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Head-up displays : effects of scene-linked instrument symbology on pilot flight performance

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**HEAD-UP DISPLAYS: EFFECTS OF SCENE-LINKED
INSTRUMENT SYMBOLOGY ON PILOT FLIGHT PERFORMANCE**

A Thesis

Presented to

the Faculty of the Department of Psychology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

Stephen G. Sheldon

May 1997

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ABSTRACT

HEAD-UP DISPLAYS: EFFECTS OF SCENE-LINKED INSTRUMENT SYMBOLOGY ON PILOT FLIGHT PERFORMANCE

by Stephen G. Shelden

Traditional, non-conformal Head-Up Display (HUD) instrument symbology has been shown to enhance most aspects of pilot flight performance, relative to head-down panel instrumentation. This thesis tested possible explanations for a further improvement in path flight maintenance using conformal, scene-linked HUD instrument symbology. The better path flight maintenance is discussed with reference to domain fusion and task integration.

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**Head-Up Displays: Effects of Scene-Linked Instrument
Symbolology on Pilot Flight Performance**

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Running Head: HUDs: EFFECTS OF SCENE-LINKED SYMBOLOLOGY

Footnotes

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Abstract

Head-Up Display (HUD) symbology has been shown to enhance certain aspects of flight performance, relative to head-down panel instrumentation (Boucek, Pfaff, & Smith, 1983). Previous studies (Foyle, McCann, Sanford, & Schwirzke, 1993) have, however, identified a specific performance problem with HUD use. In a simulated flight task, a digital altitude gauge superimposed on the forward visual scene led to improved altitude maintenance, but also to a decrement in the ability to simultaneously follow a ground path. A subsequent experiment (Foyle, McCann, & Shelden, 1995) found that this trade-off could be negated, and path maintenance in fact improved, using a virtual, scene-linked altitude gauge distributed along the ground path. The purpose of this thesis was to distinguish among three possible explanations for the improved path maintenance observed with the scene-linked HUD symbology. The first explanation was that adding the virtual altitude gauges increased the path's perceptual definition, leading to the use of the additional path cues. The second explanation was that the *dynamic* nature of the virtual gauges engaged visual/spatial attention, thereby encouraging the processing of the additional path cues. The third explanation was that the active processing of the virtual gauges, for purposes of extracting *relevant* altitude information, encouraged the 'incidental' processing of the additional path cues. In concert with the proposed explanations, a scene-linked analog altitude gauge that was either static, dynamic and irrelevant, or dynamic and relevant to altitude maintenance was tested. Negation of the noted trade-off, with a significant improvement in path maintenance was found only when the information integration was dynamic and relevant, supporting an explanation that incorporates task relevance as a necessary feature for improved performance.

Head-Up Displays: Effects of Scene-Linked Instrument Symbology on Pilot Flight Performance

It was Lt. Colonel Paul Fitts who in 1946 observed that "It has been proposed... to throw the image of certain instruments onto the windscreen so that they might be viewed while looking out of the plane" (Weintraub & Ensing, 1992). Since the first operational head-up display (HUD) debuted on a Hawker-Siddeley Buccaneer in 1960, many advances have taken place in flight deck management tools.

Aircraft flight instrument symbology has traditionally been made available on a panel-mounted, head-down display located forward of the pilot and beneath the flight deck windshield. HUD technology permits projection of flight instrumentation data (see Figure 1) onto a combiner glass located between the pilot and the aircraft windshield. HUD technology, therefore, reduces the need to look away from the environment outside the aircraft by providing flight status information head-up. With the external environment able to be monitored in tandem with the aircraft's immediate flight status, a degree of concurrent processing accessibility is afforded.

HUD Technology

The typical HUD is comprised of three basic parts (see Figure 2). The pilot control unit (PCU) permits the operator to select specific symbology for display. The pilot display unit (PDU) comprises the combiner glass and optics used to project the HUD symbology. The PDU projection system is usually an overhead unit containing a cathode ray tube on which the flight symbology is generated, and a relay lens for projection of the image onto the combiner glass.

The electronics unit (EU) is the hardware housing the HUD software that both receives and interprets input from the aircraft's sensors, navigation systems, and control surfaces, and generates the image to be projected onto the combiner glass. The EU

Figure 1. Typical composite standard HUD configuration.

Figure 2. Basic Head-Up Display Components.

processes the incoming signals and forwards the relevant output to the PDU. Through a lens system in the PDU, the HUD symbology is projected, focused at infinity, and reflected off the combiner glass. Newer HUDs incorporating an embedded substrate 'sandwiched' in the glass of the combiner are capable of more enriched symbology. While these are frequently referred to as holographic HUDs, this does not mean that the pilot views any type of 3-dimensional image.

A fully-integrated HUD instrument display certified for Category IIIa operations (no decision height minimum, 700 ft runway visual range) will feature a full complement of aircraft situational data -- pitch, roll, horizon, heading, altitude, airspeed, flight path, and flight path acceleration. Additional features may include windshear alert and glideslope reference overlays.

Two basic types of presentation formats are in use with aircraft HUDs. Conformal presentation formats place the HUD symbology in such a way that it overlays (or represents) the outside environment. For example, the HUD horizon line overlays the actual horizon, or a virtual runway outline overlays a visually obscured actual, real-world runway. In non-conformal presentation formats, the HUD symbology is projected into a fixed space in the pilot's forward field of view, through the combiner glass. This symbology is aircraft referenced rather than world referenced.

HUD Advantages

The driving force behind the development of the aircraft HUD was to project flight status symbology forward of the pilot's view (head-up) and thereby negate the need, whenever possible, to be looking away from the out-the-window environment. This remains the principle advantage of HUDs. By superimposing critical flight status symbology head-up, the need to be eyes-down is reduced and flight performance is improved along a number of measures (Fisher, Haines, & Price, 1980; Lauber, Bray,

Harrison, Hemmingway & Scott, 1982; Weintraub, Haines, & Randle, 1984, 1985; Wickens, Martin-Emerson, & Larish, 1993). Irrespective of the exact phase of flight or weather/visibility conditions, a pilot whose focus is directed outward toward the flight environment is at a minimum scanning for potential threats or other unexpected events that might otherwise require immediate action, rather than being either head-down or in transition between head-down and head-up.

Three additional advantages of HUD use extend from the premise that one should maximize the time a pilot spends head-up scanning the outside flight environment. First, HUDs eliminate the visual reaccommodation necessarily associated with scanning between the head-down instrument panel and out-the-window environment. HUD symbology is presented to the pilot so as to be focused at infinity (in actuality at a distance of approximately 60 ft ahead of the pilot). This negation of the visual reaccommodation otherwise inherent in switching between near and far objects, in this case between the "near" domain HUD instrument symbology and "far" domain outside environment, is achieved by collimating the light source projecting the symbology onto the combiner glass.

Weintraub, Haines, and Randle (1984) presented participants with a Boeing 727 HUD instrument-landing approach where the optical distance of the HUD was varied -- either projected at optical infinity, at 1.3 diopters approximating the distance to the instrument panel, or at 4 diopters approximating the distance to reading one's wrist watch. Participants were to read HUD airspeed and altitude, and if both were within tolerance levels, to then decide whether the runway was clear for landing. The amount of refocus necessary to transition from the HUD to the runway had a strong main effect on the decision time, with the collimated HUD clearly superior to the HUD projected at instrument-panel distance.

Second, HUDs utilizing conformal symbology have the advantage of presenting far domain objects (in a virtual manner) that might otherwise be totally obscured in the real world. For example, a virtual HUD runway can be projected to overlay an obscured real-world runway. The result is that the pilot can process the head-up virtual image of the runway in tandem with the aircraft's flight status, while also being in a position to transition smoothly from the HUD runway to the real-world runway upon visual acquisition.

Third, HUD symbology is a superior method for representing flight status information when compared to the array of head-down dials and gauges found on the traditional instrument panel. Boucek, Pfaff, and Smith (1983) tested this by presenting experienced pilots with HUD symbology, controlled for location, (i.e., the same symbology was presented both head-up and head-down). HUD symbology presented head-up, and HUD symbology presented head-down were clearly superior to conventional head-down instrumentation.

In summary, HUD advantages to flight management extend chiefly from their ability to keep the pilots' head up and eyes outside, scanning the flight environment, while concurrently permitting access to the aircraft's flight status and control symbology. In addition to the negation of the overt physical head or eye movement inherently necessary with the use of head-down instrumentation, visual reaccommodation between HUD aircraft symbology and the outside environment is eliminated. From a technological perspective, HUDs offer two additional unique advantages over traditional head-down instrumentation. Conformal displays can offer accurate virtual environments for use under low-visibility operations or at night or over water, and the versatility of HUDs has afforded designers an opportunity to improve upon how flight symbology data is presented to the pilot.

HUD Performance Problems

Piloting an aircraft requires the integration of information from two main sources, the near domain instrument panel, and the far domain forward visual scene. With a HUD superimposing instrument symbology over the forward visual scene, it becomes possible to have access to both sources of information simultaneously. Accordingly, it would seem reasonable to believe that the negative effects associated with the physical separation of the near and far domains in a traditional flight deck are eliminated. Unfortunately, the reality has proven to be less straightforward, with researchers having identified a number of performance problems with the use of HUDs.

Incursion Recognition. Rather than facilitating joint awareness of near and far domains, HUD use has been shown to be detrimental in certain circumstances. Fischer, Haines, and Price (1980) presented pilots with runway incursions during simulated landing approaches under both HUD-On and HUD-Off test conditions. The runway incursion in each case became visible approximately 4 to 5 s after breakout (from cloud cover), with the pilot having 7 to 8 s to initiate a missed approach, depending on exact aircraft speed and position. Each of eight pilots was exposed to two such incursions, four encountered the incursion HUD-On first, four encountered the incursion HUD-Off first.

Those flight trials where the incursion was encountered with the HUD-Off averaged 1.75 s to initiation of a missed approach. Those flight trials where the incursion was encountered with the HUD-On averaged 4.13 s to initiation of a missed approach. More significantly, those pilots who *first* encountered the incursion with the HUD-On averaged 5.5 s to initiation of a missed approach, with two pilots failing to see the incursion in time to initiate a safe go-around.

Supporting this finding, Wickens and Long (1994) manipulated location of flight symbology either head-up or head-down, while controlling for optical distance and symbology format. On the last of 24 landing trials, an aircraft unexpectedly taxied onto the approach runway. Each pilot's latency in executing a missed approach pull-up was measured. Significantly quicker detection of the runway incursion occurred in the head down display location (mean of 6 s) as opposed to the head-up display location (mean of 8 s).

Similar problems with the use of HUD symbology in actual aviation situations have been reported by McNaughton (as quoted in Roscoe, 1987). Pilots reported losing situational awareness, experiencing "confusion when trying to maintain aircraft attitude by reference to the HUDs artificial horizon and 'pitch-ladder' symbology." In fact, between 1980 and 1985 the U.S. Air Force attributed 73 aircraft losses to controlled flight into terrain, or disorientation leading to loss of control, while flying with a collimated HUD in use (McNaughton, as quoted in Roscoe, 1987).

Flight Maintenance. HUD use has also been found to be associated with performance decrements in specific level-flight tasks. Brickner (1989) had participants fly a simulated slalom course. Participants were asked to avoid hitting poles, and missing intervals between poles, while maintaining an altitude of 50 ft. Three preset (constant) speeds were tested, 70, 90, and 110 knots. Additionally, in one condition only environmental cues were present; in another condition a HUD displaying real-time altitude was present.

Altitude error was smallest with the HUD present. Of note, however, was the fact that the HUD resulted in a significantly greater number of both pylon hits, and interval misses, over the no-HUD condition. Brickner concluded that the HUD may in actuality disrupt certain aspects of level flight performance, and interfere with a pilot's use of real

world environmental information.

Along similar lines, Foyle, McCann, Sanford, and Schwirzke (1993) tested for a HUD effect on the ability of pilots to follow a ground path. Subjects were asked to fly a meandering ground path of small pyramids, while maintaining an altitude of 100 ft. On half the trials, no HUD was present. In the HUD condition, a digital, real-time altitude gauge was present, superimposed in the center of the simulated environment. The dependent measures utilized were Root Mean Square Error (RMSE) deviations from both the target altitude of 100 ft. and the ground path.

In parallel with the results of Brickner (1989), the presence of the superimposed HUD decreased altitude error around the target height of 100 ft, but also resulted in increased path following error, as compared to the no-HUD condition. This trade-off, referred to as the altitude/path performance trade-off in subsequent discussion, was replicated by Foyle, McCann, and Shelden (1995), and is presented in Figure 3.

Possible Causes of HUD Performance Problems

The HUD performance problems discussed above suggest that the two sources of information available to the pilot (the near domain HUD and far domain real-world environment) are not integrated, or are not always integrated, to the maximum benefit of the operator. Possible causes for the apparent failure of pilots to integrate environmental information in tandem with the HUD's superimposed symbology are described in the following sections.

Accommodation Misdirection. The projection of HUD symbology onto the forward visual scene using collimated images has been integral to the assumption that with both domains at optical infinity, any visual reaccommodation is negated as a precursor to switching between the two sources of information. This assumption may not, however, be accurate. Instead, an intermediate resting focus, between optical infinity

Figure 3. Altitude/path performance trade-off. Foyle, McCann, and Shelden (1995).

and the combiner glass inside the aircraft has been suggested as the point to which accommodation tends to settle (Iavecchia, Iavecchia, & Roscoe, 1988). This may necessitate visual accommodation shifts between near and far domain objects.

Additionally, pilots may focus on the physical glass itself, or on scratches, dirt, or dust on the combiner glass. This would have the effect of bringing eye accommodation inward, distorting the far domain environment (McCann & Foyle, 1995). These factors cannot, however, explain the results of studies where HUD problems persist despite using graphical displays that present both the near and far domain information on a single plane (on a simulator computer monitor).

Brickner (1989), and Foyle, McCann, Sanford, and Schwirzke (1993) found continuous flight (altitude/path performance) trade-offs with superimposed symbology and environmental information presented on the same synthetic graphical display. Wickens and Long (1994) also found the delayed reporting of runway incursions with HUD symbology presented on the same simulator display as the out-the-window environmental information. With two of the principal HUD problems, failure to detect unexpected events, and failure to maintain aircraft situational awareness shown to persist in the absence of any possible visual reaccommodation being necessary on the part of the pilot, other factors must therefore be responsible for the performance decrements associated with HUD use.

Attentional Tunneling. The apparent difficulty of integrating the far domain, out-the-window environment, with the near domain, HUD symbology, may be a cognitive shortcoming rather than physiologically driven. The cognitive psychological phenomenon of "attentional tunneling" has been cited as descriptive of this failure to efficiently divide attentional resources (Foyle, McCann, Sanford, & Schwirzke, 1993). In the case of the altitude/path performance trade-off described earlier, "attention was focused on the object

providing altitude information (the superimposed altitude indicator) resulting in inefficient processing of the terrain path information" (Foyle et al., 1993, p. 1343).

Support for attentional tunneling is drawn from object-based models of visual attention, one of two broad theories proposed as explaining the processing limitations of the visual system (Duncan, 1984; Kahneman & Henik, 1981). Unlike space-based theories, which model visual attention as a type of spotlight that processes all input from within a narrow region of the visual field, object-based theories propose a two-stage model (Eriksen & Yeh, 1985). In the first stage, the visual field is parsed into perceptual groups; in this case, the superimposed HUD symbology is grouped separately from the far domain environment. In the second stage, one of the two perceptual groups captures attention (Duncan, 1984). In this case, the HUD symbology captures visual attention, as illustrated by the earlier studies cited where HUD presence coincided with slower responses to, or outright failure to recognize, critical events in the far domain.

With finite visual attentional resources focused on no more than one perceptual group of objects at any one time, the question then becomes one of attempting to delineate the perceptual attributes within the field of view that drive the visual system to group objects. In this case, what drives the visual system to apparently parse the HUD symbology from the out-the-window environment, with a resulting tunneling of attentional resources on the HUD symbology?

Two inter-related attributes have been suggested as potential causal factors responsible for attentional tunneling on the HUD symbology -- 1) display format differences, and 2) differential motion between the HUD and the out-the-window environment.

1) Display Format. HUD symbology is largely homogenous with respect to the presentation format employed (most often stroke lines), monochrome color utilized (a

saturated green), and unvarying brightness level. The superimposed HUD symbology is also, therefore, uniquely different from the out-the-window, pictorial, multi-colored, varying brightness of the real-world terrain.

These substantial display format differences may create an integration problem for the HUD user, regardless of their equivalent optical distance, and irrespective of whether the HUD is conformal or non-conformal (Foyle, Sanford, & McCann, 1991). The two domains may be perceived as separate objects, or groups of objects, consistent with an object-based theory of visual attention that proposes the grouping of like objects in the visual field, based on their similar properties. The result may be that switching between objects, or between groups of objects, is serial, with the display format of the HUD capturing visual attention at the expense of efficient switching between the two domains.

2) Differential Motion. In operational use, the superimposed symbology of the HUD is most often non-conformal, presented in a fixed location on the combiner glass in the forward field of view of the pilot. Exceptions to this may include some specific instrument symbology such as the artificial horizon, which overlays the actual horizon, or the symbolic virtual runway, which overlays the actual runway. In general, however, the vast majority of the superimposed symbology is presented in a fixed, predictable location.

As a consequence of this fixed presentation location of the HUD symbology on the combiner glass, it can be argued that the pilot views two very separate scenes. While the HUD remains fixed relative to the pilot's position, the out-the-window environment "behind" the HUD pitches, rolls, and yaws in accordance with the aircraft's movement through space.

McCann, Lynch, Foyle, and Johnston (1993) tested differential motion effects on attention by assessing performance of a choice reaction time task during a simulated

runway approach. Task-relevant information (one of two 3-letter cues and an associated target) was made available on a HUD, in the world (on the runway), or as part of both domains. Random vertical and lateral noise was introduced on half the trials to simulate pitch and yaw buffeting.

Performance on the reaction time task (indicating whether the cue and target matched to permit a safe landing, or necessitated a "go-around"), was faster when all relevant information was available either on the HUD or in the world, as compared to when information had to be acquired from both domains. Trials where the noise was *not* present, and differential motion was not a consideration (i.e., the HUD and world were motionless), attenuated any domain effect.

These results provide support for a differential motion explanation for attentional tunneling, with the authors observing that "the ability to restrict attention to the HUD (was) more robust than the ability to restrict attention to the world" (McCann, Lynch, Foyle, & Johnston, 1993, p. 1348). These observations could be of critical importance to the pilot who needs to transition from a HUD to the real world, such as when needing to acquire a runway during low-visibility landings.

Scene-Linked Symbolology

Foyle, McCann, Sanford, and Schwirzke (1993) tested for and replicated a continuous flight decrement with use of a HUD. A superimposed digital altitude gauge (HUD) improved altitude maintenance control, but led to poorer path following performance (earlier labeled as an altitude/path performance trade-off). If this trade-off is primarily an artifact of attentional tunneling on the HUD and is driven by differential motion (as indicated by McCann, Lynch, Foyle, & Johnson, 1993), then one possible remedy might be to remove the differential motion cues. To that end, one potential HUD design alternative might be to substitute virtual instrument symbology, that appears as

part of the world, for the conventional fixed HUD superimposed symbology (Foyle, Ahumada, Larimer, & Sweet, 1992).

Foyle, McCann, and Shelden (1995) tested whether such virtual scene-linked symbology might attenuate attentional tunneling. Both a digital and analog (clock-like) HUD altitude gauge, interleaved into the flight path, and moving as virtual objects in the out-the-window scene (see Figure 4) were tested. It was hypothesized that a scene-linked HUD, removing differential motion cues from the visual environment, would evidence reduced attentional tunneling by an absence of the altitude/path performance trade-off.

This proved to be true for both the scene-linked digital and analog altitude HUD gauge incorporated into the world. Of special significance, however, was the finding that both altitude *and* path flight maintenance performance improved with the use of scene linked symbology. In fact, compared to baseline (HUD absent) performance, path flight maintenance showed an additional "bonus" improvement with a scene-linked altitude HUD present (see Figure 3).

Of course, the virtual gauges described above doubled as additional indicators as to the path to be followed, presenting a potential confound -- was the path flight maintenance improvement a consequence of the scene-linked symbology or was it due to the enhancement of the path? Regardless of the cause, the finding of better path flight maintenance is nonetheless potentially significant. Not only did scene-linking the HUD symbology have the desirable effect of apparently negating attentional tunneling, but an added "bonus" improvement in path flight maintenance emerged. Addressing the path confound, while attempting to replicate and discern the nature of the unexpected improvement in performance, is the basis for this study.

Figure 4. Schematic representation of flight simulation with scene-linked HUD symbology.

Present Study

Given the results of Foyle, McCann, and Shelden (1995) evidencing both the efficacy of scene-linked HUD symbology in negating attentional tunneling, and an unexpected "bonus" improvement in path flight maintenance, the present study had three broad goals. The first and second were to replicate the negation of the altitude/path performance trade-off found in Foyle, McCann, and Shelden (1995), and in turn evidence the "bonus" improvement in path flight maintenance. The third was to distinguish among several possible explanations for the "bonus" improvement in path flight maintenance observed with the use of scene-linked HUD symbology. To that end, three hypotheses were proposed, and paired with appropriate scene-linked HUD symbology to test whether increased path definition, gauge dynamics, or gauge relevance was the cause of improved path flight maintenance.

Hypothesis One. From the perspective of a change in the perceptual configuration of the flight environment, the insertion of the virtual altitude gauges in the earlier study had the effect of increasing the number of items delineating the path (Foyle, McCann, & Shelden, 1995). This was the basis for a confound in that study, and may have solely been responsible for the "bonus" path flight maintenance improvement observed. The *increased definition of the path* may have allowed participants to better determine the magnitude of their deviations from the path, and make appropriate corrections.

To test this possible explanation, scene-linked gauges that were static and irrelevant to altitude maintenance were incorporated into the path. With the exception that the gauges' clock-like hands did not move, they were otherwise identical to the other HUD present gauges tested.

This hypothesis, that increased path definition drives better path flight maintenance through the processing of the additional path cues, would be supported by a

result where the addition of the Static/Irrelevant gauges to the flight environment improves path flight maintenance beyond that obtained in the baseline (HUD absent) condition, concurrent with a similar improvement in both the Dynamic/Irrelevant and Dynamic/Relevant HUD conditions.

Hypothesis Two. Alternatively, there may have been a change in the nature of the participant's attentional processing of the flight environment. The virtual altitude gauges originally tested may have increased participants' visual/spatial attention to the path, over that of the baseline condition (HUD absent), due to their *dynamic* nature.

To test this possibility, scene-linked gauges that were dynamic but irrelevant to altitude maintenance were incorporated into the path. These gauges were otherwise identical to the other HUD present gauges tested, except in this case they imparted compass heading information, and were dynamic in that the clock-like hand of the gauge moved accordingly. Given the constantly curving path, compass heading information was unlikely to be useful in following the path.

This hypothesis, that the dynamic nature of the scene-linked gauges engages visual/spatial attention, thereby encouraging the processing of the additional path cues, would be supported by a result where the addition of the Dynamic/Irrelevant gauges to the flight environment produces an improvement in path flight maintenance beyond that obtained in the baseline (HUD absent) condition, concurrent with a similar improvement in the Dynamic/Relevant HUD condition.

Hypothesis Three. The third possible explanation for the improved path maintenance was that active processing of the scene-linked gauges, for purposes of extracting *relevant* altitude information, encouraged the incidental processing of the additional path cues. This HUD present condition was identical to the scene-linked analog gauge tested in Foyle, McCann, and Sheldon (1995).

This hypothesis would be supported by a result where the addition of the Dynamic/Relevant gauges to the flight environment improves path flight maintenance beyond that obtained in the baseline (HUD absent) condition, concurrent with a failure on the part of either the Static/Irrelevant or Dynamic/Irrelevant HUD gauges to evidence any improvement over their paired HUD absent conditions.

Method

Participants

For this experiment, 30 adult male participants were recruited and paid by the Bionetics Corporation. Each participant was required to be right-handed, have normal or corrected-to-normal vision, and was not to have previously participated in a HUD-type study. No previous flight experience was required. All participants were treated in accordance with the ethics and guidelines set up by the NASA Ames Research Center and the San Jose State University, Institutional Review Board - Human Subjects.

Apparatus

A Silicon Graphics Indigo2 EXtreme computer was used to present the flight simulation and collect the data. The flight simulations were viewed on a 1280 x 1024 high-resolution 19-inch (measured diagonally) color monitor from a distance of 65 cm. The monitor viewing area formed a rectangle 38 cm wide by 28.5 cm high. The horizontal and vertical viewing angles were 32.6 and 24.8 degrees, respectively. Each flight simulation trial was controlled with a spring-centered joystick built into the right arm of the participant's chair.

Each flight trial was a generic aircraft simulation flown through a virtual environment. The aircraft was stabilized, with reference to the horizon, and did not pitch up or down when climbing or descending. This restriction, though unrealistic, ensured that heading information in the virtual environment was constantly available. Roll was

accurately depicted.

The virtual environment contained a blue sky, green ground, and a white grid overlaid on the ground surface (see Figure 4). Participants followed one of eight different paths on each trial. Each path was comprised of a series of 37 brown, pyramid-shaped objects. The pyramids were 24 ft square at the base, 6 ft high, and placed 330 ft apart on the ground. Each successive pyramid was angled away, either right or left, from 15 to 30 degrees, in order to form a meandering course. Forward speed through each trial was a constant 160 knots, with each trial taking approximately 55 s to complete.

The analog altitude gauge, present on half the participant trials (HUD-On), was inserted mid-point between every second set of pyramids for a total of 18 such objects. Each gauge had a yellow clock-like face with 8 black tick marks indicating 25 ft intervals and a single black indicator bar which extended from the center of the gauge. In the Static/Irrelevant HUD condition the black indicator bar remained fixed in the 9 o'clock position. In the Dynamic/Irrelevant HUD condition the black indicator bar depicted real-time compass heading, with 0 degrees at the 12 o'clock position.

In the Dynamic/Relevant HUD condition the black indicator bar depicted real-time altitude. When in the 9 o'clock position, altitude was 100 ft, with 6 o'clock and 12 o'clock respectively depicting 50 ft and 150 ft (after Weinstein, Ercoline, Evans, & Britton, 1992). Scaled to the virtual flight environment, each gauge was 15 ft high (see Figure 4).

Random vertical (altitude) and horizontal (heading) turbulence was introduced on each trial. The turbulence (a sum of sines) was used to both replicate earlier experimental simulator conditions at low flight levels, and to create a more realistic, moderate to high-workload environment. The graphics and data collection were presented and updated at a rate of 12 Hz.

Design

A mixed, repeated measures design was utilized. The within-participant factor was HUD presence, either on or off, and the between-participant factor was HUD type, either Static/Irrelevant, Dynamic/Irrelevant, or Dynamic/Relevant.

Each participant "flew" a total of 84 trials separated into seven blocks of 12 trials. Each block consisted of 6 trials with the HUD off, and 6 with the HUD on. The order of presentation within each block was alternated. Based upon the asymptotic levels of performance found in earlier similar studies (Foyle, McCann, & Shelden, 1995; Foyle, McCann, Sanford, & Schwirzke, 1993), blocks 1 through 4 were designated practice, with blocks 5 through 7 serving as experimental trials. One of eight paths was randomly assigned to each trial, with the provision that each path be used a minimum of 10 times per participant.

The dependent measures were root mean squared error (RMSE) altitude and RMSE heading. Altitude errors were determined by measuring vertical aircraft distance (in feet) from the assigned altitude as participants flew each simulation. Heading errors were determined by measuring the horizontal aircraft distance (in feet) from the closest straight-line segment in the path as each flight simulation trial was flown. The respective RMSE data was calculated using the following formula, where e represents error, and n represents the number of data points:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n e_i^2}{n}} .$$

Procedure

Each participant took one session of approximately 2.5 hrs to complete the experiment. All participants were instructed to simultaneously maintain an altitude of 100 ft while following the ground path (of small brown pyramids) as closely as possible. Additionally, each was asked to distribute his effort across both tasks as evenly as possible, with the need for accuracy and consistency stressed. The experimenter demonstrated the flight task to each participant prior to their beginning the experiment.

Each trial began with a period of straight flight toward the first path marker, at exactly 100 ft, without any turbulence. This was designed to be a time during which the participants were to "calibrate" themselves to the visual surroundings and the appropriate altitude cues. Turbulence was introduced, and data collection began, only after the first ground path pyramid was reached.

Participants in the Static/Irrelevant HUD condition were advised that the gauges imparted no specific additional information other than the fact that they were located directly on the path to be followed. Participants in the Dynamic/Irrelevant HUD condition were advised that the gauges indicated compass heading, but that for the purposes of the experiment, this information was irrelevant to the task, save for the fact that the gauges were located directly on the path to be followed. Participants in the Dynamic/Relevant HUD condition were advised that the gauge was to be used as an indicator of altitude. Each participant in the Dynamic/Relevant HUD condition was asked to repeat back the gauge divisions (6 o'clock = 50 ft, 9 o'clock = 100 ft, 12 o'clock = 150 ft) prior to their beginning the experiment, to ensure they clearly understood the calibration of the gauge.

Participants were given a 10-min rest period at the conclusion of block 2, and again at the end of block 4. None of the participants was made aware of any delineation

between practice and experimental trials. Each participant was, however, fully debriefed upon completion of all flight trials.

Results

The dependent variable analyzed in this study was RMSE for both altitude and heading performance data. Descriptive statistics including mean RMSE, standard deviation, and standard error are provided in Table 1. Of note are the differences in the Dynamic/Relevant, HUD-Off versus HUD-On RMSE means for both the altitude and heading error data. The Dynamic/Relevant HUD-On mean of 22.42 for altitude is 31.25% lower than the HUD-Off mean of 32.61 (see Figure 5). The Dynamic/Relevant HUD-On mean of 50.19 for heading is 11.39% lower than the HUD-Off mean of 56.64 (see Figure 6).

A 3 x 2 (HUD type x HUD presence) mixed analysis of variance (ANOVA) was conducted on the altitude and heading data respectively. The results are presented in Table 2. To ensure only asymptotic performance was analyzed, successive ANOVAs were calculated that confirmed the decision to use data from blocks 5 through 7 only. No effort was made to control for family-wise error given the limited number of planned simple comparisons to be conducted and analyzed.

Altitude Performance

HUD type had no main effect on altitude performance. HUD presence, however, had a reliable main effect on altitude performance, $F(1,27)=12.21$, $p < .01$, and HUD type was found to interact with HUD presence, $F(2,27)=27.47$, $p < .01$.

Planned simple comparisons were undertaken on each of the three HUD types, across HUD presence, in order to expose where HUD type interacted with HUD presence. Neither the Static/Irrelevant or Dynamic/Irrelevant HUD types produced any statistically reliable difference in altitude performance when compared to their respective

Table 1

Mean RMSE, standard deviation, and standard error.

HUD Type	HUD Presence	Altitude			Heading		
		<u>M</u>	<u>SD</u>	<u>SE</u>	<u>M</u>	<u>SD</u>	<u>SE</u>
Static/ Irrelevant	Off	28.05	9.76	0.73	51.27	19.83	1.48
	On	30.38	10.65	0.79	49.82	16.16	1.20
Dynamic/ Irrelevant	Off	26.30	6.83	0.51	45.77	13.56	1.01
	On	26.45	7.79	0.58	44.10	13.44	1.00
Dynamic/ Relevant	Off	32.61	12.52	0.93	56.64	18.63	1.39
	On	22.42	8.61	0.64	50.19	18.42	1.37

Figure 5. Effect of HUD symbology on altitude performance.

Figure 6. Effect of HUD symbology on heading performance.

Table 2.

Analysis of Variance for HUD Type by HUD Presence

Source	df	F	
		Altitude	Heading
HUD Type	2	0.66	1.39
Error	27	(1,116.81)	(4,803.60)
HUD Presence	1	12.21**	15.78**
Type x Presence	2	27.47**	4.12*
Error	27	(146.45)	(174.13)

Note. Values enclosed in parentheses represent mean square errors. * $p < .05$. ** $p < .01$.

HUD Off control conditions, $F < 1$ for both.

The planned simple comparison of the Dynamic/Relevant HUD-On condition against its paired HUD-Off control condition indicated that RMSE altitude was lower (performance was improved) in the HUD-On condition as compared to the HUD-Off condition, $F(1,9)=50.29$, $p < .001$.

Heading Performance

HUD type had no main effect on heading performance. HUD presence, however, had a reliable main effect on heading performance, $F(1,27)=15.78$, $p < .01$, and HUD type was found to interact with HUD presence, $F(2,27)=4.12$, $p < .05$.

Planned simple comparisons were undertaken on each of the three HUD types, across HUD presence, in order to expose where HUD type interacted with HUD presence. Neither the Static/Irrelevant or Dynamic/Irrelevant HUD types produced any statistically reliable difference in heading performance when compared to their respective HUD-Off control conditions, $F < 1$ for both.

The planned simple comparison of the Dynamic/Relevant HUD-On condition against its paired HUD-Off control condition indicated that RMSE heading was lower (performance was improved) in the HUD-On condition as compared to the HUD-Off condition, $F(1,9)=44.44$, $p < .001$.

Subject Differences

The mean RMSE results illustrated in Figures 5 and 6 for the Dynamic/Relevant HUD condition and its paired HUD-Off condition appear inflated over the alternate HUD conditions tested. This may be an artifact of participant differences within the separate groups tested, stemming from the need to use a between-participants design. Such a design was necessary to avoid any potential confusion between HUD-On conditions in which the gauges were informative (relevant to altitude maintenance), and those in which

they were not informative (when the gauges were irrelevant to altitude maintenance).

In addition, a single participant from the Dynamic/Relevant HUD condition had mean RMSE scores on both altitude and heading that bordered on two standard deviations beyond the norm. Elimination of this participant's results from the data would otherwise give the mean RMSE scores illustrated in Figures 5 and 6 a more balanced appearance across conditions, without loss of the lower relative altitude and heading scores evidenced within the Dynamic/ Relevant HUD condition.

Discussion

The study had three principle goals -- 1) to replicate negation of the altitude/path performance trade-off, 2) to evidence the "bonus" path flight maintenance improvement found in Foyle, McCann, and Shelden (1995) , and 3) to attempt to distinguish between a number of possible explanations for the "bonus" improvement in path flight maintenance, observed with the use of scene-linked HUD symbology.

Evaluation of Goals and Hypotheses

Results from the Dynamic/Relevant HUD condition clearly replicate the earlier findings of Foyle, McCann, and Shelden (1995). An altitude/path performance trade-off was not evident with the use of this scene-linked HUD symbology, thereby satisfying the first stated goal. In fact, this presentation format again had the effect of resulting in not only a significant improvement in altitude maintenance, but also a "bonus" improvement in path flight maintenance, over baseline (no HUD), thereby satisfying goal two.

In an attempt to distinguish among three possible explanations for the 'bonus' improvement in path flight maintenance found with the use of scene-linked HUD symbology (goal three), a number of different HUD conditions were tested.

Hypothesis One. In the first HUD condition, the scene-linked gauges along the path were static, and thereby irrelevant to the task of maintaining altitude. It was

proposed that increased definition of the path may have been responsible for the path flight maintenance improvement observed, with participants better able to determine their course deviations and make appropriate corrections.

The results did not support this hypothesis. Additional path definition in the form of interleaved Static/Irrelevant HUD gauges did not have the effect of improving path flight maintenance. Additionally, the Static/Irrelevant HUD gauges had no apparent positive effect on altitude maintenance.

Hypothesis Two. In the second HUD condition tested, the scene-linked HUD gauges along the path were dynamic, but irrelevant to the task of altitude maintenance. It was proposed that the dynamic nature of these virtual gauges could engage visual/spatial attention sufficiently to encourage the incidental processing of the additional path cues, with the result being improved path flight maintenance.

The results did not support this hypothesis. Making the virtual scene-linked gauges dynamic did not have the effect of improving path flight maintenance. Again, the scene-linked gauges had no significant effect on altitude maintenance as compared to the baseline (no HUD) condition.

Hypothesis Three. In the third HUD condition tested, the scene-linked gauges along the path were dynamic and relevant to the task of maintaining altitude. It was proposed that the extraction of information from the gauges, relevant to the task of maintaining altitude would allow for, or encourage, the incidental processing of these additional path cues, with the result being an improvement in path flight maintenance.

The results supported this hypothesis. Making the scene-linked HUD gauges both dynamic and relevant to the task of altitude maintenance had the effect of improving flight path maintenance over baseline, while simultaneously producing the expected positive effects on altitude maintenance.

In summary, therefore, neither increased path definition or gauge dynamics alone appears sufficient to generate better path flight maintenance in this continuous flight paradigm. Making the scene-linked HUD gauges task-relevant to altitude maintenance, however, has the effect of not only greatly improving altitude maintenance, but also results in significantly better path flight maintenance.

Object/Task Fusion

In 1989, Brickner reported an altitude/path performance trade-off with the use of non-conformal HUD symbology. Presence of a fixed HUD altitude gauge could be shown to have the effect of improving altitude maintenance, but only with an associated decrement in path flight maintenance. In an attempt to discern the cause of this performance trade-off, Foyle, McCann, and Shelden (1995) tested virtual, scene-linked HUD altitude gauges. The suggestion was made that differential motion between the two scenes (the near-domain HUD and far-domain world environment) may have been responsible for an object-based attentional parsing of the two domains, with a consequent tunneling of attention on the fixed HUD symbology.

Their finding was two-fold. First, the altitude/path performance trade-off was negated with the use of the virtual scene-linked HUD gauges. To the extent that differential motion was responsible for the altitude/path performance trade-off, their hypothesis was supported. Second, an unexpected improvement in path flight maintenance was reported, over baseline, with the use of such scene-linked HUD symbology.

This present study evolved from a desire to more clearly understand that second finding, and to the extent that it better defined the necessary components for "generating" such a "bonus" path flight maintenance improvement, was a success. But questions remain. If negation of the altitude/path performance trade-off can be largely ascribed to

the removal of differential motion between the near and far domains, then what factor(s) beyond this might promote the "bonus" path flight maintenance improvement observed with the scene-linked symbology?

Wickens and Long (1994) suggest that an object-based theory of attention should predict "an added benefit" for presentation of conformal (versus non-conformal) HUD flight symbology. It was proposed that this would extend from the "fusion" of the symbology with the far domain (out-the-window environment) to form a single perceptual object, with object-based parallel processing benefits possible. Akin to the results reported from this study, the research of Wickens and Long (1994) found that "conformal symbology clearly enjoys the double benefit of reduced scanning and object fusion" (p. 9). This compares to presentation of non-conformal HUD symbology, where any reduced scanning benefits derived from (a head-up) presentation location are possibly offset by a clutter effect resulting from the overlapping of visual scenes.

Such conformal "fusion" of attention may also have positive effects beyond its visual/spatial allocation of cognitive resources to multiple flight management tasks. Duncan (1984) provided evidence that visual attention is allocated to objects, and not on the basis of spatial proximity alone. He described perceptual analysis of the visual world as taking place in two sequential stages. The *preattentive* stage first segments the visual field into separate objects on the basis of various Gestalt properties. The second stage, *focal attention*, then selects and analyzes a particular object in more detail. Importantly, Duncan found that two judgments that concern the same object could be made simultaneously without loss of accuracy.

It is this specific finding that is perhaps most relevant to the "bonus" path flight maintenance improvement under examination. If integration of the altitude and path information sources into a (true) single integrated object display has in fact been achieved

with the scene-linked symbology format used here, it is possible that the gauge is preattentively segregated from the visual field, with focal attention then capable of multiple task judgments, simultaneously, from the one object (gauge). With both altitude and path deviations being more efficiently processed for correction, this may translate into the noted "bonus" performance improvement observed.

In summary, what may account for the "bonus" path flight maintenance improvement observed is a combination of two factors. Object and task fusion resulting from the use of virtual, scene-linked symbology may lead to relatively more efficient visual scanning of relevant information sources from within the flight environment. Consequent to any possible parallel processing benefit of fused, multiple information sources may be the generation of simultaneous judgments and output of integrated responses that translate into the improved flight control observed.

Future Research

The proposal that object integration underlies the "bonus" path flight maintenance improvement begs further examination. If, as suggested, the scene-linked gauges promote the incidental processing of the additional path cues, as a consequence of extracting altitude information, then offsetting the gauges from the baseline path indicators (the small brown pyramids) may be informative. If the resulting altitude and path error mirrored that reported here, this could be taken as support for participant processing of only the scene-linked gauges for path deviation, and *not* for any type of peripheral processing of the path (the pyramids) as a whole. It may be that a form of attentional tunneling only on the "fused" objects, the gauges, is occurring. The effect of this type of conformal HUD presentation on the reporting of a peripheral event could also be examined.

Alternatively, if object integration in the form of the scene-linked gauges permits or even promotes multiple or integrated response selection, this may be evidenced by examining the joystick movements made by participants. It may be that in the original Brickner (1989) and Foyle, McCann, Sanford and Schwirzke (1993) studies, where the altitude/path performance trade-off with attentional tunneling on the non-conformal HUD was observed, participant joystick movements were concentrated more heavily along the north--south axis controlling altitude, possibly illustrating a serial-type processing of a single domain (the altitude HUD).

In the scene-linked HUD symbology format, it may be the case that integrated, simultaneous response selection translates into "diagonal" (NNE, NNW, SSE, etc.) joystick inputs by participants. In each case, stick input could be measured and compared to the relevant HUD type employed, allowing for inferences to be drawn regarding the strategy employed in managing altitude and path deviation.

In summary, future research should be directed toward determining whether the scene-linked gauges studied here create a flight environment where visual/spatial attention is better focused, response selection is simultaneous, or some combination of events prevails to drive the improved performance. In addition, while the flight simulation tested here mirrors a true flight environment in many respects, there can be no dismissing the need for further testing in simulators capable of higher fidelity, and in real flight situations.

Conclusion

Advances in flight deck display technology and instrumentation formats may permit design and engineering changes that invalidate past performance criteria and allow for flight management improvements with increased safety. Any changes must, however, be warily examined. Just as the advent of HUD technology was a welcome

improvement, it has not come without certain operational performance costs.

Understanding the basis for improved performance with the use of virtual or conformal symbology is critical to both better design in the future and to exposing potential drawbacks to this new display technology as it becomes increasingly available.

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Appendix

HSIRB Approval

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TO: Stephen G. Shelden
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Moffett Field, CA 94035

FROM: Serena W. Stanford *Serena W. Stanford*
AAVP, Graduate Studies & Research

DATE: November 28, 1995

The Human Subjects-Institutional Review Board has approved your request to use human subjects in the study entitled:

"HEAD-UP DISPLAYS: Effects of Scene-Linked Instrument
Symbology on Pilot Flight Performance"

This approval is contingent upon the subjects participating in your research project being appropriately protected from risk. This includes the protection of the anonymity of the subjects' identity when they participate in your research project, and with regard to any and all data that may be collected from the subjects. The Board's approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Serena Stanford, Ph.D., immediately. Injury includes but is not limited to bodily harm, psychological trauma and release of potentially damaging personal information.

Please also be advised that each subject needs to be fully informed and aware that their participation in your research project is voluntary, and that he or she may withdraw from the project at any time. Further, a subject's participation, refusal to participate, or withdrawal will not affect any services the subject is receiving or will receive at the institution in which the research is being conducted.

If you have any questions, please contact me at (408) 924-2480.