HUD experience. Repeated measures analyses of variance (ANOVAs) were conducted on the RMSE measures for vertical velocity, altitude, airspeed, heading, and bank for the four tasks as appropriate (e.g., RMSE for heading would be irrelevant during the vertical S delta, which requires maintenance of a 30-degree bank and no set heading). HUD experience was used as a grouping factor for the ANOVAs, while HUD configuration and task type were used as within-subjects factors. There were no significant effects due to HUD experience; consequently, the data for the two groups were combined.

Objective Data

The mean vertical velocity RMSE for the five HUD configurations and the two vertical S tasks are shown in Table 1. Vertical velocity RMSE was analyzed for the vertical S tasks; there was a statistically significant main effect due to HUD configuration (F(4,68)=17.57, p < .001). A main effect due to task type was also significant (F(1,17)=12.42, p < .01). A marginally significant (F(4,68)=2.57, p=.05) interaction effect of HUD by task type was found and is illustrated in Figure 3.

Table 1. Mean of RMS Error for Vertical Velocity (ft/min) for the five HUD Configurations and the Two Vertical S Manuevers

TASK	HUD				
	DIAL	TAPE	DIGIT	ARC + DIGIT	ARC
Vertical S Alpha	420.63	589.96	582.10	350.50	364.00
Vertical S Delta	658.48	650.78	626.95	429.13	463.03

A Bonferroni post hoc comparison revealed that the dial configuration resulted in less accurate performance on the vertical S delta task than it did on the vertical S alpha task. (Note that the .05 significance level was used for all post hoc tests.) The pattern of the interaction suggests that the maintenance of vertical velocity is consistently more accurate during the vertical S alpha than during the vertical S delta, and the pattern is similar for four of the five configurations. This pattern suggests that some attribute of the dial configuration may result in differential utility for that design depending on the task to be accomplished.

Altitude maintenance was only required during the straight and level portions of the experiment. Therefore, the altitude RMSE data were only analyzed for the two segments requiring straight and level flight. There was no display effect during the straight and level portion without perturbations (Task 1). Therefore, only the data obtained during Task 4 will be discussed. Figure 4 illustrates the statistically significant effect (F(4,68) = 3.78, p < .01) for altitude RMSE during the straight and level task with perturbations (Task 4). A Bonferroni post hoc comparison revealed that the arc and arc with digital readout configurations resulted in significantly more accurate altitude control than did the digital configuration alone. The test also revealed that the arc display allowed for significantly more accurate altitude control than did the tape configuration.

VERTICAL VELOCITY ERROR AS A FUNCTION OF TASK TYPE AND VVI CONFIGURATION

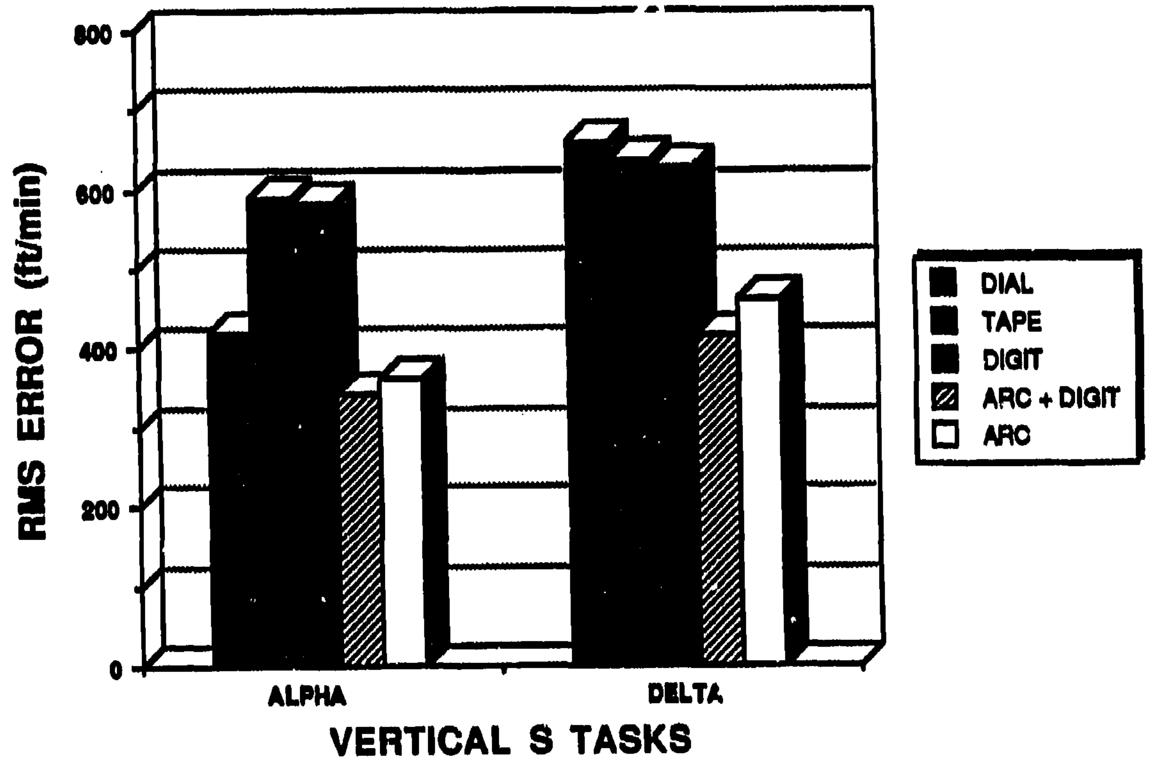

Figure 3
Root mean square error (vertical velocity) in feet per minute as a function of vertical S task type and VVI configuration

Airspeed maintenance was required during all four flight manuevers. There was a statistically significant effect of task type; both vertical S tasks had a larger airspeed RMSE than did the straight and level segments (F(3,68) = 21.32, p < .001). However, there was no effect of VVI configuration on airspeed control.

Heading error was analyzed for the two straight and level tasks and the vertical S alpha task. There was a significant effect due to task type, with the tasks including perturbations showing increased RMSE over the straight and level task without perturbations (F(2,68) = 14.67, p < .001). This finding is not surprising because the perturbations were designed to increase the difficulty level of the tasks.

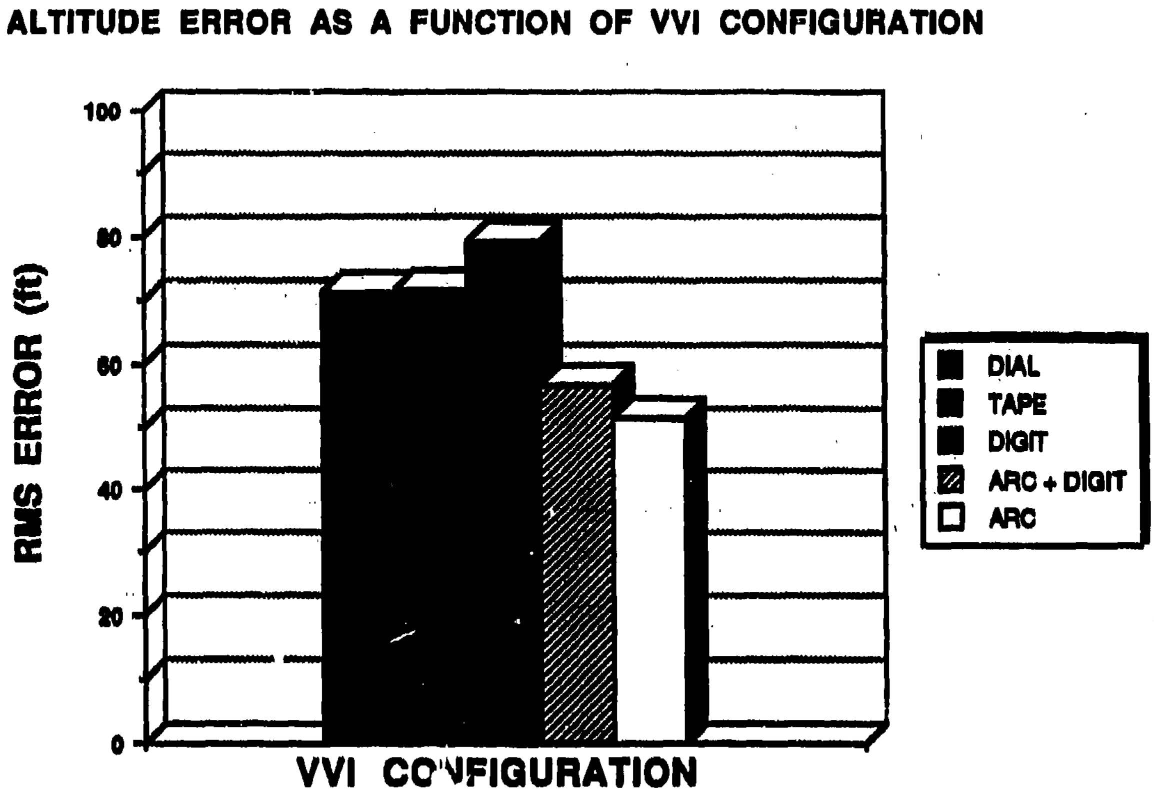

Figure 4
Root mean square error (altitude) in feet as a function of VVI configuration

Bank maintenance was required only during the vertical S delta. The RMSE in bank as a function of VVI configuration is shown in Figure 5. Although the overall error rates in bank angle were very small (approximately 2 degrees), there was a statistically significant effect due to VVI configuration. A Bonferroni post hoc comparison revealed that bank errors were significantly greater with the arc and arc with digital readout than with the tape or digital readout. Although the difference is small, this finding may reflect some unique properties of the arc display that will be explored in the discussion.

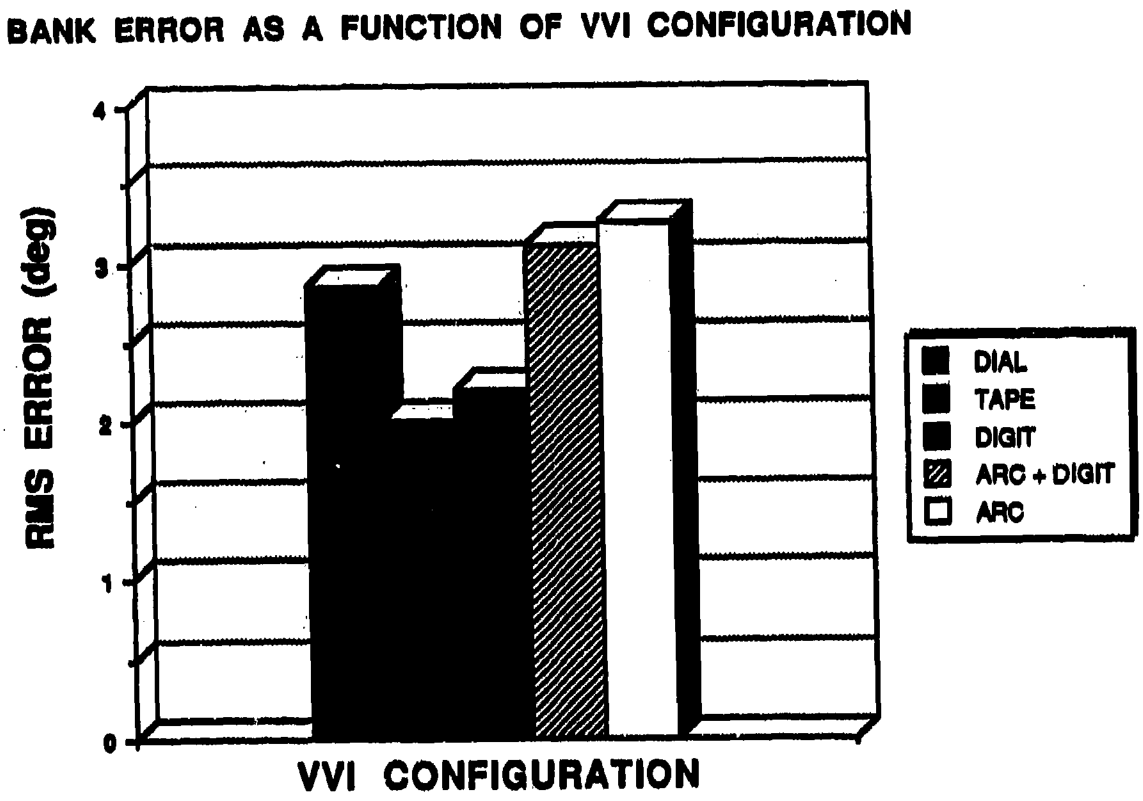

Figure 5
Root mean square error (bank) in degrees as a function of VVI configuration

Subjective Data

At the completion of the session, each subject completed a preference questionnaire. Table 2 shows the mean ratings for the five displays in the four flight tasks.

The results of that survey supported the objective findings, in that pilots preferred either configuration that included the altimeter arc (a design previously unknown to them) over the digital or tape configurations. An ANOVA was conducted on the ratings and revealed a significant main effect due to HUD type ($F(4,68) = 21.13$, $p < .001$). Bonferroni T tests (post-hoc comparison) revealed that the two arc configurations were preferred over the tape and digital VVIs. Preference for the dial was also significantly greater than that for the digital VVI. Non-parametric tests conducted on the subjective ratings revealed similar results.

Table 2. Mean Ratings (Collapsed Across Task) for the Five HUD Configurations. The Scale was from "1" to "7", Where a Rating of "1" Indicated that the VVI was Completely Ineffective and a Rating of "7" Indicated Highly Effective.

	HUD				
	DIAL	TAPE	DIGIT	ARC + DIGIT	ARC
MEAN RATINGS	4.24	3.70	2.74	4.84	5.01

DISCUSSION

Subject Matter Experts (SMEs)

SMEs (and their availability) are a concern in any research program. A recent study has shown that SMEs should be used whenever possible (Vidulich, Ward & Schueren, in press). For evaluating HUD symbology, pilots with a substantial amount of HUD flying time would be preferred. The current study was conducted using some HUD-experienced pilots and some non-HUD-experienced pilots. The performance measures revealed that there were no differences due to prior HUD experience (and subjective ratings matched objective performance). At first glance this may seem to disagree with the results of the Vidulich study; however, a better understanding of the tasks shows that the findings are not contradictory.

In the current study, the pilots were asked to fly a series of basic instrument maneuvers that all pilots are taught during pilot training. The performance information necessary to complete the tasks was displayed on the HUD in an arrangement very similar to that of a typical head-down instrument panel. Therefore, all of the subjects were familiar with the physical arrangement of the basic performance information. The pilots' task of performing the maneuvers with the HUD was not substantially different from accomplishing the maneuvers on traditional instruments. In essence, when it comes to instrument flight, an SME is any pilot qualified to fly an aircraft in instrument conditions, provided the displayed information is consistent with the physical layout of the traditional head-down displays.

The expertise of HUD-experienced pilots is certainly preferred in subjective comparisons of proposed HUD symbology designs with current designs; and in evaluations of mission-specific symbology (i.e., weapon aiming symbols), HUD-experienced SMEs familiar with the particular mission scenario used in the display evaluation are absolutely essential. Thus, although there may be no performance differences due to prior HUD experience, it is appropriate for HUD-experienced pilots to be used in at least some part of the evaluation of proposed HUD symbology designs.

Whether vertical velocity is integrated with the forward velocity and displayed via the flight path marker or displayed separately, the format for presentation of the vertical velocity information is critical to the level of pilot workload. In a design that requires little cognitive interpretation and is located within the pilot's previously established crosscheck area, the pilot can more easily maintain an accurate and frequently updated mental representation of the vertical velocity of the aircraft. Safe landings cannot be made without some reference to vertical velocity information; and since the HUD is now used for take-offs, "go-arounds", and landings, the HUD symbology must be designed with the presentation of vertical velocity in mind.

In general, a good HUD symbology design must reduce unwanted visual clutter while minimizing the time required for the pilot to locate and interpret needed information. This is true of any well designed display, with one important caveat--the HUD is used to see through. Therefore, any HUD design must take into account the need to minimize occluding symbology.

In accordance with these design principles, we tried in the current study to develop alternative methods of displaying vertical velocity information when the flight path marker could not be used accurately (because of limited travel resulting from the narrow field of view). Based on the results of the current study we can make recommendations for future VVI designs.

VVI Design

The results showed that in terms of objective flight performance and subjective preference, either VVI configuration that includes the altimeter arc would be an effective design. The altimeter arc designs resulted in more accurate vertical velocity and altitude maintenance than did the other three configurations, and the pilots' subjective ratings correlated strongly with their objective performance. There may be several reasons for the advantages noted, which are unique to the altimeter arc design.

First, the altimeter arc reduced clutter on the display. This criterion should apply to all HUD symbology. The arc consisted of a thin line without digits to read. Numerical value approximations were made by noting the location of the tip of the indicator on an already existing scale (the dots of the altimeter), but using a different set of units for vertical velocity. When the aircraft was not climbing or descending, the indicator was not visible.

Although the subjects flew under simulated instrument meteorological conditions (i.e., no view of the outside world), and therefore their view through the HUD was not considered, it is obvious that a decrease in visual clutter would be beneficial during visual flight. Aside from the consideration of transparency, a decrease in clutter generally makes a display easier to use. Reduced clutter results in fewer distractions and less wasted scanning time.

Second, the altimeter arc was located in close proximity to the altimeter for easier integration of altitude and vertical velocity information. Integration was essential for decision making, and was in keeping with the compatibility of proximity hypothesis as discussed by Boles and Wickens (1983). The VVI and altimeter, the former presenting information that is the first derivative of that presented by the latter, could be incorporated into the same visual fixation during the crosscheck. Close physical proximity of related information should result in less mental workload.

Third, in addition to allowing for easier mental integration as described in the first two reasons, the arc configuration reduced the overall area that the pilot attended to during crosscheck. The physical layout with the digits, tape, and dial displays required the pilot to attend to the area below the altimeter, increasing the crosscheck area relative to that obligated by the arc configurations. The arc configurations maintain visual focus within the bounds of the traditional "T" crosscheck of the airspeed indicator, altimeter, heading, and attitude references. Therefore, an arrangement of symbology that includes the altimeter arc should reduce scan time. The reduced crosscheck area would seem to be particularly important in a high workload situation when the pilot has less time to scan the instruments. The addition of digits to the arc configuration did not affect significantly the pilot's flight performance. However, subjects' comments suggested that the addition of digits to the arc was preferred because the digits provided a redundant source of vertical velocity information.

Limitations

While the arc does reduce the physical area of the instrument crosscheck for airspeed, altitude, attitude, and vertical velocity, the bank RMSE data suggest that this reduction may result in the pilot not attending to precise bank information. Information such as bank, presented in peripheral locations on the HUD, may be more difficult to incorporate into the crosscheck. The reversed pattern of performance noted for the displays in terms of bank RMSE may attest to this potential limitation.

It is proposed that the reduction in bank accuracy with the arc is the result of a failure to attend to the bank scale while using the arc. Because the arc reduced the need to focus on the portion of the HUD below the altimeter, an area that brings the bank scale into the central visual field, it is likely that the bank scale was less frequently in the pilot's field of view when the arc was used. As a result, changes on the bank scale may not have been noticed as soon, or responded to as quickly, as they would have been with the non-arc designs. If this reduction in bank accuracy is determined to be a major concern, the problem might be alleviated by moving the bank scale to the top of the HUD where the pilot's attention would tend to be focused more of the time.

SUMMARY

Analog vertical velocity information allows pilots to perform instrument flight manuevers more accurately than does only digital vertical velocity information. Subjective evaluation of the displays supported the performance data. An inflight evaluation of the altimeter arc should be completed before definitive recommendations can be made regarding the utility of including the display on the standard HUD symbology set.

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