EFFECTS OF A VIRTUAL AIR SPEED ERROR INDICATOR ON GUIDANCE ACCURACY AND EYE MOVEMENT CONTROL DURING SIMULATED FLIGHT

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We examined whether flight-control performance might be improved by presenting airspeed information to peripheral areas of the visual field using virtual head-up displays (HUDs), and whether participants process these displays using peripheral, rather than central, vision. We found that, compared to a standard HUD speed indicator, a peripherally located virtual speed indicator produced superior altitude control and equivalent or better speed control. Participants' gaze dwell times were more concentrated on flight-path and altitude control information as compared to speed information for the virtual HUD speed indicator. Gaze patterns showed that participants processed the virtual speed indicator with peripheral vision while they needed to directly fixate the traditional military standard HUD speed indicator in central vision. We believe the virtual display allowed participants to acquire speed information in a manner consistent with naturally-evolved orienting processes and therefore reduced central visual field load, attentional demand, and overall mental workload, freeing resources for better flight-path control.

INTRODUCTION

For safe and effective control of flight, pilots must maintain spatial orientation: the accurate perception of their aircraft's current location, orientation, trajectory, and speed. However, the vast array of information displayed in modern cockpits can overwhelm pilots' perceptual and cognitive resources, particularly for missions such as nap-of-the-earth (NOE) flight, which require pilots to focus attention directly on the visual scene outside the aircraft to safely maintain spatial orientation. Non-alphanumeric displays incorporating naturalistic representations of actual flight parameters—known as virtual displays—can enhance pilots' abilities to maintain spatial orientation (Hallet, 1991) and have been shown to increase overall pilot performance and reduce workload (Hettinger, Brickman, Roe, Nelson, & Haas, 1996). Our purpose here was to examine the potential performance benefits of virtual displays presented to the visual periphery for providing airspeed error information and to determine if such displays are indeed processed using peripheral vision.

To accurately read most aviation displays, pilots must directly fixate their gaze upon the display and allocate enough mental resources to interpret the alpha-numeric information presented. Roscoe (1980) estimated that 90 percent of aircraft control is performed using the central visual field. However, a virtual display could present speed information to a pilot without taxing overburdened attentional resources by taking advantage of natural orienting (Brandt, Dichgans, and Koenig, 1973) and motion coding processes (Egeth & Yantis, 1997) that are particularly robust in peripheral vision. Airspeed information is an excellent candidate for peripheral presentation due to the fact that the task of speed control is not integrated with altitude control (Haskell & Wickens, 1993) and thus by the proximity compatibility principle (Barnett & Wickens, 1988) its display should be separated from the display of other navigational information. Placing a virtual speed indicator in the periphery may reduce the attentive demands of speed perception and control, thereby creating a greater degree of parallel processing of speed and flight path information.

In the context of simulated flight, Cox (2000) compared the head-up display (HUD) speed indicator defined by MIL-STD-1787B (see Figure 1) to a virtual speed error indicator composed of moving fields of arrows projected to the visual periphery (assuming the participant's gaze was oriented straight ahead, see Figure 2). Cox found that observers' more accurately controlled speed and altitude when using the virtual speed indicator as compared to the military standard speed indicator, particularly in experimental conditions demanding higher workload. Consistent with this performance advantage, Cox (2000) also found that subjective workload ratings were lower for the virtual speed indicator. However, one limitation of this study was that eye movements were not monitored, so there was no objective measure of whether participants processed the virtual display with peripheral vision, as intended. Here, we expand upon this work by determining whether pilots process the peripherally located virtual speed indicator with peripheral vision, rather than by direct eye fixation, since a primary advantage of such a display is its potential for allowing pilots to focus central visual processing resources on tasks other than perception of speed.

METHOD

Participants

Eight students from the University of Idaho volunteered for participation in this experiment. All participants were naïve to the purpose of the experiment and had at least 20/30 corrected Snellen acuity. One participant could not complete the experiment due to unreliable eye tracking. A second participant was eliminated from the analyses due to unusually large performance errors that suggested he either disobeyed instructions or misunderstood the experimental tasks.

Stimuli and Apparatus

The displays simulated flight over a textured terrain and were presented on two rear-projection screens arranged side by

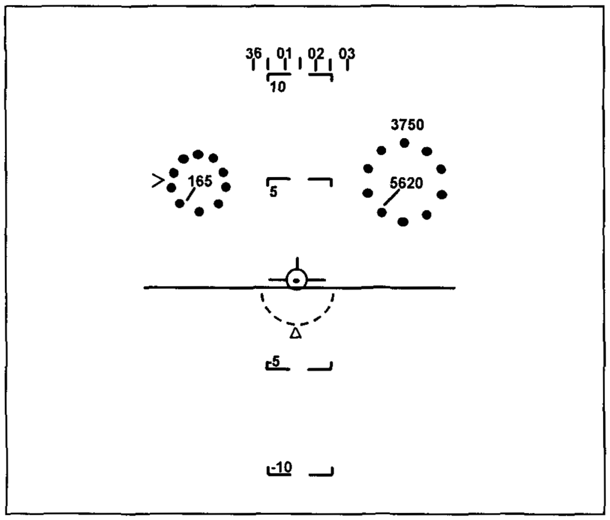

Figure 1. Pictorial representation of the MIL-STD-1787B HUD. The airspeed dial is on the left with a carrot indicating the target airspeed, the altimeter on the right with the target altitude displayed numerically above. Also shown are a heading indicator, artificial horizon, bank indicator, and pitch ladder.

side at an angle of 135 degrees. The participants binocularly viewed the displays from the projectively-correct eye-point, located at the intersection of perpendicular lines radiating from the center of both displays, at a distance of 1.5 m. Together, the screens presented a spatial resolution of 2560x1024 pixels (H x V) subtending 90 x 34 degrees (H x V) of visual angle with a refresh rate of 60 Hz. Display animation was controlled by a Hewlett Packard C3000 Visualize graphics workstation that updated the scene every other screen refresh, creating a frame rate of 30 Hz. Participants controlled their flight over the simulated terrain using a right-hand flight stick for first-order control of pitch and roll, a left-hand throttle for second-order control of speed (acceleration), and rudder pedals for first-order control of yaw.

Eye and head movements were continuously monitored at 60 Hz using an Applied Science Laboratories (ASL) Model 5000 system with head-mounted optics and a Flock of Birds magnetic head tracker. This system has an optimal spatial resolution of 0.5 degrees of visual angle and allowed participants to look anywhere in the displays by moving their eyes, head, or both. Digital records of gaze position within the displays were recorded at 60 Hz for all trials.

Like Cox (2000), two airspeed indicators were examined in combination with the MIL-STD-1787B HUD altimeter, flight-path marker, pitch ladder, bank indicator, and heading indicator. The *mil-standard airspeed indicator* (Figure 1) was based on the MIL-STD-1787B HUD specification and depicted a 10-point dial with either a carrot indicating target speed when speed error was less than 40 units•s^{-1}, or an alphanumeric display of the current target speed when error exceeded 40 units•s^{-1}. (Spatial units within a simulation or

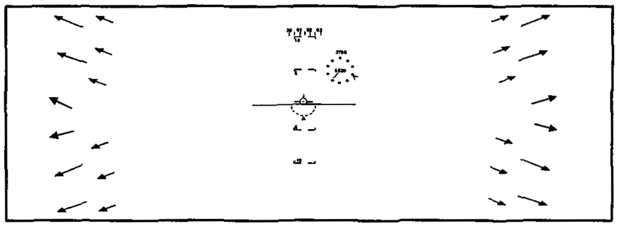

Figure 2. Pictorial representation of the virtual HUD. Note the virtual airspeed error indicator comprised of moving arrows has replaced the airspeed dial. The altimeter, heading indicator, artificial horizon, bank indicator, and pitch ladder are as specified by MIL-STD-1787B HUD.

virtual environment are arbitrary, hence we express all spatial parameters for our simulations as "units" rather than SI or English units.) The *virtual airspeed error indicator* (Figure 2) replaced the standard dial indicator with moving arrows presented to the periphery. The size, speed, orientation and direction of movement of the arrows in the virtual speed indicator represented the magnitude and direction of speed error relative to the target speed. If the pilot was within 10 units•s^{-1} of the target speed, the arrows disappeared. As the magnitude of speed error increased, the size of the arrows increased incrementally for every 10 units•s^{-1} of speed error, while their speed increased linearly with speed error. The arrows pointed and moved toward the pilot when airspeed exceeded target speed, and away from the pilot when airspeed was less than target speed. Pushing the throttle forward increased airspeed, while pulling it back decreased airspeed, hence the orientation and movement of the arrows directly mapped onto the direction of control input necessary to correct speed errors, thereby maintaining stimulus-response (S-R) compatibility, (Wickens and Hollands, 1999). The moving arrows were confined to areas located both left and right of the central HUD bounded by horizontal visual angles of magnitude 25 and 45 degrees and vertical visual angles of -17 to 17 degrees relative to the center of the HUD.

The simulated environment consisted of two square ground planes 18,000 units per side, defined by smoothly shaded randomly colored squares 1000 units in size and covered with 600 randomly placed trees ranging in size from 50 to 100 units. One plane was located at an elevation of 0 units, while the other was located at an elevation of 1000 units. The two planes were connected by a vertical cliff face of grey smoothly shaded squares 1000 units per side. Ten waypoints were defined in a pseudo-random semi-circular pattern that spanned both planes with the first five waypoints placed over the lower plane and the last five waypoints placed over the upper plane. The altitude, position, and orientation of the waypoints varied randomly so that the semi-circular pattern was similar but unique for each trial. At any given time only the next way point was indicated in the display by a floating red square 200 units per side. The left vertical edge of each waypoint box was blue and participants were instructed to fly

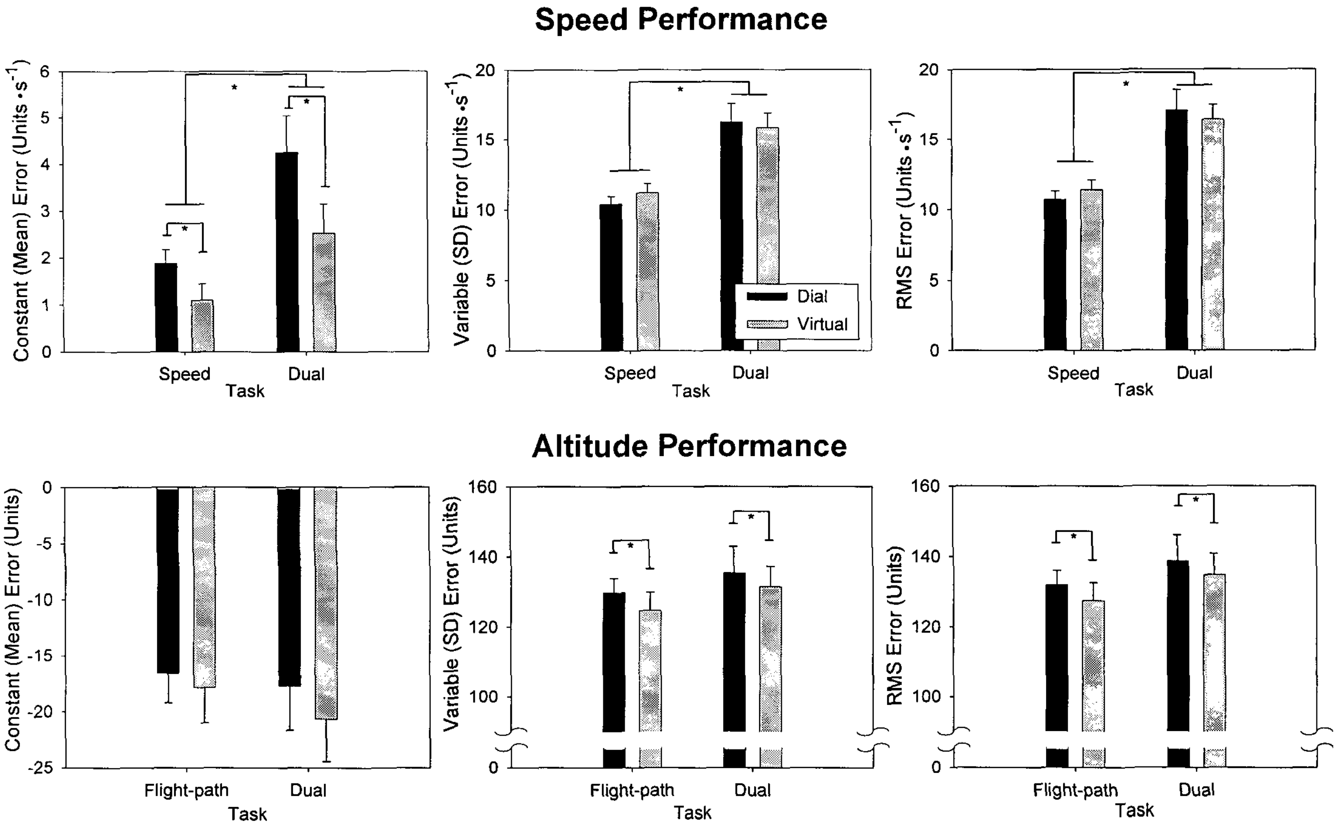

Figure 3. Speed and altitude control performance (top and bottom panels, respectively) as functions of airspeed indicator (virtual vs. dial) and task (speed-control, flight-path-control or dual-control). Left-most panels represent constant (mean) error, center panels represent variable (standard deviation) error, and right-most panels represent RMS (root-mean-squared) error. Whiskers represent 1 standard error of the mean. Statistically reliable differences ($p < .05$) are highlighted by the starred (*) brackets.

through each box so that the blue side was to their left with an upright attitude.

To increase the difficulty of flight path and speed control, the simulation included wind disturbances defined by a sum of five sine waves of prime frequencies. A fore-aft speed disturbance had frequencies of 0.04, 0.08, 0.12, 0.16, and 0.2 Hz with amplitudes of 2.5, 2.5, 1.25, 1.25, & 0.625 unit·s^{-1}. A vertical (altitude) disturbance simulating wind shear had frequencies of 0.04, 0.08, 0.127, 0.16, & 0.2 Hz with amplitudes of 2, 2, 1, 1, & 0.5 unit·s^{-1}. Rotational disturbances about the pitch, roll, and yaw axes had frequencies of 0.03, 0.06, 0.09, 0.12, & 0.16 Hz with amplitudes of 2, 2, 1, 0.5, & 0.5 degrees·s^{-1} for roll, and 1, 1, 0.5, 0.5, & 0.25 degrees·s^{-1} for pitch and yaw. Phases for all wind disturbances were determined randomly at the beginning of each trial.

Design & Procedure

We used a 2 x 3 x 6 factorial design with two speed indicators (*dial* vs. *virtual*) crossed with three types of control task (*speed* control, *flight-path* control, and *dual* control—both speed and flight-path) and six sessions. For speed control trials, an autopilot guided the participant through the waypoints in a manner designed to mimic human control inputs while the participant controlled speed (single task). For flight-path control trials, the autopilot maintained speed at or near the target speed while the participant guided themselves through the waypoints (single task). For dual control trials, the participant controlled both speed and flight path (dual task). For each session, participants completed the three flight control tasks in separate blocks whose order was counterbalanced within observers across the six sessions. Each block consisted of two randomly ordered trials, one with the traditional dial speed indicator and one with the virtual speed indicator. The six 30-minute sessions were completed over three days and the eye-head tracking apparatus was reset and recalibrated at the beginning of each session.

Participants were instructed to maintain target speed and target altitude while flying through all ten waypoints. As they passed near or through a waypoint, auditory feedback regarding performance (hit, direct hit, or miss) was provided, the waypoint disappeared, and the next waypoint was displayed along with a new target speed and target altitude. Trials were initiated by the participant pressing the trigger button on the joystick and ended when all waypoints were passed or five minutes had elapsed, whichever came first. Typically, trials lasted approximately 220 s. The magnitude of constant (mean) error, variable (standard deviation) error, and RMS error (vector sum of constant and variable errors) in forward speed and altitude were recorded as the performance measures for each trial.

Before formal data collection began, participants were familiarized with the flight-control task and controller dynamics with one or more example trials where they controlled only flight-path with the mil-standard dial speed indicator present. Training trials ended when a subject navigated near or through all ten waypoints on a given trial.

RESULTS

Speed and Altitude Control Performance

For both speed and altitude, constant, variable, and RMS errors for all conditions were compared using 2 x 2 x 6 (indicator x control task x session) within-subjects ANOVAs. Because participants did not control speed in the flight-path control task, and did not control flight-path in the speed control task, these conditions were omitted from their respective error analyses. Figure 3 summarizes the data.

In general our results replicated those of Cox (2000): participants were better at controlling speed and altitude while using the virtual airspeed error indicator as compared to the traditional dial airspeed indicator. A significant main effect of indicator was found for constant speed error $F(1, 5) = 12.43$, $p = 0.017$, MSE = 4.55, with the virtual indicator resulting in overall lower constant speed errors than the dial. Further, significant main effects of indicator were found for both variable and RMS altitude error, $F(1, 5) = 12.00$, $p = 0.018$, MSE = 61.36 and $F(1, 5) = 9.75$, $p = 0.026$, MSE = 64.44, respectively. No other effects of indicator were found ($p > .05$). Taken together, these effects suggest that the virtual airspeed error indicator supported more accurate control of speed and more precise control of altitude as compared to the dial.

Further, significant main effects of task were found for constant, variable, and RMS speed errors, $F(1, 5) = 8.43$, $p = 0.034$, MSE = 15.37, $F(1, 5) = 37.33$, $p = 0.002$, MSE = 26.86, and $F(1, 5) = 35.63$, $p = 0.002$, MSE = 32.80, respectively. Dual control of both speed and flight-path resulted in overall higher speed errors than control of speed alone. No effects of task were found on altitude error and there were no other reliable effects ($p > .05$). Overall, the pattern of performance results closely replicates Cox (2000).

Spatial Distribution of Gaze Dwell Times

For each participant, the digital records of gaze position were combined across all sessions to form composite records for each combination of speed indicator and control task. The spatial distribution of gaze dwell times was computed by first summing the total amount of time each participant's gaze fell within a square window, 4 degrees per side, centered on a particular position in the display. These dwell times were computed for each position in a 90 x 34 grid of display locations separated by one degree of visual angle, and divided by the total dwell time for the entire display, thereby creating a "map" of the percentage of gaze dwell time for locations

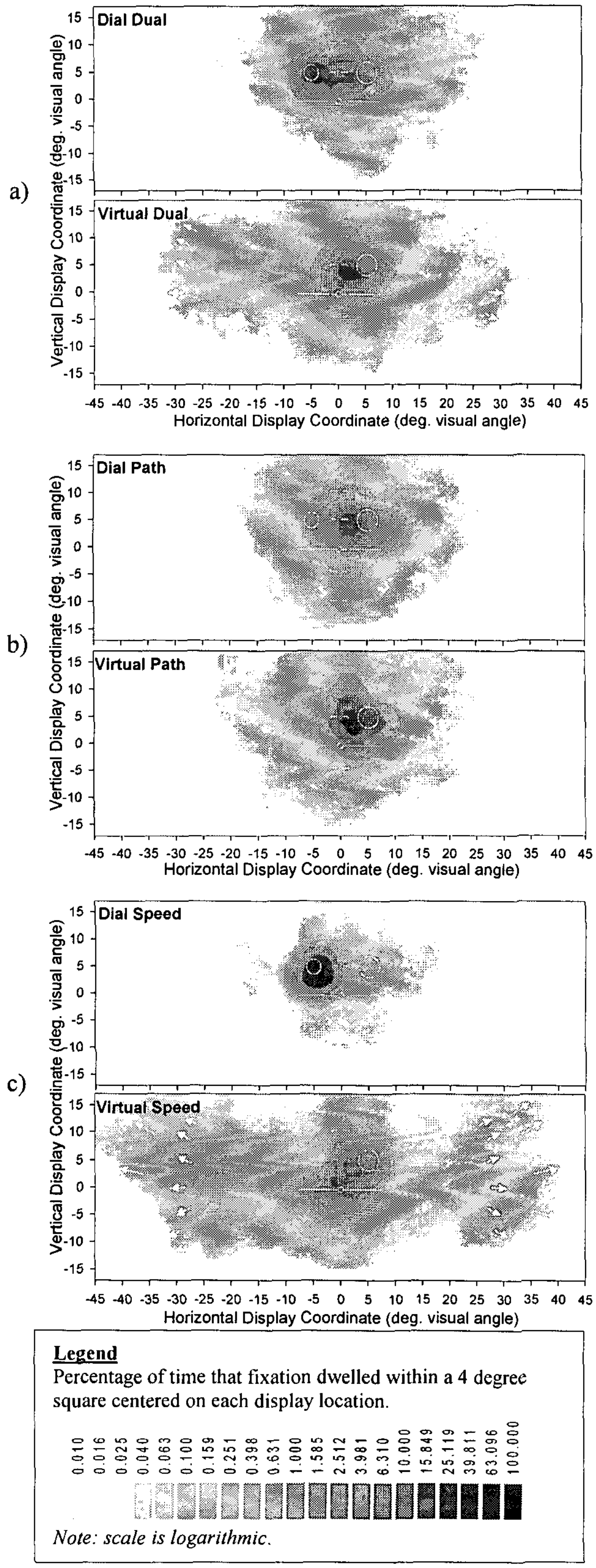

Figure 4. Distributions of fixation dwell percentage for dial and virtual speed indicators (upper and lower panels, respectively) summed across all trials for all participants. a) Dual-task trials, b) Flight-path control trials, c) Speed control trials.

spanning the entire display surface. These maps are depicted graphically in Figure 4 with overlays depicting the relative position of the HUD elements. Because dwell patterns were consistent across participants, the panels of Figure 4 show composite dwell times for all participants as a function of speed indicator for dual-control, speed-control, and flight-path control, respectively. Three conclusions are clear from a visual examination of the dwell time distributions (note the logarithmic scale). First, the dwell patterns for single-task control of flight-path (panel b) are consistent across the dial and virtual speed indicators. These patterns most probably reflect the normal scanning needed to navigate between waypoints and maintain altitude since speed was controlled by the autopilot during these conditions. Second, control of speed using the dial speed indicator resulted in high percentages of dwell time on or near the dial indicator, both in the dual and single task conditions (upper panels a and c). Participants clearly needed to process the dial indicator with their central visual field and this reduced the dwell time on the altimeter for the dual task condition (upper panel a). Third, participants processed the moving arrows of the virtual speed indicator almost entirely with their peripheral visual fields, particularly in the dual-task conditions (lower panel a). Even for the single-task speed-control trials, participants spent more time looking near the center of the display than the peripherally located virtual speed indicator (lower panel c).

DISCUSSION

Our control performance results replicate those of Cox (2000): overall the virtual display reduced speed and altitude control errors. Given that the auditory feedback rewarded precise control of flight-path and punished participants for flight-path errors, we believe that participants treated flight-path (and hence, altitude) control as their primary task. The improvement in primary task performance with the virtual speed error indicator, combined with no increase in secondary task performance (speed control) suggests that the virtual speed error indicator allowed participants to devote fewer resources to controlling speed without a loss in performance and therefore more resources were available to control flight-path. Our gaze dwell results suggest that part of the advantage conferred by the virtual speed error display was that participants could process it without having to look directly at it, in stark contrast to the gaze dwell patterns for the mil-standard speed dial, which required direct fixations to process. Taken together, the performance and gaze dwell results show that for untrained observers flying a simplified flight simulation, speed control is better served by peripherally located virtual displays that take advantage of the natural orienting processes in which peripheral vision excels. Whether this advantage holds for experienced pilots in real flight situations needs to be evaluated with further research.

These results have important implications for the design of future HUDs. Clearly, the peripheral visual fields are a potentially important visual resource that is underused with current HUDs and may be a particularly valuable resource for processing flight parameters related to spatial orientation, such as control of airspeed. Virtual displays of these parameters may provide pilots with information in a natural manner that minimizes the impact on pilot workload and central visual field processing, thereby freeing resources for processing other flight information and increasing flight safety.

ACKNOWLEDGMENTS

This research was sponsored in part by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF, under grant Nos. F49620-97-1-0093 and F49620-98-1-0482. The U.S. Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

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