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Cognitive tunneling: mitigating effects of HUD symbology locaton

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COGNITIVE TUNNELING:

MITIGATING EFFECTS OF HUD SYMBOLOGY LOCATION

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ABSTRACT

COGNITIVE TUNNELING:
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Cognitive tunneling occurs when the pilot's attention is captured on non-conformal, superimposed head-up display (HUD) symbology, while neglecting to scan the out-the-window scene, as a result of locating the HUD symbology near (in visual angle) the outside scene information (Foyle, McCann, Sanford & Schwirzke, 1993). Previous studies have shown that cognitive tunneling could be eliminated by placing the HUD symbology at least 8 deg from the out-the-window path being tracked. Limitations of previous research have included experimental designs that tested participants in multiple HUD information locations without fostering an efficient eyescan strategy for any one HUD location. This thesis dedicates a participant to a single HUD location with blocked presentation. The results indicate that cognitive tunneling is not only eliminated by placing HUD symbology greater than 8 deg from the path, but path tracking performance improves with symbology placed in an upper location on the HUD.

Acknowledgements

For my gracious teachers, Kevin Jordan, Dave Foyle, and Tony Andre, Mark Twain (1906) wrote:

"It is noble to teach oneself, but still nobler to teach others."

My sincere appreciation for your guidance on this course of study.

For Becky Hooey, my gratitude for your patience with questions and your logic with answers.

For my mother and brothers, whose support throughout the years reminds me what family means.

For my night rainbow, Anthony Loscalzo, for teaching me when you lose the key, to throw away the house.

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Finally, this thesis is dedicated to a woman who rode a Greyhound bus 1700 miles to visit her granddaughter because she was afraid to fly. Her courage throughout life has given me wings.

To my grandmother, Alta Mae Harkins.

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Abstract

Cognitive tunneling occurs when the pilot's attention becomes locked on non-conformal, superimposed head-up display (HUD) symbology, while neglecting to scan the out-the-window scene, as a result of locating the HUD symbology near (in visual angle) the outside scene information (Foyle, McCann, Sanford & Schwirzke, 1993). Previous studies have shown that cognitive tunneling could be eliminated by placing the HUD symbology at least 8 deg from the out-the-window path being tracked. Limitations of previous research have included experimental designs that tested participants in multiple HUD information locations without fostering an efficient eyescan strategy for any one HUD location. The present study dedicates a participant to a single HUD location with blocked presentation. The results indicate that cognitive tunneling is not only eliminated by placing HUD symbology greater than 8 deg from the path, but path tracking performance improves with symbology placed in an upper location on the HUD.

Introduction

The benefits of aircraft head-up displays (HUDs) have been investigated and well documented for positive contribution to altitude control in aviation (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997). Previous empirical studies have revealed increased pilot control in altitude maintenance when an altitude display was present versus absent (Sanford, Foyle, McCann, & Jordan, 1993; Levy, Foyle, & McCann, 1998). Furthermore, studies of simulated flight over a designated path have shown that the placement of the altitude display within the HUD can positively or negatively influence optimal path performance (Foyle, McCann, Sanford, & Schwirzke, 1993; Sanford, Foyle, McCann, & Jordan, 1993). In strategic flight maneuvers, where both path navigation and altitude maintenance are required, optimal placement of displayed altitude information is imperative. Results from dual task experiments encompassing path navigation and target altitude maintenance support contrasting models of attention. These models suggest either efficient or inefficient joint processing of visual information on the HUD and in the world, depending on the type and location of HUD symbology. Possible explanation for performance benefits and decrements that occur with different types of HUD symbology may be explained in the application of attentional models.

Models of Attention

Space-based model. Space-based models of attention assume that concurrent processing of the visual domain occurs when items are proximally located. This model utilizes a "spotlight metaphor" of visual attention (Palmer, 1999, p. 545-546). The spotlight metaphor describes the viewer as selecting a region of space to illuminate, allowing all items within the "spotlight" to be processed simultaneously. According to this model, all information illuminated by the visual spotlight will be processed regardless of belonging to the same object or two separate objects. Wickens (1997) suggested that application of space-based models of attention could offer an explanation for degraded performance when visual scanning between separated sources is necessary. Space-based theories of attention suggest serial processing of the visual world occurs as the attentional spotlight shifts from focal point to focal point (Wickens, 1997). In visual environments with closely spaced information sources, the impact of clutter can impair the ability to focus on any single information source, regardless of joint illumination by the attentional spotlight. Subsequently, space-based theories of attention do not explain failures to concurrently process proximally located information that results in serial processing of information sources due to clutter. On the other hand, space-based attentional focus may explain impeded visual search due to the cost of eye movements required to process separated sources. In the context of HUD design, symbology can only be processed when focally attended with a cost of saccade for separated information sources and a cost of clutter for proximal information sources.

Object-based model. Object-based models of attention assume that concurrent processing of the visual domain occurs when items are perceived as part of the same object (Palmer, 1999, p. 547-548). Thus, preattentive processing and the perceptual grouping of objects become germane to the application of the model. Perception of a whole can be influenced by salient visual cues (i.e., relative motion, proximity, continuity, similarity) that cause the visual system to group and parse the world accordingly (Treisman, 1986). Jarmasz, Herdman, and Johannsdottir (2001) investigated HUD elements perceptually grouped by common fate, terming associated elements an "object layer." Their findings supported an object-based model of attention with results that revealed more efficient processing of information for sources located within the same object layer than sources between layers.

Discontinuities between visual cues (i.e., differential motion) within the area of attentional focus can become the basis for segregating sensory data into separate objects, including figure and ground. Once perceptually separated, attentional focus shifts between objects in a serial manner (Lasswell & Wickens, 1995). According to a space-based model of attention, distance between objects is not as relevant for concurrent processing as the perception of a unitary object. In the context of HUD design, differential motion between symbology (near domain) and terrain (far domain) may cause a perceptual segregation, thus preventing concurrent processing (Foyle, McCann, & Shelden, 1995).

Distribution of Attention and Types of Symbology

Fischer (1979) conducted early research on the pilot's ability to attend to near (HUD symbology) and far domain (outside world) by presenting slides to pilots composed of HUD scenes, external world scenes, and world scenes overlaid with HUD information (superimposed scene). Pilots were asked to respond to questions regarding occurrences on the HUD only, in the world only, or regarding HUD and world events. Findings showed that pilots' response accuracy when selectively attending to nonconformal HUD symbology (altitude symbol) was decreased, as compared with response accuracy when attending to conformal symbology (velocity vector). Suggestions from these findings included the possibility that the integration of information sources (HUD symbology and external world) was facilitated by conformal symbology that fostered the perceptual fusion of information sources. Thus, a division of attention between information sources was supported when conformal symbology was presented. Conversely, nonconformal symbology facilitated perceptual segregation; thereby failing to support divided attention.

Martin-Emerson and Wickens (1997) noted that characteristics of the symbology affect the extent to which attention can be distributed. Research has suggested that HUD symbology presented as a virtual analog of objects in the world or conformal with items in the far domain supports a division of attention, yielding performance advantages when compared with superimposed symbology (Fadden, Ververs, & Wickens, 2001; Wickens & Long, 1995). In an extension of previous research, "scene-linked symbology", was designed to support divided attention (Shelden, Foyle, & McCann, 1997), by cognitively linking near and far domains with aircraft information depicted as part of the external world. As such, the symbology conformed to the external world with an appearance that it belonged in the environment. In accordance with object-based theories of attention, scene-linked symbology attempted to foster parallel processing by perceptually fusing HUD information with external world events (Levy, Foyle, & McCann, 1998).

Research investigating the practical application of attentional models on HUD design found partial empirical support for the object-based theory of attention and no support for the space-based model (Sanford, Foyle, McCann, & Jordan, 1993). More specifically, results suggested that fixed (superimposed) HUD symbology and terrain were parsed into separate perceptual objects due to *differential motion* and yielded improved cognitive processing due to *visual scan*. By contrast and paradoxically, performance decrements occurred when superimposed HUD symbology (near domain) was located proximally to items in the world (far domain), resulting in reduced visual scan. Similarly, delayed attentional switching from near domain to far domain and the detection of a truly unexpected event (potential runway incursion), has been cited as a HUD disadvantage when utilizing nonconformal symbology (Wickens, Martin-Emerson, & Larish, 1993).

Superimposed Symbology

Superimposed, nonconformal symbology on aircraft HUDs was designed to allow pilots more time directly viewing the external world, while maintaining awareness of aircraft status (Weintraub, Haines, & Randle, 1985). Symbology detailing aircraft status information (i.e., altitude readout) is collimated at optical infinity on the HUD and aligned with the pilot's forward field-of-view (Foyle, McCann, Sanford, & Schwirzke, 1993). Non-conformal symbology is presented in a fixed HUD location superimposed on the out-the-world view, such that digits on the HUD show differential motion with the terrain overlaid. In accordance with object-based models of attention, fixed-location superimposed symbology has the potential to foster perceptual segregation of near and far domains due to differential motion, which can result in the need to engage, shift, and reorient between the sources of information presented (Ververs & Wickens, 1998). Delays between these steps can lead to the misallocation of attentional resources.

Cognitive Tunneling

The inability to successfully allocate attentional resources due to inherent characteristics of the HUD may foster cognitive tunneling (Ververs & Wickens, 1998). This phenomenon occurs when the pilot's attention becomes locked on one source of information, while neglecting to process other items in the environment. Weintraub and Ensing (1992) warned that HUDs are "ready made for cognitive capture," due to placement of an always present display in front of a world that can be degraded and/or occluded (p. 104). Weintraub and Ensing (1992) issued a caveat for HUD use based on the explanation that no cognitive cues existed for necessary attentional switches to return to the environment from the HUD fixation.

Pilots flying with a HUD may fixate on HUD symbology to the detriment of optimal situational awareness. When flying with compelling HUD symbology and confronted with an unexpected event in the world, pilots have shown increased event detection times, suggesting cognitive tunneling (Lasswell & Wickens, 1995; Ververs & Wickens, 1998; Fadden, Ververs, & Wickens, 2000). Pilots are particularly vulnerable when cognitively locked on compelling HUD symbology, thus narrowing information processing of events occurring in the world.

Symbology compellingness. The compellingness of superimposed HUD symbology has been shown to capture attention at the expense of detecting unexpected events in the visual environment (Ververs & Wickens, 1998). Past research has focused on the unexpected presence of another plane (i.e., runway incursion) and increased latency of detection to suggest attentional allocations (Fischer, Haines, & Price, 1980; Wickens, Martin-Emerson, Larish, 1993; Wickens, 1997). Although statistical power remains an issue in testing truly unexpected events, studies have noted trends for slower reaction times in the detection of surprising events for pilots flying with HUDs (Wickens, Fadden, Merwin, & Ververs, 1998).

Symbology location. Foyle, McCann, Sanford and Schwirzke (1993) reported failures to simultaneously process both superimposed HUD symbology and environment (out the-window path), when information source locations were less than 8 visual degrees apart. Conversely, when HUD symbology was located farther than 8 deg from path information, efficient processing of both HUD (near domain) and path information (far domain) was achieved. Foyle et al. (1993) proposed that a mitigating effect of saccadic eye movements, necessitated by visual distance, may break cognitive tunneling on the HUD symbology.

Information Processing and Visual Accommodation

Roscoe (1987) has suggested that failures to concurrently process near and far domain occur because differential accommodation is required between HUD symbology and outside world visual scene. That is, HUD symbology may cause pilot's accommodation to shift inwards toward the resting dark focus level away from a focus to optical infinity. Roscoe's explanation was not supported by subsequent findings of Brickner (1989) and Foyle, Sanford and McCann (1991), who demonstrated the failure to concurrently process outside world information and HUD symbology information with a noncollimated graphics display, eliminating any differential accommodation. Both studies found a *performance tradeoff* between path tracking performance (outside world task) and altitude maintenance performance (HUD task). More specifically, HUD altitude information superimposed on the center field of view, yielded better altitude maintenance, but with decreased out-the-window path performance. Conversely, the absence of HUD digital altitude information yielded poor altitude maintenance, but improved path tracking performance.

Performance Tradeoff in Dual Task Flight Simulation

Both Brickner (1989) and Foyle, Sanford, and McCann (1991) found a performance tradeoff between path tracking performance (outside world task) and altitude maintenance performance (HUD task). Errors in flight performance with superimposed symbology suggest a decrement in path tracking performance may be associated with a cost in attentional shifting between near and far domains (Shelden, Foyle, & McCann, 1997).

Sanford, Foyle, McCann, and Jordan (1993) investigated the performance tradeoff by manipulating placement of the HUD symbology with regards to the outside world visual scene. White HUD symbology, displaying altitude information, was located in one of three fixed-screen locations: 0, 8.14, or 16.28 degrees visual angle from the path information. Participants were tested across all HUD location conditions in a dual task consisting of an altitude maintenance task and path tracking task. Findings revealed a path performance tradeoff for experimental trials tested in the center HUD location, such that altitude maintenance was enhanced with the altitude symbology, but path tracking was hindered. An absence of the performance tradeoff was found in the superimposed HUD locations positioned greater than 8 degrees from path information, such that altitude maintenance was improved with altitude symbology and no associated decrement in path tracking performance was found. Results suggested that symbology located greater than 8 deg visual angle from the central visual scene could alleviate deleterious effects of cognitive tunneling by necessitating an eye saccade.

Further extending the results of Sanford, Foyle, McCann, and Jordan (1993), Foyle, Dowell, and Hooey (2001) sought to eliminate possible confounds that could lead to other explanations for the presence of a performance tradeoff. Confounds of differential contrast, complexity, and motion between HUD and background were identified and addressed in an attempt to eliminate them. Previously unmatched luminance levels of sky and ground were perceptually matched utilizing the technique of heterochromatic flicker photometry method (see Cornsweet, 1970). HUD symbology was changed from white to bright green in order to portray more realistic flight instrumentation. Two levels of symbology-to-background luminance were established and defined by contrast ratios (symbology luminance divided by background luminance): 28.80 (High Contrast) and 7.48 (Low Contrast).

Superimposed HUD symbology was located at equal screen distances both above and below the horizon, in order to independently assess the effects of distance and effects of background varying in complexity and motion. HUD digital symbology was presented in four unique screen locations (see Figure 1). The four HUD locations were measured in degrees of visual angle from the path information as follows: Center (0 deg, directly overlaying the path information); Mid-Upper (7.71 deg, intermediate distance upwards from the path information); Upper (15.43 deg, left corner of the screen, far from the path

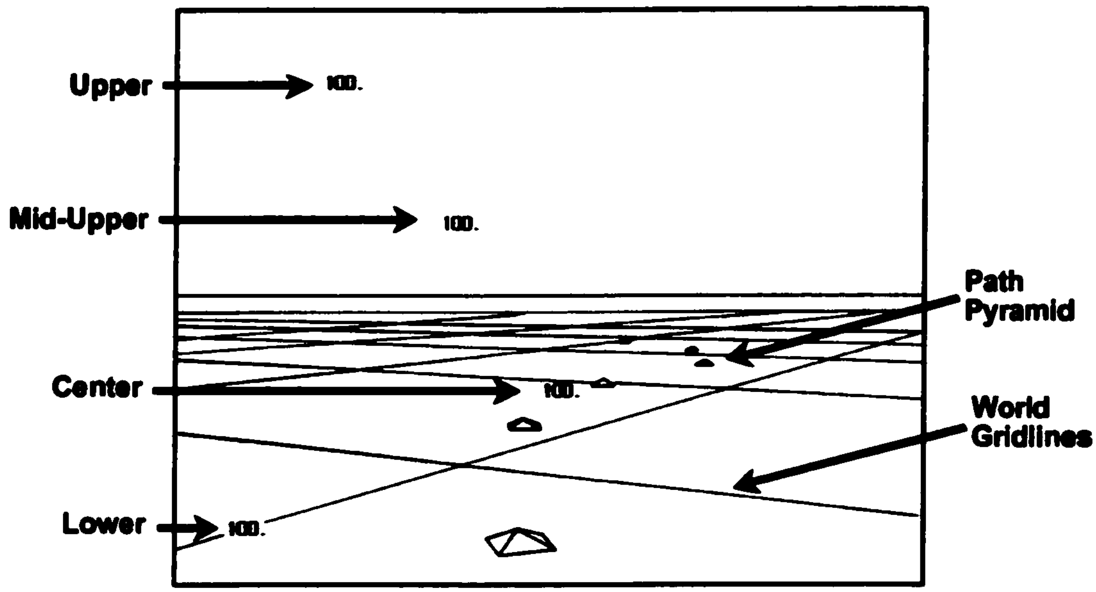

Figure 1. Scaled composite representation of the four possible HUD locations presented by Foyle, Dowell, & Hooey (2001).

information); Lower (15.43 deg, left corner of the screen, far from the path information). Participants were tested in a single contrast level (between factor) in each of four HUD locations. All subjects were tested on the four locations plus a fifth HUD Absent condition serving as an experimental control (within factors).

Results from this study found no effect of Contrast for both Altitude and Path RMSE dependent measures. Replicating previous findings (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997), altitude maintenance performance without a HUD digital display (HUD Absent condition) was worse than when HUD altitude information was presented in any location (Figure 2). When HUD altitude information was displayed in the Center location, path tracking performance was worse than when presented in any other HUD locations or when the HUD was absent. Additionally, path tracking performance for Mid-Upper and Lower HUD locations was equal (not significantly different) to performance when no HUD was presented (HUD Absent).

In an extension of previous findings, placement of HUD symbology in the Upper location yielded path tracking performance significantly better than all other HUD locations (including absent), with no associated performance tradeoff in the altitude maintenance task. Foyle, Dowell, and Hooey (2001) concluded that when HUD symbology is located greater than 7.71 degrees from the path information (Mid-Upper HUD location), the dual task performance tradeoff is eliminated. Visual distance was suggested as a necessary component to allow efficient processing of HUD and outside world information, thereby mitigating cognitive tunneling through requisite eye

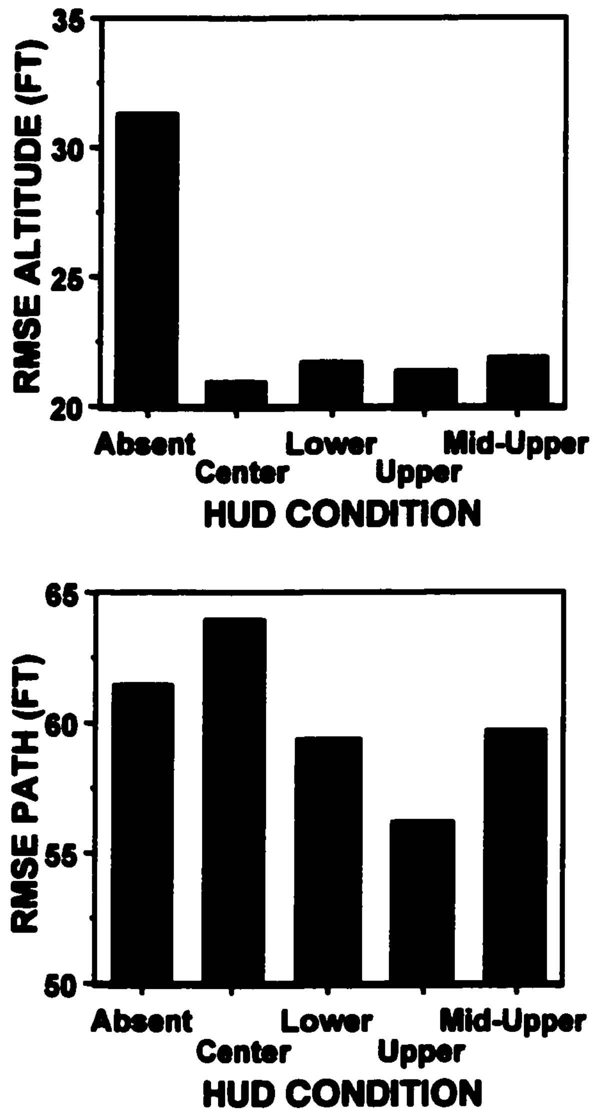

Figure 2. Mean performance results averaged over the two contrasts tested (n = 32): Effect of HUD condition on Altitude RMSE (above) and Path RMSE (below).

movements. Superior path tracking performance when presented with an altitude display in the Upper HUD location as compared with the Lower HUD location, was attributed to possible differences in background content and movement.

Limitations of Previous Research

Results from previous research (Foyle, Sanford, & McCann, 1991; Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001) have been limited because performance scores were gathered from within-subjects design experiments where subjects were tested across all HUD locations. Research by Foyle, Dowell, and Hooey (2001) tested subjects in four HUD locations with a fifth HUD absent condition serving as an experimental control. Participants performed experimental trials 20% of the time in each HUD location, including an absent condition. HUD location was randomized as an exclusive series, such that the strategy and visual scan pattern needed to process HUD symbology for that trial could not be anticipated. While expectancy can affect the allocation of attention (Wickens, 1997), this unblocked presentation of HUD symbology likely prevented participants from developing efficient eye scan for any one HUD location. In addition, use of a HUD absent control condition presented only one fifth of the experiment could have affected participants effort level on this qualitatively different task condition: maintaining a specific altitude without an altitude display.

Purpose of the Study and Hypotheses

The purpose of this study was to investigate the effects of symbology location on flight performance in a dual task simulation, where participants might develop eyescan strategies by testing in a single HUD location with a HUD Absent condition serving as an experimental control. It was expected that participants might improve strategies for maintaining altitude without a digital altitude readout if dedicated to this task 50% of the experiment. Furthermore, it was anticipated that a blocked HUD presentation would foster the development of eyescan patterns and performance strategies, yielding overall improved performance. Thus, this study was intended to examine HUD performance tradeoffs in a more realistic setting (one display location) and to determine which HUD location (Center, Upper, Lower) would yield the best combination of altitude maintenance and path tracking performances.

Specifically, it was hypothesized that regardless of HUD location, subjects would perform better on the altitude maintenance task with an altitude display than without. Furthermore, it was hypothesized that participants presented with a Center HUD location (0 deg, directly superimposed) would show a decrement in the path tracking task, yielding an altitude/path performance tradeoff since the distances were less than 8 deg. Lastly, it was hypothesized that participants would both show superior performance on the path tracking task when presented with an Upper HUD location (15.43 deg) and incur no associated performance tradeoff on the altitude maintenance task, when compared with other HUD locations. In testing this hypothesis, it was predicted that an improved eye scan strategy from blocked presentation and a single HUD location tested would offer more robust findings for overall improved performance in the Upper HUD location than previously reported (Foyle, Dowell, & Hooey, 2001). It was anticipated that performance advantages previously found would be amplified from the presentation of a HUD in a single location, thus differentiating effects of HUD symbology located above

and below the horizon line.

Method

Participants

Forty-eight right handed, male participants with normal or corrected to normal vision were tested in this experiment. All participants were 18 - 30 years old with normal ability to perceive color. Participants had no previous experience with HUDs in either simulated or actual flight. As with previous studies (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001), participants did not need flight experience due to the basic nature of the skills necessary for the task. Monetary compensation was given to all recruited participants on a standard negotiated pay scale.

Apparatus

Participants completed the simulation while seated in a dark room insulated for sound reduction. A Silicon Graphics Indigo2 Impact computer was used to present the flight simulation and record raw data. The flight simulation was viewed on a 19-inch Silicon Graphics color monitor, located 65 cm from the participant's vantage point. Control of simulated flight was maintained through the operation of a spring-centered joystick located in the right arm of the participant's chair. Forward and backward movement of the joystick actuated descent and ascent in the simulated flight, respectively. Left and right movement of the joystick generated corresponding lateral flight direction. Joystick sampling, data collection, and graphic presentation were updated at 12 Hz.

Simulation

The experimental simulation represented operation of a pitch-stabilized rotorcraft flown through a virtual environment at dusk. The scene presented was analogous to the forward, out-the-window view from a rotorcraft. The virtual environment measured 32.18 degrees wide by 24.31 degrees high. The rotorcraft simulation did not pitch up or down with joystick movements. This restriction was necessary for heading information, including horizon line, to be consistently present in the visual scene.

The virtual environment depicted a blue sky adjacent to a green ground, with a horizon line dividing the screen in equal halves (Figure 3). Perceived equal luminance values for sky and ground were established through averaged subjective assessments (n = 4), utilizing the heterochromatic flicker photometry method (see Cornsweet, 1970). Equal luminance of sky and ground were presented to control for possible differences in flight performance due to symbology/ground contrast variation. Photometric measurements were recorded for sky and ground luminance, 2.66 cd/m^2 and 2.02 cd/m^2 respectively. Minor variations in luminance measurements of sky and ground were expected due to the greater acuity of the photometer to detect variance, when imperceptible to the human. The contrast ratio of HUD luminance to background luminance was 28.80. A brighter green grid with measured luminance of 5.12 cd/m^2 was superimposed on the virtual ground. Pyramids overlaying the virtual ground were drawn to appear 3 dimensional by utilizing incremental shades of brown for each side. Pyramid luminance ranged from 24.2 cd/m^2 to 35.9 cd/m^2 depending on the side viewed.

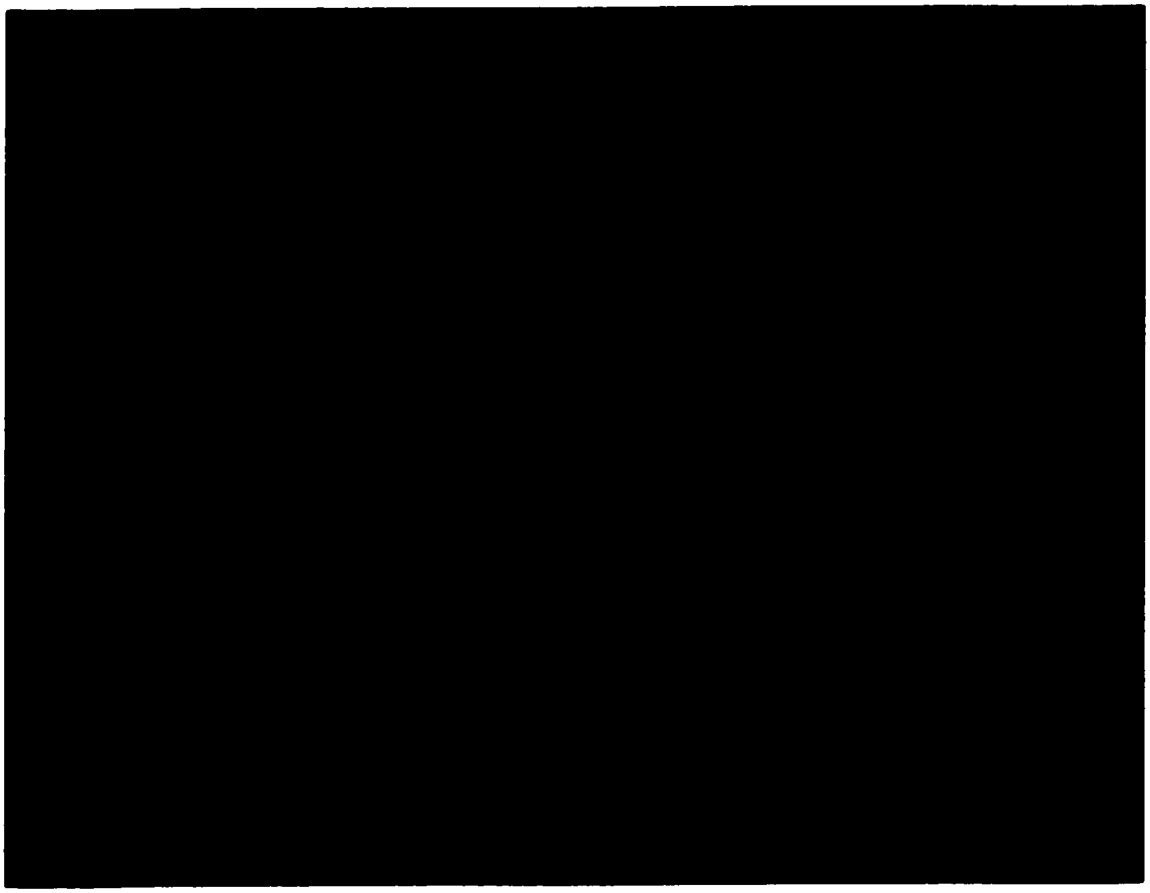

Figure 3. Composite scaled representation of the flight simulation. The three HUD locations shown: Lower (15.43 deg); Center (directly superimposed, 0 deg); and Upper (15.43 deg).

Eight paths were constructed such that pyramids, measuring 24 ft. wide x 24 ft. deep x 6 ft. high marked the designated route. Pyramids were distanced 330 ft. apart in the virtual world. Measurements given represent the scaled size and distance in the virtual environment. Paths consisted of 38 total pyramids, divided into 9 segments, comprised of 4 pyramids each. Four successive, equal arcs in a single direction (left or right) combined to form 60°, 90°, or 120° angles that defined overall path geometry. Angles of turn defining the path were randomized as an exclusive series before repeat presentation. Left and right turns alternated within the path to form a serpentine geometry. Items located on the ground in the virtual world scaled appropriately as a function of altitude. Every path was initiated at the 100 ft. target altitude with a fixed airspeed of 160 knots for the simulation. The initial flight approach for each path, requiring approximately 10 seconds, contained no wind disturbance. Beyond this point, vertical and lateral turbulence was present in all eight paths.

Superimposed HUD symbology, depicting relevant altitude information, was presented in one of three screen locations: Upper, Center, or Lower (Figure 4). Placement of HUD symbology was measured from the center of the screen overlaying the path (nominally, 0 deg) and recorded in degrees of visual angle. Visual angle was calculated using the following formula: Visual Angle (minutes of arc) = 2Arctan X/Y, where X = 1/2 length of stimulus and Y = distance from eye to viewing plane. Upper and Lower HUD symbology were located equally distant from path information, each measuring 15.43 degrees from center screen. Center HUD symbology was collocated with path information, measuring a nominal 0 degrees from center screen. The digital altitude

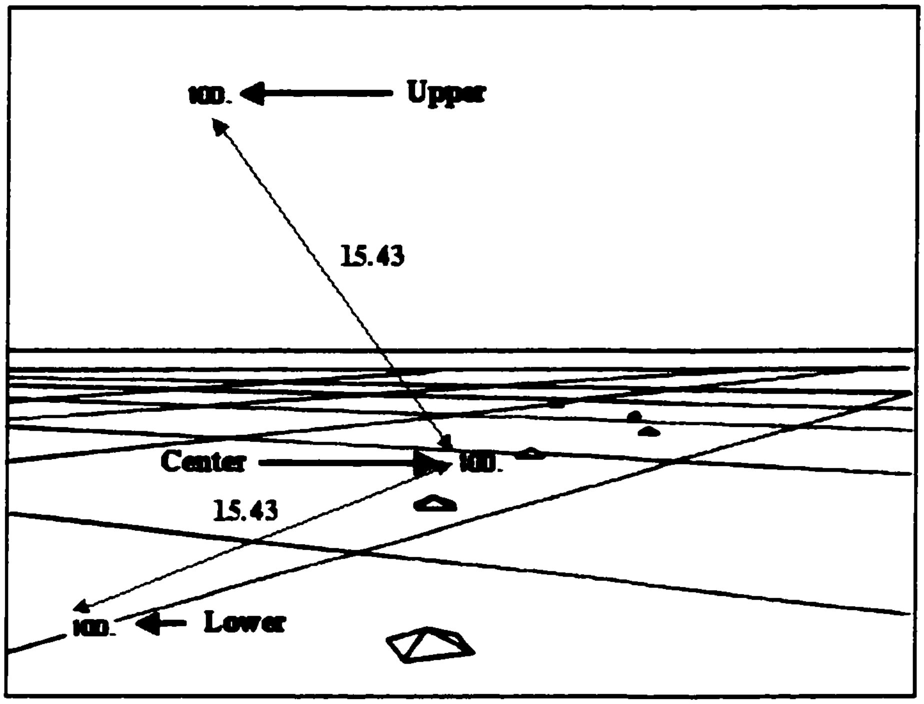

Figure 4. HUD symbology locations. Upper and Lower HUD locations equidistanced from center screen, measured in deg visual angle.

display measured .62 degrees vertically and 1.06 horizontally at the desired goal attitude of 100 feet. Digits were displayed in brightest green (RGB value 0, 255, 0), simulating LCD technology used in HUDs. An absent condition where no digits were presented served as an experimental control.

Experimental Design

A mixed design with repeated measures was conducted (Figure 5). The between variable was HUD location, consisting of three levels: Upper, Center, and Lower. The within variable of interest was HUD presence (On/Off). Experimental within variables were Block (1 - 7) and Trial (1 — 6), lending the ability to analyze for learning and carryover effects. HUD location was blocked with counterbalanced presentation, such that 6 trials displayed HUD symbology and 6 did not, for a total of 12 trials per block (Figure 6). An equal number of participants (n = 16) were randomly assigned to one of the three HUD locations tested. Each participant completed a total of 84 trials. Paths for each trial were randomly assigned as an exclusive series before a subsequent presentation. The dependent measures were root mean square error (RMSE) altitude and RMSE heading. Errors in altitude performance were determined by deviations from the target altitude (100 ft.). Errors in heading performance were determined by deviations from a hypothetical line segment connecting pyramids, demarcating the optimal path. The formula used to calculate RMSE, where e represents error and n represents the number of datapoints:

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

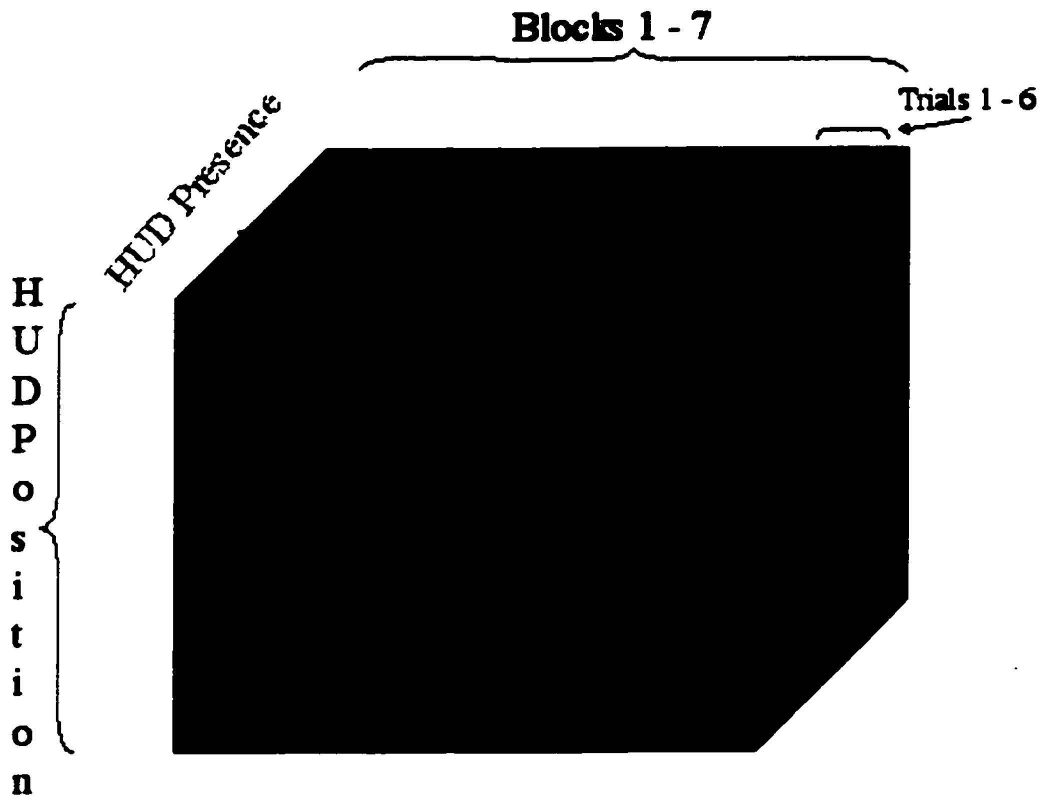

Figure 5. Experimental Design: Between variable (HUD Position) x within variables (HUD Presence, Block, Trial).

			WITHIN VARIABLES													
			HUD Presence *counterbalanced presentation													
			*Absent * Present*							*Present * Absent*						
			Block													
			1		*2*		*3*		*4*		*5*		*6*		*7*	
			Trial													
BETWEEN VARIABLE	HUD Position	Center	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6
		Upper	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6
		Lower	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6	1-6

Figure 6. Experimental matrix: 3 (HUD Location) x 2 (HUD Presence) x 7 (Block) x 6 (Trial).

Depending on the incidence of random turbulence, joystick input by the participant served to null simulation driven error, as well as actuate desired heading and altitude. Uncorrected error was calculated by averaging path RMSE and altitude RMSE over 30 trials on a straight path with equal length to the paths tested (Path $M = 49.10$, $SE = 12.69$; Altitude $M = 27.59$, $SE = 6.62$).

Procedure

Each participant completed one 2.5 hour experimental session. Written instructions were given describing the virtual world and the dual task to be performed (Appendix A). Instructions included information about error scoring and feedback at the end of each trial. It was explained that error scores would be calculated and displayed on the monitor with verbal feedback from the experimenter via intercom. Experimenter feedback entailed generic comments to maintain task effort over 84 trials (e.g., "Nicely done," or "The path seemed to get away from you, remember to divide your attention equally between path and altitude.") Prior to experimental trials, participants were verbally instructed on the importance of optimizing both scores with the goal of reducing error in both performances. The experimenter emphasized the equal importance of both altitude and heading performance with an assurance that both sets of data would be analyzed. A demonstration of the apparatus and simulated flight in each condition (HUD present/absent) was given by the experimenter followed by 8 practice trials flown by the participant (4 in each condition).

Ability to control the flight simulation had been established a priori as ability to complete the first two experimental blocks (24 trials) with no more than two 360-degree turns along the path. Inability to follow this guideline by executing a third 360-degree turn resulted in early termination of the experiment. Dismissed participants were made unaware of the true reason for dismissal, instead blaming a computer failure for the premature ending.

Two predetermined 15-minute breaks were given after the 30^{th} and 60^{th} trials. Participants were instructed to alert the experimenter should they wish to stop the experiment for any reason. At the conclusion of the experiment, participants were debriefed on the study.

Results

Data analyzed was a subset of data collected, determined by identifying asymptotic performance with a technique used previously (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997; Foyle, Dowell, & Hooey, 2001). Successive ANOVAs were conducted on the complete data set, eliminating initial blocks sequentially until no significant effects of Block were found. As a result of this technique, Blocks 5 - 7 [3 replication blocks of 2 levels of HUD presence (Present/Absent) containing 6 trials each for a total of 12 trials per block] were deemed to be asymptotic, and included in the analysis (Figure 7). Only data from these 36 trials are reported. Two participants were dismissed prior to completion of the experiment: one for apparent intoxication, one for inability to execute the task. According to the a priori criterion, ability to control the flight simulation was defined as ability to complete the first two experimental blocks (24 trials) with no more than two 360-degree turns along the path. Consequently, one participant was dismissed after executing a third 360-degree turn during the second experimental block of trials.

Outlying data points were identified as those trials where the participant lost the path from his visual scene without awareness of which direction would lead back to the path (Figure 8). Maneuvers executed during these trials included 180-degree or 360-degree turns, resulting in path RMSE scores of 337.75, 302.67, 233.40 across three participants (Participant ID 27, 29, 46, respectively). In one case, the trial ended before the participant could rejoin the path. Trials where participants lost a visual of the path resulted in a single task experiment because path tracking could no longer be

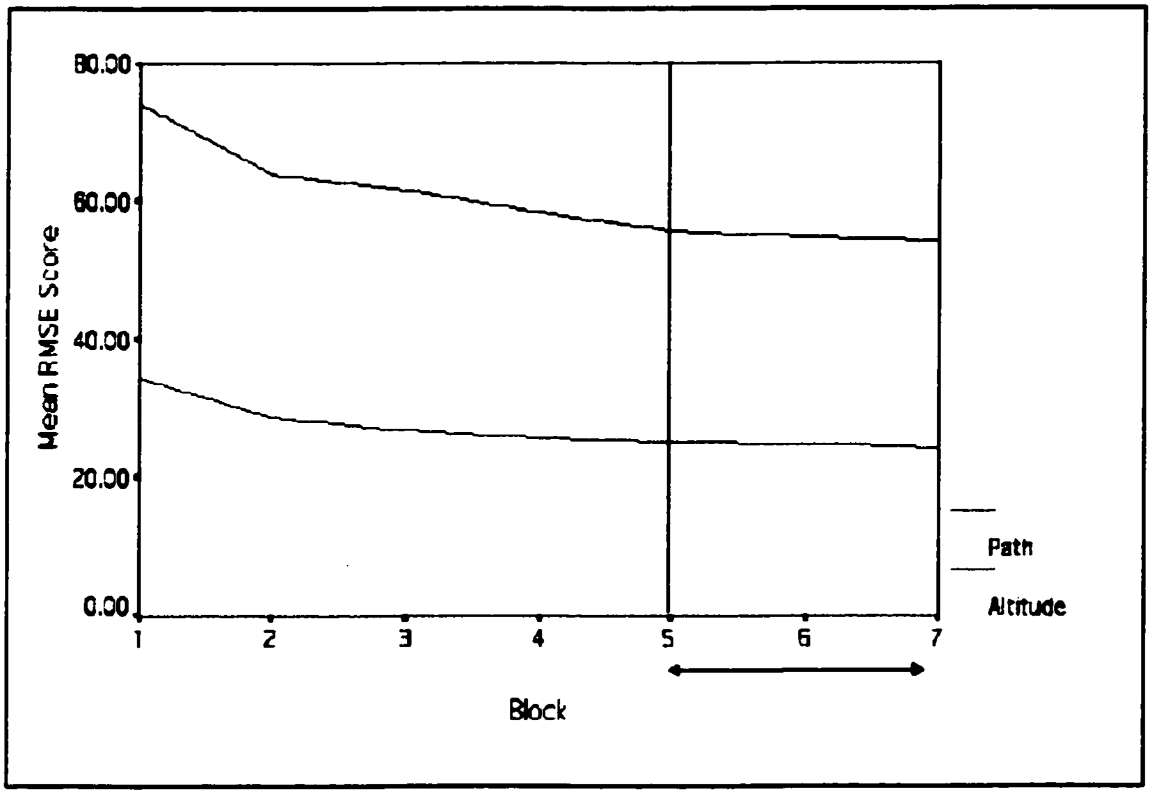

Figure 7. Collected data with demarcation of asymptotic altitude and path performance included in analysis (Blocks 5 — 7).

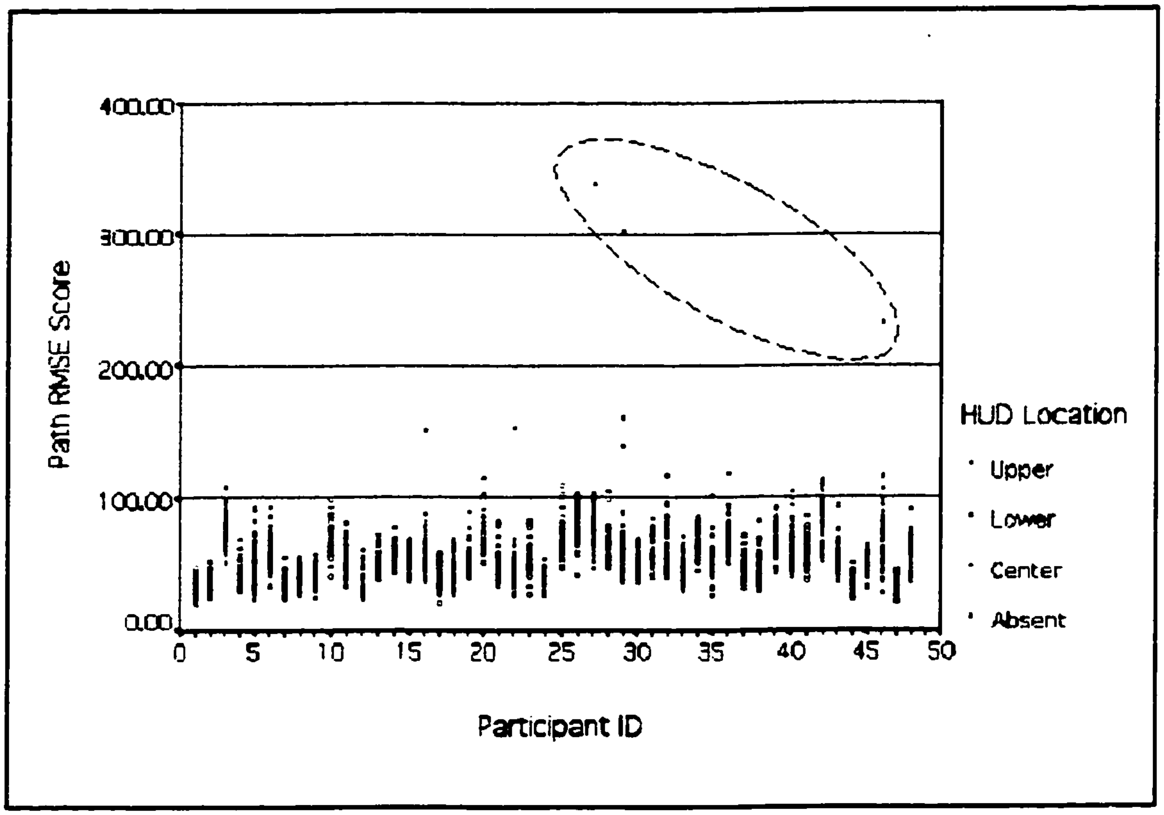

Figure 8. Path RMSE scores (Blocks 5 — 7) with identified outliers.

accomplished. Under the supposition of testing within a dual task environment, these trials recording only altitude maintenance, were deemed unrepresentative of the task assigned and therefore not analyzed. Following this definition, three datapoints were replaced with the average path RMSE score of the participant for that block and that HUD condition, resulting in the average of 5 scores. The corresponding altitude RMSE scores for these datapoints were replaced in the same manner.

A 3 x 2 x 3 x 6 mixed design ANOVA (HUD Location x HUD Presence x Block x Trial) was conducted separately on Altitude and Path RMSE data. Planned comparisons were examined on experimental factors as related to altitude and path performance independently. Two-tailed tests of significance were conducted unless otherwise noted.

Altitude Performance

As expected, results for altitude performance showed a main effect of HUD presence, such that target altitude was better maintained with an altitude digital display than without, $F(1, 45) = 114.30, p < .001$(Table 1). No main effect of HUD Location was found (Figure 9). No interactions between factors were found. In summary, altitude performance was better with an altitude display than without. No other effects were significant.

Table 1

3 x 2 x 3 x 6 Mixed Design ANOVA for Altitude Performance

Source	SS	df	MS	F
		Between subjects		
HUD Location (HL)	1224.46	2	612.23	.71
Error	38819.46	45	862.65	
		Within subjects		
Block (B)	288.37	2	144.18	2.59
HL x B	107.83	4	26.96	.48
Error	5009.78	90	55.66	
HUD Presence (HP)	33548.22	1	33548.22	114.30*
HL x HP	644.22	2	322.11	1.10
Error	13207.51	45	293.50	
Trial (T)	64.17	5	12.83	.34
HL x T	353.72	10	35.37	.93
Error	8524.72	225	37.89	
B x HP	206.19	2	103.09	1.88
HL x B x HP	278.75	4	69.69	1.27
Error	4945.25	90	54.95	
B x T	465.87	10	46.59	1.27
HL x B x T	700.38	20	35.02	.96
Error	16462.27	450	36.58	
HP x T	159.00	5	31.80	.91
HL x HP x T	347.59	10	34.76	1.00
Error	7839.17	225	34.84	
B x HP x T	324.81	10	32.48	.91
HL x B x HP x T	830.17	20	41.51	1.16
Error	16099.41	450	35.78	

Note. $^{*}p < .001$.

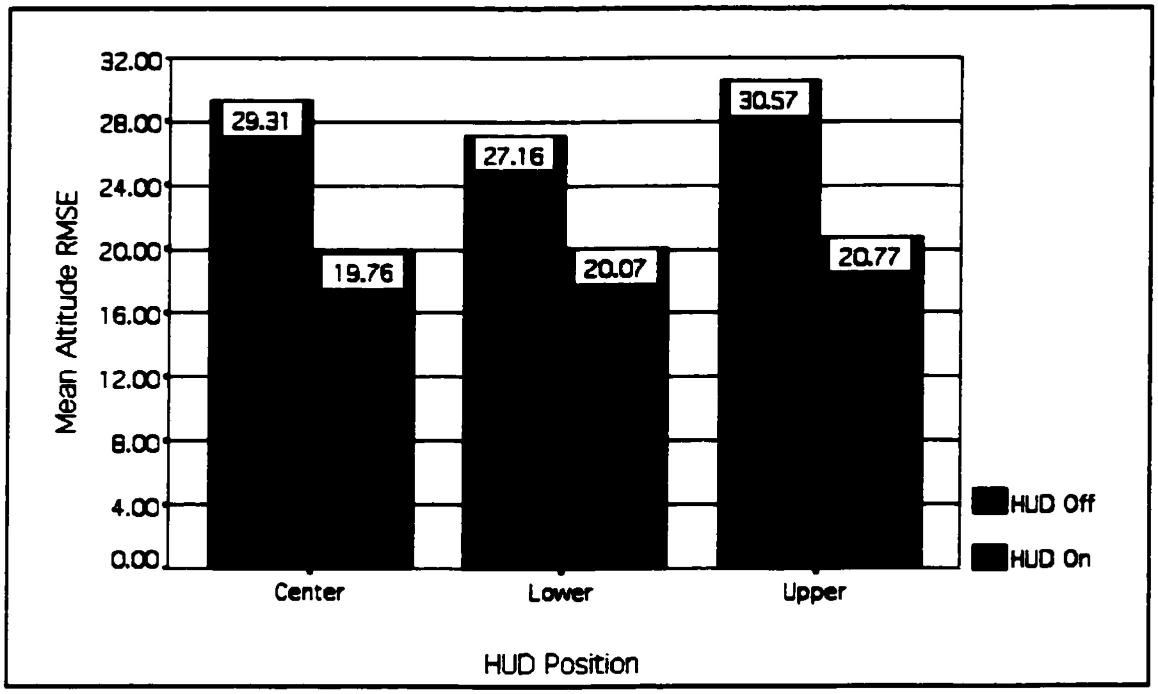

Figure 9. Mean altitude RMSE scores for HUD locations tested in both Absent and Present conditions ($n = 48$).

Path Performance

Analyses on Path RMSE scores yielded no main effects of HUD Presence or HUD Location. Results on path performance included a marginally significant interaction between factors: HUD Location x HUD Presence, F (2, 45) = 3.14, p = .05 (Table 2). Findings of marginal significance were consistent with the hypotheses and replicated previous research that reported an interaction of HUD placement with HUD presence/absence (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001). A discussion of this repeated finding, albeit marginally significant, is relevant. Planned pairwise comparisons within HUD locations between the HUD absent and HUD present conditions revealed a reversal in performance ability when examining the Center and Upper HUD locations. Previous research findings (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001) supported directional hypotheses in performance comparisons for the Center and Upper HUD locations, which made one-tailed t-tests of significance appropriate.

In the first comparison, path tracking performance with a Center HUD altitude display yielded significantly better performance when the HUD was absent (M = 55.79, SD = 10.95) than present (M = 58.04, SD = 13.36), t (one-tail)(15) = 1.56, p = .07 (Figure 10). A reversal of these results was found in comparing path tracking performance when an Upper HUD display was absent (M = 57.65, SD = 15.86) versus present (M = 55.24, SD = 12.49). Path tracking performance with an Upper HUD display location yielded significantly lower error scores when the altitude display was present than absent, t (one-tail)(15) = 1.59, p = .065. No difference in error scores for the Lower HUD location was

Table 2

3 x 2 x 3 x 6 Mixed Design ANOVA for Path Performance

Source	SS	df	MS	F
		Between subjects		
HUD Location (HL)	11784.61	2	5892.31	.99
Error	266586.52	45	5924.14	
		Within subjects		
Block (B)	475.84	2	237.92	1.12
HL x B	159.05	4	39.76	.19
Error	19097.70	90	212.20	
HUD Presence (HP)	28.20	1	28.20	.11
HL x HP	1587.42	2	793.71	3.14*
Error	11376.45	45	252.81	
Trial (T)	785.08	5	157.02	.96
HL x T	2284.99	10	228.50	1.39
Error	36905.76	225	164.03	
B x HP	257.83	2	128.91	.75
HL x B x HP	294.44	4	73.61	.43
Error	15534.20	90	172.60	
B x T	1916.49	10	191.65	1.29
HL x B x T	3330.88	20	166.54	1.12
Error	66957.75	450	148.80	
HP x T	264.95	5	52.99	.32
HL x HP x T	1422.49	10	142.25	.86
Error	37001.87	225	164.45	
B x HP x T	1548.91	10	154.89	.91
HL x B x HP x T	2234.33	20	111.72	.77
Error	65060.55	450	144.58	

Note. *$p = .05$.

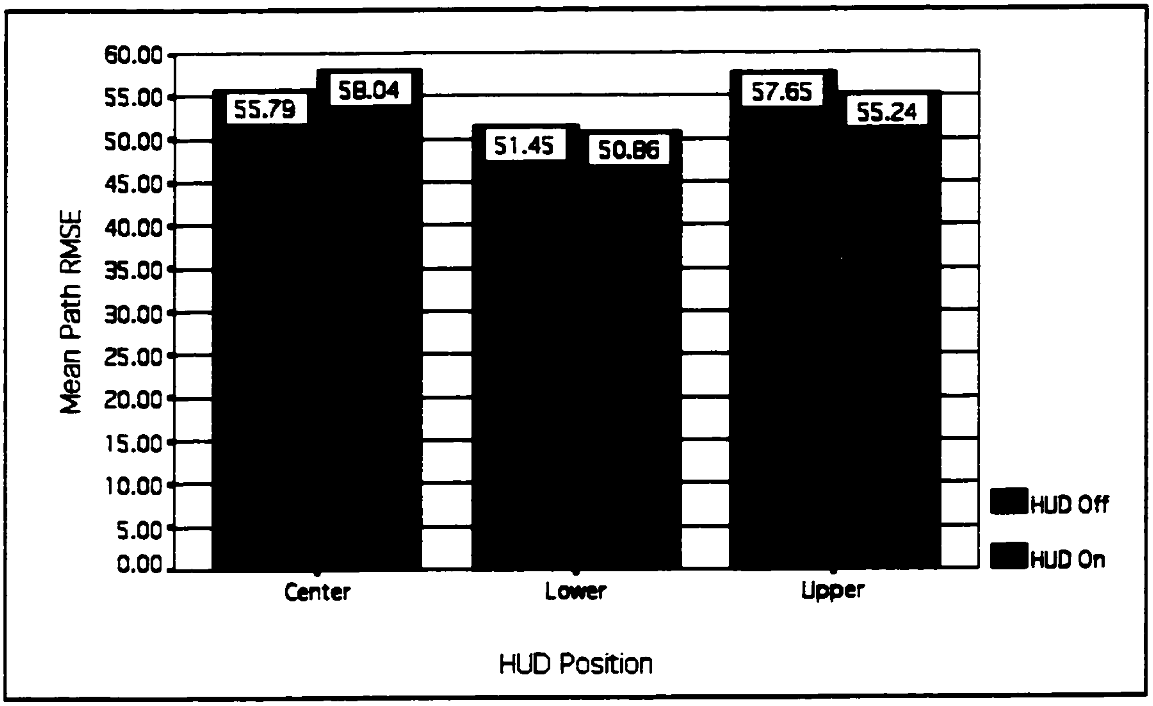

Figure 10. Mean Path RMSE scores for HUD locations tested in both Absent and Present conditions ($n = 48$).

recorded, regardless of presence ($M = 50.86$, $SD = 12.30$) or absence ($M = 51.45$, $SD = 13.13$), $t(15) = .62$, $p = .54$.

In summary, path performance was negatively affected when the altitude display was presented in the center of the visual scene (overlaying the path), whereas path performance was positively affected when the display was presented in the upper portion of the visual scene (15.43 deg from the path). The presence or absence of the HUD in the lower portion of the visual scene had no effect on path performance. Although performance differences in the Upper and Lower HUD locations were operationally small, it can be hypothesized that statistical differences might amplify within the context of actual flight, thus yielding operational significance. The anticipated interaction of HUD location and HUD presence supported the experimental hypothesis and previous studies demonstrating a performance tradeoff when symbology is presented near the flight path.

Discussion

The purpose of this study was to investigate the effects of HUD symbology location on a path tracking and altitude maintenance task. Negligible differences in altitude performance regardless of display location were not surprising in consideration of previous findings for improved altitude performance when an altitude gauge was present (Sanford, Foyle, McCann, & Jordan, 1993; Shelden, Foyle, & McCann, 1997). Analyses of Path RMSE data showed a degradation of performance when symbology was directly overlaying the path, which replicated previous findings (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001). Furthermore, the data revealed enhanced altitude maintenance when symbology was placed in the Upper location, without an associated cost in path tracking. In general terms, the positioning of an altitude HUD in the upper portion of the visual scene allowed for both better altitude maintenance and better path tracking performance. By comparison, the positioning of an altitude HUD in the center and lower portion of the visual scene yielded a performance tradeoff and no performance tradeoffs, but no performance advantages, respectively.

Evaluation of the Hypotheses

This thesis tested three hypotheses in the context of a dual task flight simulation that measured the ability to maintain a target altitude while successfully navigating a winding path. The first hypothesis stated that given an altitude gauge, participants would be able to maintain a specified target altitude better than when no gauge was present. Findings of the study supported this hypothesis, such that performance on the altitude task was better with a gauge in any location, than without a gauge. These results were not surprising due to the relevant feedback an altitude gauge provides on altitude performance. In upholding the hypothesis, this study has replicated earlier studies (Sanford, Foyle, McCann, & Jordan, 1993; Shelden, Foyle, & McCann, 1997) for improved altitude performance through HUD display information. However, a positive recommendation for all superimposed HUD display locations can not be made until the possibility of associated performance tradeoffs has been evaluated.

The second hypothesis stated that participants presented with a Center HUD location (directly superimposed, less than 8 deg visual angle) would show a decrement in the path tracking task, yielding an altitude/path performance tradeoff. Results from this experiment upheld the hypothesis, such that a performance tradeoff was found when presented with a display in the center screen position only. Although improved performance on the altitude maintenance task occurred whenever a display was present, an associated decrement on path tracking performance occurred when the display was less than 8 deg visual angle from path information. This study replicated previous findings for a performance tradeoff associated with HUD symbology collocated with out-the-world information (Foyle, McCann, Sanford, & Schwirzke, 1993; Foyle, Dowell, & Hooey, 2001).

The third hypothesis stated that participants would both show superior performance on the path tracking task when presented with an Upper HUD location (15.43 deg) and incur no associated performance tradeoff on the altitude maintenance task, when compared with other HUD locations. In evaluating this hypothesis, findings revealed improved altitude maintenance when information was displayed in the Upper

HUD location with no associated tradeoff in path tracking ability. Furthermore, results showed a significantly improved *path* performance with a HUD altitude gauge present in the upper location, when compared with absent. Although the presentation of an *altitude* HUD gauge offered no contextual feedback on *path* performance, these findings showed an improvement on path tracking performance when HUD information was located in the upper visual scene. This unique finding for not only a lack of performance tradeoff, but a performance enhancement with HUD symbology positioned in the upper portion of the visual scene, extended previous findings regarding the benefits of visual distance tested within a blocked presentation. Thus, placement of display information greater than 8 deg from central focus and located in the upper portion of visual scene mitigated cognitive tunneling and facilitated more efficient information processing.

General Discussion

As hypothesized, this experiment was able to stabilize and parse differences between Upper and Lower HUD locations by testing subjects in a single HUD location. Significant performance benefits with HUD information placed in the upper portion of the visual scene is a finding unique to this study. Comparisons between Lower and Upper HUD locations suggest that differential path performance might be attributed to the differences in background scene information/symbology (Figure 11).

In the review of literature, perceptual segregation due to differential motion was suggested to induce cognitive tunneling (Ververs & Wickens, 1998). Within the context of this flight simulation, symbology located in the lower visual scene overlaid terrain with more robust visual cues for differential motion than symbology superimposed in the

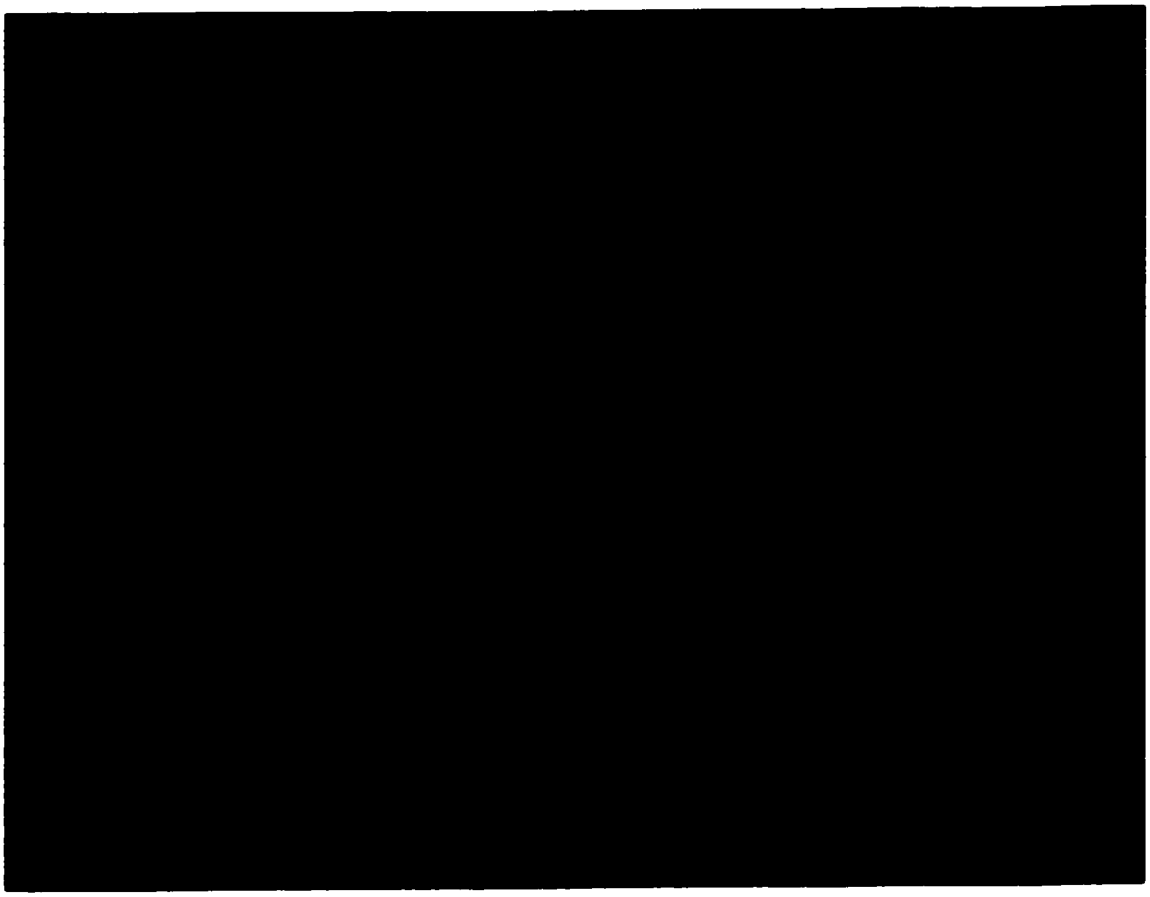

Figure 11. Perception of differential motion may be enhanced for symbology located on ground versus sky due to more complex terrain (i.e., gridlines and pyramids).

upper visual scene. Symbology in the lower visual scene was superimposed on a complex ground with intersecting gridlines and pyramids perceptually varying in size as function of motion. Although located equidistant from center screen (both symbology 15.43 deg), the upper visual scene lacked similar objects that might foster cognitive tunneling as a result of a strong percept of differential motion. Disparate findings on the effects of HUD symbology located above and below the horizon suggest that symbology overlaying complex terrain may facilitate a perceptual segregation due to differential motion of symbology/background. Attentional switches necessary to negotiate tasks involving both HUD information and out-the-world information may be hindered or slowed once perceptual segregation has occurred, thus mitigating cognitive tunneling. Conversely, improved ability to process both HUD information and out-the-world information when information sources have reduced cues for differential motion suggests a facilitation of attentional switching. Related to models of attention, these findings suggest an object-based model revealed in performance improvements when cues that segregate information sources (differential motion) were reduced.

Another explanation for performance variance between symbology locations is based in the differences of clutter from overlaid contours of symbology placed on a more detailed ground as compared with a solid, detail free sky (Figure 12). Wickens (1997) stated that benefits from HUD displays and the successful allocation of attention must be understood in consideration of the necessary visual scanning and cost of clutter. Symbology that consists of contours overlaying a contoured ground could be scanned

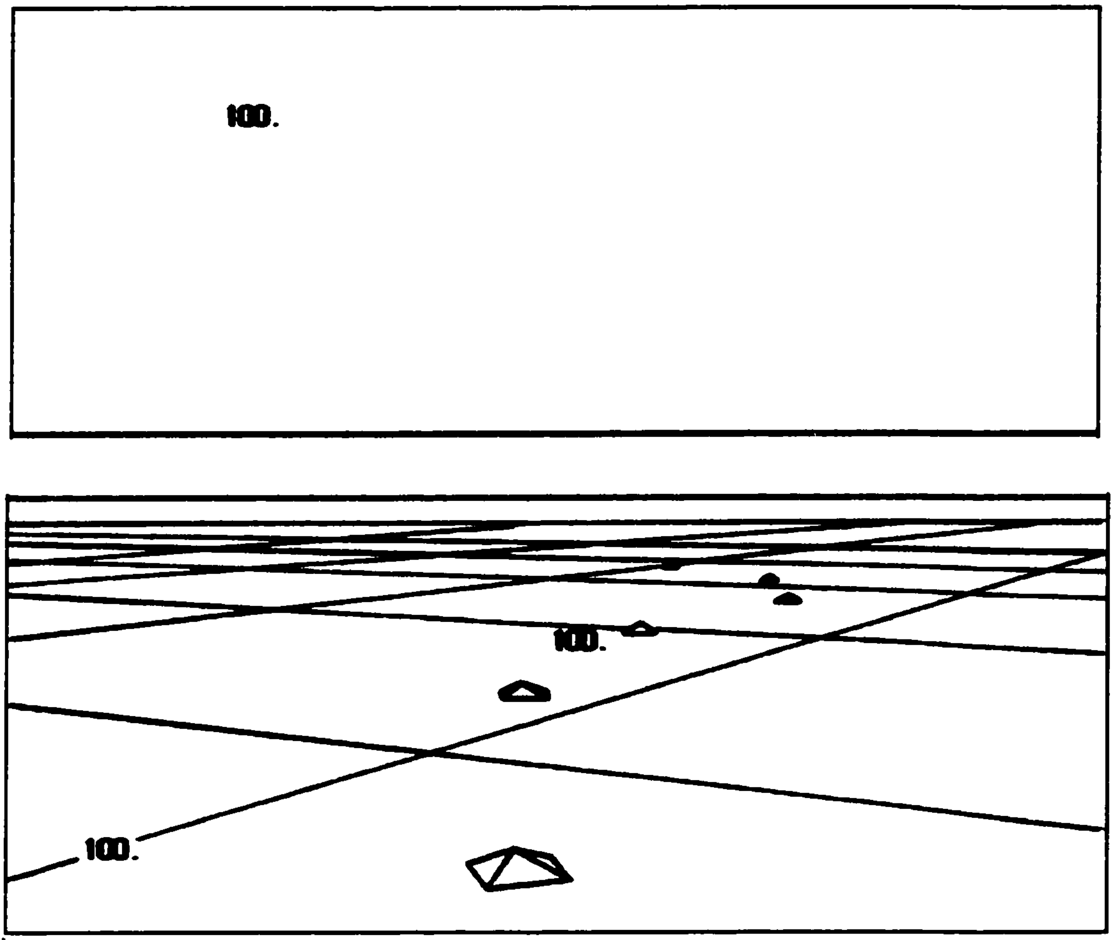

Figure 12. Sparse sky/symbology visual scene (above) versus detailed contours of ground/symbology visual scene (below).

more slowly and thereby processed less efficiently than symbology overlaying a sky without contours. The misallocation of attention resulting from attempts to parse and process cluttered information sources might therefore explain performance differences in more and less detailed symbology/terrain environments.

Finally, the effect of visual scan to a single HUD location practiced within a blocked presentation should be noted. While the mitigating effect of visual distance had been noted in previous studies (Sanford, Foyle, McCann, & Jordan, 1993; Foyle, Dowell, & Hooey, 2001), the benefits of testing within a single HUD location had not been investigated. As anticipated, previous effects of HUD symbology located above and below the horizon were amplified, such that differences between Upper and Lower HUD placement might be examined. Expectancies formed from repeated presentation of HUD information in a specified location may have combined with benefits of visual distance and reduced clutter to yield the best combination of altitude/path performance for symbology placed in the upper visual scene. Additionally, visual scanning behavior favoring top to bottom, left to right may have contributed to improved performance in the upper (top) versus lower (bottom) visual field (see Senders, 1976). Finally, in replicating performance advantages found for symbology located above the horizon (Foyle, Dowell, & Hooey, 2001), and testing with a more appropriate experimental design, benefits of HUD display location are further illuminated.

Implications of the Findings

This study has important implications for the placement of HUD information in cockpit environments. First, utilizing a more appropriate experimental design, previous findings were confirmed; showing that centrally located HUD information can induce cognitive tunneling and impair performance on the task where the HUD is superimposed. Second, this study shows that cognitive tunneling can be eliminated only when the HUD information is presented in the upper portion of the visual scene (greater than 8 deg from central focus), as opposed to an equidistant location in the lower portion of the visual scene. Lastly, the differences in performance between symbology locations is rooted in the differential nature and amount of background elements found in the sky versus ground, with the former producing less visual/attentional conflict with the HUD symbology.

Limitations of the Study

It should be noted that these findings were based on data taken from a part-task desktop simulation presenting a single instance of display information (altitude gauge). By contrast, real world pilots attend to multiple sources of information superimposed on the HUD, as well as instruments in a head-down position and the outside world. It is expected that perceptual segregation of HUD symbology and the outside world would amplify as additional items on the HUD provided cues for grouping the HUD and world as separate objects. While part-task simulations can be helpful in investigating attentional issues related to HUDs, higher fidelity simulations allow for more robust evaluations of the true complexity of integrating multiple sources of display information.

Future Research

In an attempt to investigate the effects of differential motion on the perceptual segregation of symbology/ground, future studies might assess flight performance with

HUD symbology overlaying various levels of detailed terrain. Possible differences might further illuminate the effects of perceptual grouping due to differential motion regardless of location within the vertical plane. Additional research is warranted before explicit associations can made between symbology location in the lower visual scene and cognitive tunneling. Although visual angle was matched in the upper and lower visual scene, it is possible that learned preferences for visual saccade direction facilitate or degrade performance based on symbology location. Further study of symbology placement that is redundant or in opposition to learned visual scanning behavior might differentiate benefits of upper and lower visual scene into further sectioned left and right halves.

Conclusion

In summary, a caveat for HUD use was issued because cognitive tunneling can occur when pilots are presented with non-conformal symbology superimposed on the outside world visual scene (Weintraub & Ensing, 1992). Attentional capture on superimposed, screen-fixed symbology can lead to the inefficient joint processing of HUD display information and events in the environment, thus compromising situational awareness and pilot safety. Previous research (Foyle, Dowell, & Hooey, 2001) showed that efficient joint processing of HUD information and world information was facilitated by necessary eye saccades between separated information sources (at least 8 deg). Limitations of previous research included experimental designs that tested participants across multiple display locations, not allowing for the development of efficient eyescan strategies. By testing participants in a single location for display information, this study attempted to more closely represent a cockpit equipped with a HUD and the resulting instrument scanning strategies developed by the pilot. Within the context of these findings, the mitigating effect of an eye saccade on cognitive tunneling has been further defined by demonstrating the performance advantages of HUD symbology placement in the upper visual scene specifically. Because cognitive tunneling can impact pilot situational awareness and subsequently the prospect of safe flight, further study of mitigating factors is not only warranted, but imperative.

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Appendix

Participant Instructions

1. General Description
In this experiment, you will use a joystick to "fly a helicopter" along a computer-generated path. The total time it will take you to complete the experiment is approximately 2.5 — 3 hours.

2. The Task
You have two objectives of equal importance in this task: (1) to navigate your helicopter along the path, delineated by brown pyramids on the ground, and (2) to maintain an altitude (height in the air) of 100 feet. You control the movement of your helicopter with a joystick. In order to control your path position, you can make lateral (side to side) deflections (left movements to fly towards the left; right movements to fly towards the right). In order to control the height of your helicopter, you can make deflections forward to descend (go down) or backward to ascend (go up). You do not have to control the forward movement of the helicopter it is set at a constant speed.

On every trial, there will be brown pyramids and green grid lines on the ground. The size and perspective of these objects vary depending on your altitude. For the first 10 seconds of every trial, you will automatically fly towards the path at 100 ft. During this time you should pay careful attention to what your environment looks like so that you can use these ground objects as altitude cues. Do not alter your heading (i.e. your forward direction) or height in the air until you reach the first pyramid.

During your flight, there will be turbulence, affecting both your lateral position and your altitude. Therefore, you need to monitor your movement and altitude throughout the trial and make appropriate joystick movements in order to accomplish your 2 goals.

a. Path Movement
The path is delineated by brown pyramids on the ground. You should attempt to "fly" right over them by moving the joystick to the left and right. You will be directly over the path if the pyramids pass directly under the middle of the display screen. Therefore, one of your goals is to have the pyramids pass directly under the middle of the display screen.

b. Altitude Maintenance
At the beginning of each trial, your helicopter will be flying your "goal-altitude" of 100 ft. On some trials, the pyramids and grid lines will be your only altitude cues. However, on other trials, there will also be an altitude gauge indicating your current altitude. You should also use this gauge to help you maintain your altitude at 100 ft. The gauge is made

up of green digital numbers. Utilize the first 10 seconds of each trial to orient yourself to your goal altitude of 100 ft., referencing the digital gauge if present.

Please note: both aspects of this task, (1) to follow the path, and (2) to maintain your altitude at 100 ft., are equally important. You should try to direct an equal amount of time and attention to each aspect of the task.

3. Feedback
A separate path and altitude error score will appear on the screen at the end of each trial. I will also give you information about your performance on both the path and altitude components of the task at the end of each trial. Lower scores (like golf, for example) indicate good performance. A score of zero would indicate perfect performance. You are not, however, expected to receive such a score because of the turbulence.

The 2 error scores (for **path following** and **altitude maintenance**) are scaled differently, so you should not try to equalize the scores. Instead, attempt to earn low scores for each by allocating equal attention and effort to each component of the task.

4. Questions
If you have any questions, please ask them now. You may also ask questions at the end of each trial. Should you experience any physical uneasiness during the trial, please let the principal investigator know promptly via intercom.

In summary, you should attempt to:
1) Follow the path, as delineated by the brown pyramids, and maintain your altitude at 100 ft.
2) Pay close attention to object sizes at the start of each trial, when you are flying exactly 100 ft. Judge your altitude throughout the trial by comparing the size and perspective of objects on the ground to that in your memory of them during the first 10 seconds of the trial. If an altitude gauge is present, also use it to maintain your altitude.
3) Attempt to earn low error scores for both path following and altitude maintenance; do not attempt to score equally low scores because they are computed on different scales.

Good luck