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For flight training, head-worn displays represent low-cost, wide field of regard, deployable systems when compared to traditional simulation facilities. However, current head-worn systems provide limited effective fields of view. Wide field of view alternatives promise to increase transfer of training effectiveness through enhanced situation awareness. To test this proposition, this experiment manipulated the pilot's effective field of view and examined subsequent flight performance, which was measured primarily by runway alignment error and vertical track error. Results indicated a significant and quantifiable change in visual scan pattern, head movement, and flight control performance as the effective field of view was sequentially decreased. As field of view decreased, the average visual scan pattern changed to focus less out the window and more on the instruments inside the cockpit. The head range of movement significantly increased below an 80° horizontal × 54° vertical effective field of view as well as significantly decreasing runway alignment and vertical track performance, which occurred below 120° horizontal × 81° vertical effective field of view.

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The training of a pilot is presently a relatively prolonged and evidently expensive business. The cost of producing an effective and licensed commercial helicopter pilot, for example, continues to increase in terms of both resource expenditure and time to completion (Bristow Academy, 2007). Not only must one train such pilots, but their skills must be maintained through periodic refresher and reinforcement training as well as programs such as line-oriented flight training (LOFT; Eastern Caribbean Civil Aviation Authority, 2005). At the same time, flight expenses for in-aircraft training also continue to increase. All this is occurring against the background of a ubiquitous mandate to seek to reduce operational expenses. One of the major methods that aviation has consistently relied on to resolve this conundrum is the use of simulation (Flexman & Stark, 1987).

Conventional flight simulators consist of an emulated cockpit and the associated instruments and controls. Added to this physical assemblage is a visual display ranging in sophistication from a single flat monitor to the 360° field of regard dome. Field of view here is defined as the momentary subtending visual angle of the scene at the pilot's eye. Thus, the field of view at any one moment is a subset of the overall possible field of regard, which itself is typically measured in degrees and is contingent on the capacities of the immediate image generation system. Mobile simulation systems most often use simple cathode ray tube or liquid crystal display monitors. In contrast, static facilities such as high-fidelity simulator domes provide a significantly greater degree of immersion (Ames, 2005), but naturally at the expense of far less deployment flexibility. Limited effective fields of view provided by a single computer might suffice for cockpit familiarization, but they are largely impractical for providing realistic out-the-window situation awareness for advanced pilot training (Proctor, Panko, & Donovan, 2004). Desktop computer simulations are also impractical for providing realistic crew coordination training for aircrews (Stewart, Dohme, & Nullmeyer, 2002). Unfortunately, it is neither practical nor feasible to deploy a conventional dome system to mobile aviation units to sustain either initial or refresher pilot training proficiency. This constraint is especially true for training in cockpits with side-by-side seating, for which the display system is inherently large.

Head-worn display technologies have been touted as possible alternatives and are often associated with fully immersive virtual reality simulations (Cakmakci & Rolland, 2006). Augmented reality head-worn display technologies are thus being considered as novel alternatives to provide operational cockpit heads-up displays and also embedded training in a low-cost, wide field of regard system (Rodriguez, Foglia, & Rolland, 2003). However, there are inherent differences in characteristics among different head-worn displays and between forms of augmented reality displays and conventional displays (Pausch, Crea, & Conway, 1992; Rolland & Hua, 2005). For example, the field of view in most head-worn displays is less than 60° horizontal × 45° vertical (assuming a 4:3 format), which is far narrower than the human's normal field of view of approximately 200° horizontal × 135° vertical (Arthur, 2000). A pilot will normally use peripheral vision during a flight a

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head-worn display with a wide 200° horizontal × 135° vertical field of view is not only challenging to design but, at present, would also prove very expensive to fabricate (Sisodia et al., 2007). Additionally, there are other system performance-limiting parameters associated with wide field of view devices such as latency and resolution. Much of the effectiveness of simulator training is conceived to be contingent on the fidelity of these systems.

A pilot will use a learned visual scan pattern to perceive his or her environment. This scan pattern is crucial in developing and maintaining that pilot's situation awareness. Endsley (2000) defined situation awareness as the "perception of elements in VE, comprehension of their meaning, and projection of their status in near future" (p. 3), which leads to a decision and ultimately a performance of action (and see also Smith & Hancock, 1995). If we consider that situation awareness is largely dependent on the visual stimulus to provide the perception of data and the elements in the environment, then we can infer that the reduction of field of view will also have an effect on the contributing process of perception, comprehension, and projection, which in turn will affect decisions and task performance for a pilot navigating in a virtual world.

For fully immersive binocular head-mounted displays, and target search and track tasks, field of view effect experiments indicate that smaller fields of view lead to degraded task performance (Wells & Venturino, 1989) and increased head radial displacement and radial velocities (Venturino & Wells 1990). Subjective mental workload experiments also indicate that field of view is important for heading perception (Richman, Stanfield, & Dyre, 1998). A more recent Air Force experiment in a dome simulator indicates a significant head roll displacement, referred to as the opto-kinetic collic reflex, during aircraft angle of bank (i.e., turning) regardless of effective field of view (Gallimore, Brannon, & Patterson, 1998). Venturino and Wells (1990) and Gallimore et al. (1998) showed that during small angle of bank, head pitch and yaw displacement did increase with decreasing field of view due to pilot need for cockpit instrument information. Unfortunately, this was only a subjective analysis based on videotapes and the analysis of variance (ANOVA) results only showed average magnitude of the head movement and not frequency information. Additionally, eye movements were not measured and analyzed in conjunction with head movements. Venturino and Wells (1990) subjectively inferred that with smaller fields of view, there is a synergistic effect of reduced eye movements to compensate for the faster head velocity movements. To gain further insight into how a pilot will gather visual cues to develop spatial awareness, eye movement information into defined areas of interest would have needed measurement and associated analysis. Additionally, there is a need to quantify and model these field of view effects.

To evaluate this proposition, we examined the performance of experienced pilots in circumstances in which their visual field of view was systematically manipulated.

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EXPERIMENTAL METHOD

Participants

Through cooperation with a local Florida flight simulation and training facility we solicited a group of experienced Bell 206 certified instructor pilots who volunteered to participate in this experiment. A total of 7 pilots (6 male, 1 female), varying in age from 21 to 35, who each had a minimum of 300 hr in the Bell 206, were eventually included in our sample. None had any self-described sources of debilitation, which would have interfered with their presently required performance.

Equipment and Materials

A local training facility provided a Bell 206 flight simulator for this experiment. It was an Aero Simulators Flight Navigation Procedure Trainer (FNPT) II. The FNPT II has a 170° horizontal × 75° vertical wrap-around field of regard, rear-projected display. The entire helicopter simulator was housed in a self-contained 18-ft trailer classroom, complete with instructor station. All pilot volunteers were intimately familiar with the FNPT II operation and the airport visual scene used. We used an InterSense IS-1200 VisTracker for head orientation tracking and an Arrington Research ViewPoint EyeTracker® system with EyeFrame Hardware (Arrington & Geri, 2000) to monitor eye movements and fixation location. Effective field of view masks were created and custom fit to the EyeTracker goggles as shown in Figure 1.

Experimental Design

In this study, our pilots were tested in the flight simulator with varying fields of view. The development of an optimized effective field of view for a stereoscopic

FIGURE 1 Pilot wearing head and eye tracking system with mask.

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augmented reality-based display system to perform such tasks requires an understanding of field of view effects. These effects are related to the function of different visual pathways in the brain such as (a) the dorsal stream, whose function relates primarily to spatial orientation, heading control, sense of immersion, and visual-motor tasks requiring a wide field of view; and (b) the ventral stream, whose function relates more to targeting, object recognition, and visual-motor tasks requiring a narrower field of view (see Winterbottom, Patterson, & Pierce, 2006). We hypothesized that, depending on the task, limiting a pilot's effective field of view would impose an additional workload due to the limited peripheral image data. As a pilot's effective field of view is artificially reduced, measurable changes in pilot eye scan behavior would presumably change, as would head movement range (in degrees), which we hypothesized would increase, and head rate of movement (in degrees per second), which we expected to increase to compensate for the reduced peripheral visual information assimilation capacity.

A question for investigation is what level of change in natural eye and head movements are permitted in a task to allow the user to still perform according to what is considered an acceptable level. We thus postulated that a threshold exists at which decreasing the effective field of view below this threshold means a pilot can no longer compensate sufficiently to maintain an adequate image of the overall environment, thus leading to a measurable decrease in response proficiency. Somewhere between the onset of measured eye and head movement changes and the measured decrease in task performance, negative transfer becomes a concern. Such field of view effects can provide insight into an augmented reality or virtual reality head-worn display field of view design for this type of flight simulation application. To evaluate these respective propositions, a single group, within-participant repeated measures design was employed. This is a common approach when only a few high-level experts are available as participants. The primary independent variable was the pilot's effective field of view, which was varied across each consecutive test run according to a previously imposed random order. The primary dependent variables were head and eye movements and resultant flight profile changes.

Procedures

All testing was conducted during the evening hours when the commercial simulator was available. The pilot volunteers were briefed on the procedures and the functioning of the head and eye tracking system. Each volunteer was asked to read and sign an informed consent form before any experimentation began. All simulation test runs began with a pilot initialized at the base leg of a visual flight rule pattern at 600 ft and 85 kt. The pilot wore a helmet with the IS-1200 VisTracker camera and the Arrington Research ViewPoint EyeTracker system and goggles with the appropriate masking to achieve the randomly selected effective field of view.

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The pilot maneuvered to make a coordinated turn to line up with the runway, while descending to land at the runway intersection. Time to land, flight path over the ground, and descent path were recorded in each run. Each pilot completed a total of five such runs.

Random selections from a Latin Square were used to determine the sequence of test runs to address the potential problem of asymmetric transfer effects (Lowry, 2007; Poulton, 1973). Consequently, before each run, each participant was assigned to one specific sequence of effective field of view conditions. The independent variable was the pilot's effective field of view as a percentage of maximum unobstructed standard human 200º horizontal × 135º vertical field of view, which is defined here as the 100% baseline value. The five possible fields of view for testing were 160° horizontal × 108° vertical (80%), 120° horizontal × 81° vertical (60%), 80° horizontal × 54° vertical (40%), 40° horizontal × 27° vertical (20%), and 20° horizontal × 13.5° vertical (10%), where the percentage values are expressed as a function of the defined 100% maximum. Each pilot completed five test runs, taking approximately 4 min for each run, depending on his or her individual performance. This short, simulated visual landing task was preplanned to prevent pilot fatigue due to spending more than a half-hour in the simulator. Masking portions of the EyeTracker goggles restricted the effective field of view to the five respective conditions (80%, 60%, 40%, 20%, and 10%). The different horizontal and vertical effective field of view openings of the mask were calculated based on an eye-to-mask distance of 15 mm. These dimensions ranged from 170.1 mm × 41.3 mm at the maximum extent to a 5.3 mm × 3.6 mm aperture at the minimum extent.

Head and eye behavior metrics. Head and eye movement patterns were categorized based on the three factors that influence where a pilot looks: areas of interest (AOIs), effort, and importance (Wickens, Xu, Hellenberg, Carbonari, & Marsh, 2000). The pilot's AOIs are those in which they can gather visual information. For the aircraft simulator used in this experiment, this area is shown in Figure 2. The number of eye fixations, defined as dwells greater than 100 msec per AOI within a 0.5º radius from the AOI boundary (Guest & Rolland, 1999; Manor & Gordon, 2003), was the measure collected to represent dwell frequency per AOI. The 0.5º radius corresponds to half of the EyeTracker's angular accuracy. Also, how long the eye fixated in an AOI was a value measured as the mean dwell duration in an AOI (Poole, Ball, & Phillips, 2004). These eye-dwell metrics were collected to provide an indication of pilot scan pattern changes during the simulated visual approach and landing phase as the effective field of view was varied.

Inside the cockpit, certain instrument panel gauges are differentially important for communication of information during different phases of the simulated flight. As a result, all transitions to and from the instrument panel were recorded. Likewise, for the out-the-window (OTW) views, different AOIs pro-

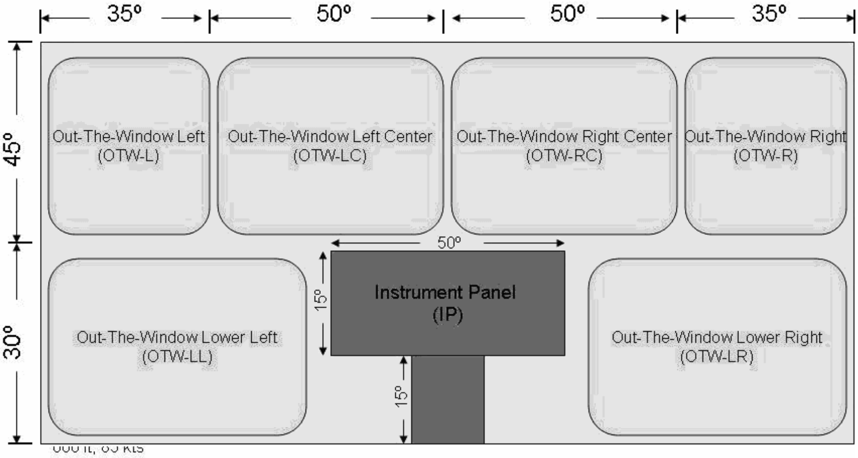

FIGURE 2 Bell 206 cockpit areas of interest (AOIs).

vided the needed information during various phases of the simulated flight. The OTW view was divided into six large AOIs, evenlyto the left and to the right of the simulator. All pilots were seated in the right seat for the simulation runs. Head movements were recorded to understand the pilot's degree of effort exerted in gathering visual data from their environment; the greater the movement range (measured in degrees), the greater the effort (Wickens et al., 2000). Pitch, roll, and yaw head movements were recorded by the head tracking system and converted to vector form and the scalar values were plotted for each pilot for each simulation run. For importance, head movement velocity (in degrees per second) were calculated and plotted for each pilot during each simulation run. Also, each pilot was videotaped to validate head tracking data collected during each simulation run. After all sequence runs for the pilot were complete, a postflight debriefing documented the overall field of view effects perceived by the pilot.

Flight performance proficiency. The FNPT II simulator only provides a recording of aircraft course over ground and vertical movement for each simulation run. This file allows subsequent performance analyses similar to the one conducted by Keller, Schnell, Lemos, Glaab, and Parrish (2003), for example, where they calculated runway alignment error (RAE) and vertical track error (VTE). RAE is the angle formed between the extended runway centerline and aircraft track as it rolls out of the turn for the straight-in approach. VTE here is represented by the maximum vertical deviation of the aircraft's actual position from the ideal path or vertical glide slope.

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RESULTS

The data extracted from the head and eye tracker measurements were based on the previously described factors that influence where a pilot looks: AOI, effort, and importance. For each simulation run, the simulator recorded aircraft course over ground and elevation. The results described here represent an analysis of these measures and tracking performance as the effective field of view was changed for each simulation run.

Dwell Frequency Per AOI

The average dwell frequency per AOI by effective field of view for all pilots is shown in Table 1. The large values indicate that pilots tend to look mainly outside left of center (OTW-LC) and also outside right of center (OTW-RC), as well as at the instrument panel for flight information, with some glances outside at far left (OTW-L), outside at far right (OTW-R), and outside at lower right (OTW-LR), when landing the aircraft. Also, as the effective field of view is decreased, the data indicate an increasing trend for a greater focus on the OTW-L and instrument panel AOIs.

These measurements are for the base course, turn, and final approach phases combined. After conducting a single-factor ANOVA *F* test with an alpha factor of .05 across the five effective field of view groups, it was discovered only the OTW-L AOI had a statistically significant change when comparing the 80% and the 10% effective field of view data points.

To analyze the field of view effect during each phase of the simulated flight, the dwell frequency per AOI data were processed separately for each phase of the simulation run. The results are reported in Table 2, which shows the average dwell fre-

TABLE 1
Average Dwell Frequency per Area of Interest

Effective Field of View	*Average Dwell Frequency per Area of Interest*						
	OTW-L[1]	*OTW-LC*	*OTW-RC*	*OTW-R*	*IP*[1]	*OTW-LL*	*OTW-LR*
10%	3.57	13.86	14.43	0.14	20.43	0.00	0.29
20%	3.00	17.57	9.14	0.29	19.71	0.00	0.14
40%	2.71	16.57	7.57	0.14	16.14	0.00	0.43
60%	1.43	18.00	8.00	0.29	15.71	0.00	0.29
80%	1.29	16.57	9.29	0.00	14.57	0.00	0.00

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

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TABLE 2
Average Dwell Frequency per Area of Interest by Phase

Base	*OTW-L*	*OTW-LC*	*OTW-RC*	*OTW-R*	*IP*[2]	*OTW-LL*	*OTW-LR*
10%	1.00	3.14	1.14	0.00	2.43	0.00	0.00
20%	1.43	4.29	0.86	0.00	2.71	0.00	0.00
40%	0.71	3.00	0.57	0.00	2.71	0.00	0.00
60%	0.43	3.00	1.43	0.00	2.43	0.00	0.00
80%	0.86	4.57	2.00	0.00	2.86	0.00	0.00
Turn	*OTW-L*[1]	*OTW-LC*	*OTW-RC*	*OTW-R*	*IP*[1]	*OTW-LL*	*OTW-LR*
10%	2.57	6.71	0.86	0.00	6.14	0.00	0.00
20%	1.57	6.43	1.14	0.00	6.71	0.00	0.00
40%	2.00	6.71	1.00	0.00	4.86	0.00	0.00
60%	1.00	4.71	1.86	0.00	4.14	0.00	0.00
80%	0.43	4.57	1.71	0.00	4.00	0.00	0.00
Approach	*OTW-L*	*OTW-LC*	*OTW-RC*[1]	*OTW-R*	*IP*	*OTW-LL*	*OTW-LR*
10%	0.00	4.00	12.43	0.14	11.86	0.00	0.29
20%	0.00	6.86	7.14	0.29	10.29	0.00	0.14
40%	0.00	6.86	6.00	0.14	8.57	0.00	0.43
60%	0.00	11.43	5.86	0.29	9.71	0.00	0.43
80%	0.00	7.43	5.57	0.00	7.71	0.00	0.00

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

quency per AOI by phase. The data indicate that for a decreasing field of view, there is a decreasing trend for the instrument panel in the base phase, then an increasing trend for OTW-L and OTW-LC and the instrument panel in the turn phase, followed by a decreasing trend for OTW-LC, and an increasing trend for OTW-RC and the instrument panel in the approach phase.

By analyzing each phase separately, changes in scan pattern as measured by dwell frequency per AOI appear to indicate increased eye movement as the pilot transitions from one phase of the simulated flight to the next. In general, when a pilot's field of view is restricted, he or she tends to make more frequent looks to the horizon in the direction of turn to gather more runway and aircraft relative orientation information, and more frequent looks at the instrument panel to gather more aircraft orientation information (e.g., altitude, airspeed, rate of descent). During the turn phase the pilot normally needs to gather more spatial orientation information to the runway and heading control information in preparation for the approach phase. When transitioning to the straight-in approach phase, pilots make more frequent looks at the horizon straight ahead of them and

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at the instrument panel as the effective field of view decreased. The only OTW decrease in mean dwell frequency was during the approach phase, when the pilot needed less OTW-LC information. Although mean dwell frequencies per AOI indicated a change in scan pattern due to a changing effective field of view, the single-factor ANOVA *F* test did not indicate a statistically significant change for any of the AOIs.

In summary, the measured mean dwell frequency changes indicate the pilot's normal scan pattern changed with the decreasing size of effective field of view. It was statistically significant in the measured overall dwell frequency changes in OTW-L. We might infer this is pilot dwell frequency compensation due to decreasing situation awareness (e.g., orientation to runway, attitude, altitude, rate of descent, airspeed).

Mean Dwell Duration

Values for mean dwell duration are shown in Table 3, which details pilot duration averages for the AOIs that registered any dwell time, listed by effective field of view. The data indicate a decreasing trend for OTW-LC and OTW-RC and an increasing trend for the instrument panel AOIs as the effective field of view is decreased. However a single-factor ANOVA *F* test did not indicate a statistically significant change for any of the AOIs.

The mean dwell duration was also processed for the base, turn, and approach phases, and results are shown in Table 4. As the effective field of view decreases, the pilot dwells more OTW-L and less OTW-LC and OTW-RC during the base phase, then dwells less for OTW-LC, but slightly more for the instrument panel during the turn phase, followed by dwelling less for OTW-RC and for OTW-LR during the approach and land phase. This mean dwell duration measurement also

TABLE 3
Mean Dwell Duration

Effective Field of View	*Mean Dwell Duration*						
	OTW-L	*OTW-LC*^{2}	*OTW-RC*^{2}	*OTW-R*	*IP*^{1}	*OTW-LL*	*OTW-LR*^{2}
10%	1.25	2.07	3.52	0.27	1.26	0.21	0.37
20%	0.98	2.23	4.14	0.16	1.12	0.00	0.76
40%	1.15	2.95	7.46	0.10	0.97	0.00	1.30
60%	1.32	3.00	7.56	0.15	0.90	0.00	1.27
80%	0.64	3.27	7.27	0.00	1.03	0.00	0.00

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

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indicates a change in scan pattern with a changing effective field of view. In general, when restricting a pilot's field of view, they tend to dwell less OTW in all phases of flight, and dwell slightly longer on their instrument panel during the turn phase. One can infer the pilots were gathering less orientation and navigation information from OTW and more from their instrument panel during the turn as their peripheral vision was reduced. Although mean dwell durations per AOI indicated a change in scan pattern due to a changing effective field of view, the single-factor ANOVA *F* test did not indicate a statistically significant change for any of the AOIs.

After analyzing the scene camera video during these phases, with a decreasing effective field of view, it appeared the pilots reverted to previously learned instrument flight rule visual scan pattern behavior in setting up for the approach phase, requiring more information from the instrument panel AOI and less from OTW. Once on the approach phase, the pilots tended to revert back to previously learned visual flight rule visual scan pattern behavior, as indicated by the significant drop in dwell time on their instrument panel.

TABLE 4
Mean Dwell Duration by Phase

Base	*OTW-L*[1]	*OTW-LC*[2]	*OTW-RC*[2]	*OTW-R*	*IP*	*OTW-LL*	*OTW-LR*
10%	0.83	0.93	0.39	0.00	1.46	0.00	0.00
20%	0.71	1.13	1.03	0.00	1.16	0.00	0.00
40%	0.50	1.42	0.28	0.00	1.18	0.00	0.00
60%	0.24	1.74	1.55	0.00	0.90	0.00	0.00
80%	0.54	1.87	2.06	0.00	1.29	0.00	0.00
Turn	*OTW-L*	*OTW-LC*[2]	*OTW-RC*	*OTW-R*	*IP*[1]	*OTW-LL*	*OTW-LR*
10%	1.16	1.61	1.02	0.00	1.57	0.00	0.00
20%	0.87	1.99	1.08	0.00	1.16	0.00	0.00
40%	1.10	1.88	1.59	0.00	0.85	0.00	0.00
60%	1.24	3.33	1.56	0.00	0.85	0.00	0.00
80%	0.33	4.06	1.54	0.00	0.88	0.00	0.00
Approach	*OTW-L*	*OTW-LC*	*OTW-RC*[2]	*OTW-R*	*IP*	*OTW-LL*	*OTW-LR*[2]
10%	0.00	3.30	4.07	0.06	1.08	0.00	0.16
20%	0.00	2.67	5.23	0.16	1.13	0.00	0.76
40%	0.00	3.69	11.14	0.10	0.93	0.00	1.30
60%	0.00	2.46	14.77	0.15	0.87	0.00	2.08
80%	0.00	3.53	19.59	0.00	0.97	0.00	0.00

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

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The product of the dwell frequency and mean dwell duration (in seconds) for each pilot and AOI, the sum for all the AOIs for an effective field of view yields an accurate total simulation run time (in seconds). This also provides a good indication of important AOIs during a particular phase of flight. For a decreasing effective field of view, the data indicate pilot decreasing focus on OTW in all phases and an increasing focus on the instrument panel during turn and landing phase. A single-factor ANOVA *F* test did indicate a statistically significant change for OTW-LC in the base phase, OTW-LC, and the instrument panel in the turn phase, and OTW-LC in the approach phase. To visualize these numerical data graphically, the values were transformed to circles superimposed on their respective areas of interest, as shown in Figure 3.

In summary, with a decreasing field of view, pilots tend to focus more on their instruments for situation awareness and less on the horizon during the turn phase. One can infer pilots revert to previously learned instrument scan patterns with more frequent checks of the horizon as their effective field of view is reduced, essentially reverting to a low-visibility instrument landing behavior. This could be because they are familiar with instrument scan patterns and feel more comfortable reverting to these scan patterns when their effective field of

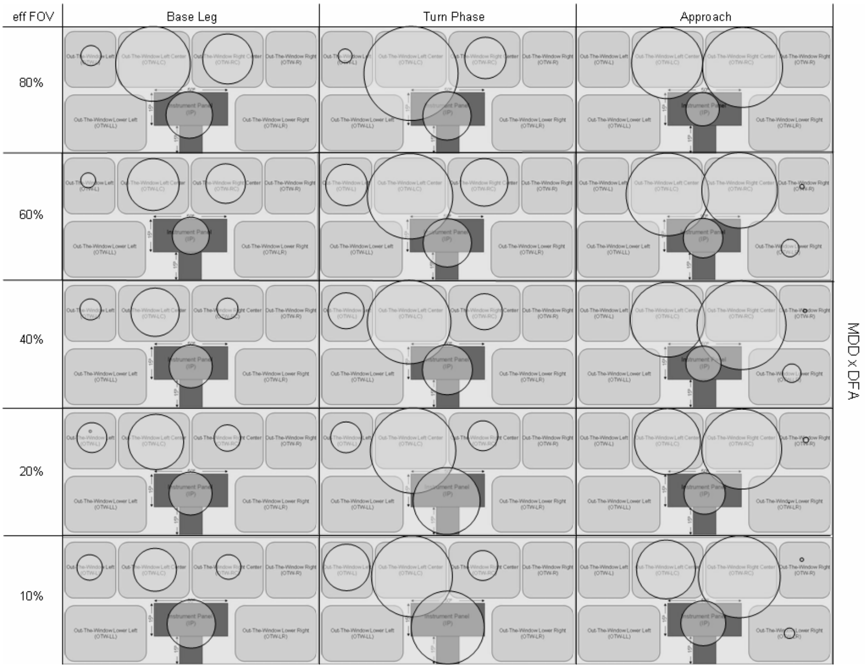

FIGURE 3 Product of average dwell frequency and mean dwell duration represented as the area in a circle for each effective field of view and area of interest.

view restricts the information normally provided by the OTW AOIs to maintain good situation awareness. This change in normal visual scan pattern behavior caused by an artificially restricted field of view is of concern in a training environment because a normal scan pattern is an important skill to learn for safe flight.

Effort Behavior

All pilots had a tendency to increase their head movement maximum range in pitch and yaw as the effective field of view was decreased. Figure 4 contains the calculated average head movement maximum range and its associated standard deviations across the effective fields of view tested for each phase of flight. The data indicate the original hypothesis of increased head movement to compensate for limited peripheral data was correct for all phases of all simulation flights. The head movement is most apparent during the turn phase. We infer that pilot effort to gather visual data tends to increase with a decreasing effective field of view in all phases of the simulation run, but it is most significant in the turn phase to gather needed environmental data. Using a trend line function, a best fit curve for the turn phase head movement maximum range was a second order polynomial ($y = 2.35x^2 - 22.384x + 66.78$). For all phases, a significant change occurs below 40% effective field of view, with the turn phase showing the greatest field of view effect. In summary, a decreasing effective field of view reveals an overall increasing trend in head range of movement, with the most significant change occurring below a 40% effective field of view, which corresponds to an 80° horizontal × 54° vertical field of view.

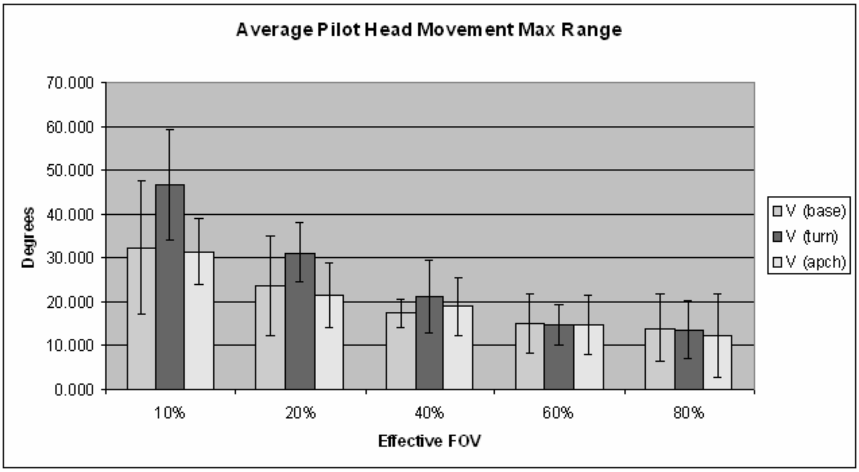

FIGURE 4 Average head movement maximum range.

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Importance Behavior

Every pilot tested had a tendency to increase his or her head movement velocity as the effective field of view was decreased. Figure 5 contains the calculated average maximum head velocity and the accompanying standard deviation by effective field of view for each phase of flight. The data indicate that the original hypothesis of increased head rates of movement to compensate for limited peripheral data was correct for all flight phases. It should be noted that 2 pilots only drove the standard deviations higher than normal for the 10% effective field of view. We infer that the pilot's need to obtain visual data tends to increase with a decreasing effective field of view in all phases of the simulation run, especially in the base and turn phase. It should be noted that all head movement patterns seemed to show the greatest increase below 20% effective field of view.

In summary, a decreasing effective field of view reveals an overall increasing trend in head rate of movement, with the most significant change occurring below 20% effective field of view, which corresponds to a 40° horizontal × 27° vertical field of view. Recall we hypothesized that a threshold exists while decreasing the effective field of view at which a pilot can no longer compensate sufficiently to maintain an adequate cognitive mental image, thus leading to a measurable decrease in task performance. From this hypothesis, one infers that participants' performance would deteriorate rapidly at a certain point as the effective field of view is decreased.

Performance

The RAE was measured for each participant's trial and the mean value was plotted. A decreasing effective field of view reveals an increasing trend in RAE, which is

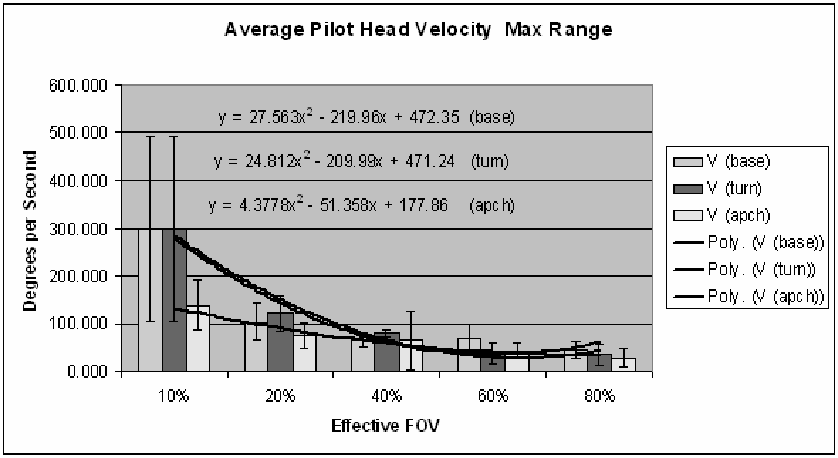

FIGURE 5 Average head velocity maximum range.

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shown in Figure 6. The increasing trend becomes significant below a 60% effective field of view that corresponds to a 120° horizontal × 81° vertical field of view. The VTE was measured for each participant's run and the participant mean was plotted. Decreasing effective field of view reveals an increasing (linear) trend in VTE.

The methodology used in this experiment was to influence the pilots' visual stimulus and situation awareness by controlling their effective field of view and then quantifying the associated pilot behavior and performance response.

Behavior Data Normalization Analysis

Because each pilot had unique measured maximum and minimum values with regard to AOI, head movement range, and head velocity range, a subsequent normalization of pilot data points was conducted to fit their values between 0 and 1; essentially, the data were converted to a percentage of the range of values for that specific pilot, prior to averaging the normalized values for all the pilots. Because each pilot had a unique measured range of data for each effective field of view, his or her normalization provides a common effective field of view scale among all pilots.

Areas of Interest Analysis

The maximum and minimum range values for each pilot in each AOI, across all effective fields of view, were normalized and averaged for the dwell frequency per

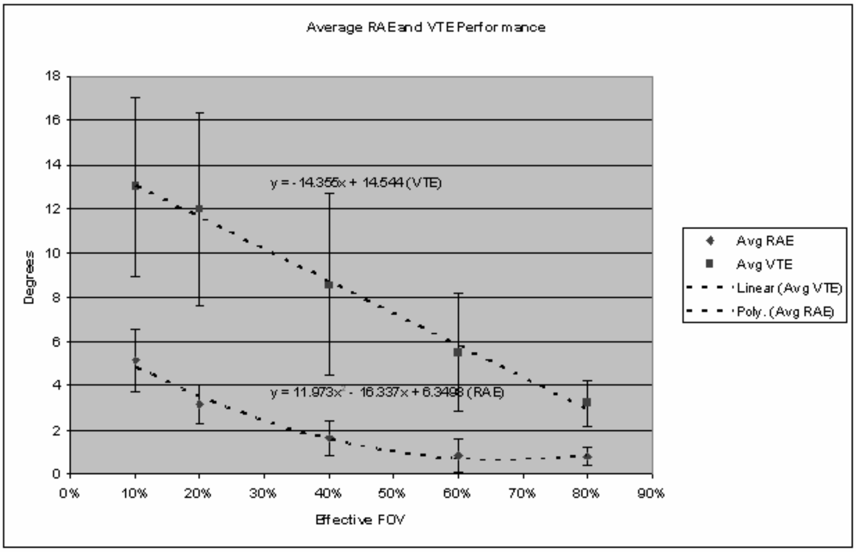

FIGURE 6 Average runway alignment error (RAE) and vertical track error (VTE).

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AOI. There was no evident trend for the base phase of flight. However for the turn phase, and decreasing effective field of view, Table 5 shows a decreasing trend for OTW-L and OTW-R with an increasing trend for the instrument panel and OTW-LC. During the approach phase, there was a decreasing trend for OTW-LC and OTW-R and an increasing trend for OTW-LR. We need to confirm here that the normalized average dwell frequency trends in Table 5 are similar to the nonnormalized average dwell frequency trends in Table 2.

For the normalized mean dwell duration data points, and decreasing effective field of view, Table 6 indicates a decreasing trend for OTW-LC in the base phase, decreasing trend for OTW-L and OTW-RC with an increasing trend for the instrument panel and out the window lower left (OTW-LL) during the turn phase, and a decreasing trend for OTW-LC and the instrument panel with an increasing trend for OTW-R for the approach and landing phase. Again, the normalized mean dwell duration trends in Table 6. are similar to the nonnormalized mean dwell duration trends in Table 4.

TABLE 5
Normalized Average Dwell Frequency by Phase

Base	*OTW-L*	*OTW-LC*	*OTW-RC*	*OTW-R*	*IP*	*OTW-LL*	*OTW-LR*
10%	0.52	0.30	0.43	0.00	0.32	0.00	0.00
20%	0.57	0.64	0.37	0.00	0.50	0.00	0.00
40%	0.26	0.24	0.18	0.00	0.43	0.00	0.00
60%	0.14	0.28	0.41	0.00	0.32	0.00	0.00
80%	0.55	0.57	0.69	0.00	0.40	0.00	0.00
Turn	*OTW-L*[2]	*OTW-LC*[1]	*OTW-RC*	*OTW-R*[2]	*IP*[1]	*OTW-LL*	*OTW-LR*
10%	0.29	0.73	0.61	0.18	0.24	0.47	0.00
20%	0.24	0.47	0.68	0.46	0.21	0.63	0.00
40%	0.59	0.53	0.77	0.29	0.04	0.44	0.00
60%	0.65	0.38	0.34	0.33	0.14	0.24	0.00
80%	0.79	0.27	0.48	0.52	0.13	0.28	0.00
Approach	*OTW-L*	*OTW-LC*[2]	*OTW-RC*	*OTW-R*[2]	*IP*	*OTW-LL*	*OTW-LR*[1]
10%	0.00	0.00	0.18	0.14	0.65	0.14	0.54
20%	0.00	0.23	0.07	0.21	0.41	0.29	0.53
40%	0.00	0.42	0.13	0.16	0.47	0.14	0.38
60%	0.00	0.80	0.21	0.29	0.49	0.29	0.36
80%	0.00	0.89	0.14	0.29	0.47	0.00	0.20

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

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TABLE 6
Normalized Average Mean Dwell Duration by Phase

Base	*OTW-L*	*OTW-LC*[2]	*OTW-RC*	*OTW-R*	*IP*	*OTW-LL*	*OTW-LR*
10%	0.60	0.16	0.25	0.00	0.64	0.00	0.00
20%	0.49	0.32	0.24	0.00	0.37	0.00	0.00
40%	0.29	0.48	0.11	0.00	0.57	0.00	0.00
60%	0.10	0.53	0.46	0.00	0.16	0.00	0.00
80%	0.38	0.72	0.51	0.00	0.60	0.00	0.00
Turn	*OTW-L*[2]	*OTW-LC*	*OTW-RC*[2]	*OTW-R*	*IP*[1]	*OTW-LL*[1]	*OTW-LR*
10%	0.18	0.51	0.20	0.25	0.20	0.62	0.00
20%	0.19	0.56	0.25	0.33	0.14	0.40	0.00
40%	0.48	0.54	0.41	0.22	0.01	0.09	0.00
60%	0.65	0.33	0.51	0.32	0.16	0.09	0.00
80%	0.76	0.39	0.54	0.36	0.11	0.26	0.00
Approach	*OTW-L*	*OTW-LC*[2]	*OTW-RC*	*OTW-R*[1]	*IP*[2]	*OTW-LL*	*OTW-LR*
10%	0.00	0.14	0.29	0.36	0.33	0.09	0.42
20%	0.00	0.20	0.11	0.29	0.49	0.22	0.61
40%	0.00	0.52	0.13	0.27	0.60	0.14	0.39
60%	0.00	0.62	0.05	0.13	0.62	0.29	0.32
80%	0.00	0.90	0.10	0.35	0.57	0.00	0.36

Note. For decreasing effective field of view, 1 indicates an increasing trend. For decreasing effective field of view, 2 indicates a decreasing trend. OTW-L = out the window left; OTW-LC = out the window left of center; OTW-RC = out the window right of center; OTW-R = out the window right; IP = instrument panel; OTW-LL = out the window lower left; OTW-LR = out the window lower right.

Normalized Head Movement Analysis

The maximum and minimum range values for each pilot in each phase and across all effective fields of view were normalized and averaged to obtain Figure 7. From normalization, Figure 7 clearly shows a similar trend as the nonnormalized Figure 4, with a decrease in standard deviation in the turn phase data at 10% effective field of view. Figure 7 shows a statistically significant trend for head movement in the turn phase, modeled by a second order polynomial.

Normalized Head Movement Analysis

The maximum and minimum range values for each pilot in each phase and across all effective fields of view were normalized and averaged to obtain Figure 8. The graph indicates a statistically significant trend for head velocity range in the base and turn phase, modeled by two similar second order polynomials.

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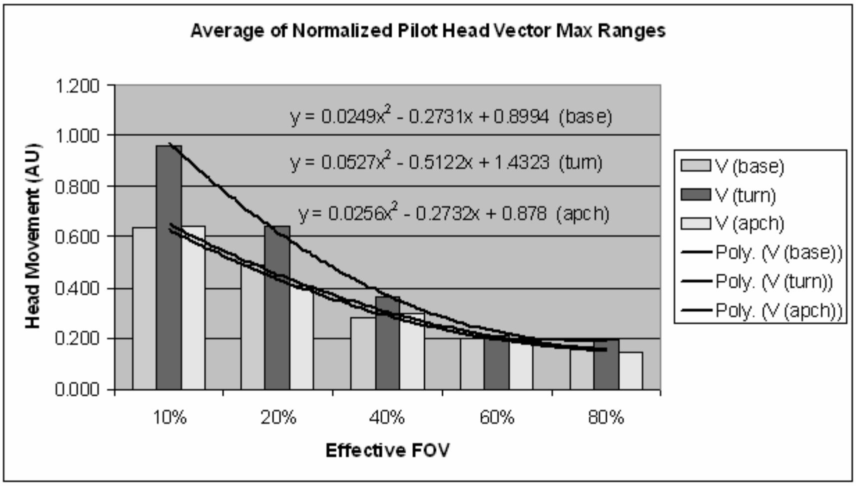

FIGURE 7 Average normalized head movement maximum range.

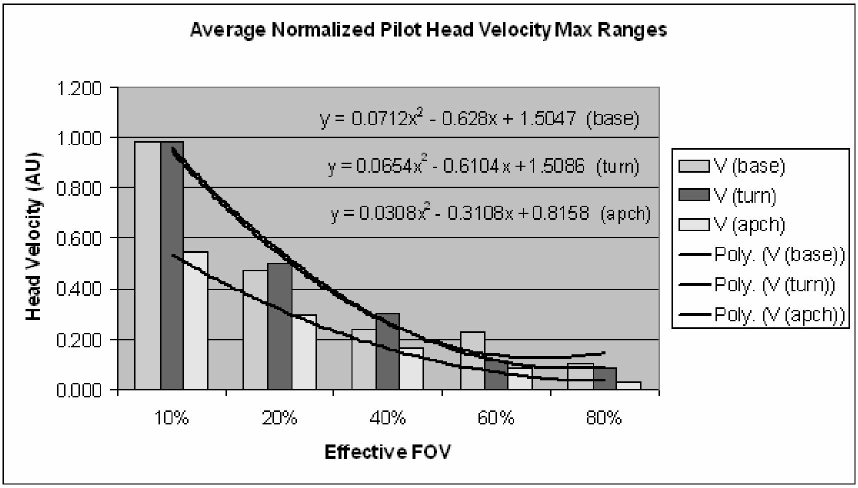

FIGURE 8 Average normalized head velocity maximum range.

Regression Analyses

A simple regression analysis using Microsoft Excel curve fit functions reveals a relation between the pilot head movement behavior and performance with respect to the effective field of view. Using the average of the 7 participants tested, the re-

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gression equation for the dependent variable effort (head movement range in degrees) is a second order polynomial function. In Table 7 we list the polynomial coefficients, which varied depending on the base, turn, or approach phase of flight. Similarly, the regression equation for pilot importance is a second order polynomial function where the dependent variable is head velocity range (in degrees per second) of movement. Table 8 lists the polynomial coefficients, which varied depending on the base, turn, or approach phase of flight.

The regression equation for pilot performance in runway alignment is a power decay/growth function ($k = –0.8822$, $y0 = 0.7154$). This model predicts that a reasonably skilled pilot with unrestricted field of view will have a normal RAE of slightly less than 1°. VTE follows a linear function (slope = –14.355, y intercept = 14.544, x intercept = 0.19). This model predicts that a reasonably skilled pilot with unrestricted field of view will have a normal VTE of ~ 0.2° from a normal glide slope.

DISCUSSION

Overall performance results indicate that pilots will significantly alter their normal visual scan pattern (see Tables 1–7), along with a significant head movement pattern change below 40% effective field of view, which corresponds to 80° horizontal × 54° vertical. Results are based on pilot AOI, effort, and importance behav-

TABLE 7
Effort Behavior Regression Analysis

	a	*b*	*c*
Base	2.35	–22.38	66.78
Turn	1.35	–12.65	43.58
Approach	0.94	–10.13	39.80

Note. y = max head movement range scalar; x = effective field of view; a, b, and c are second order polynomial coefficients.

TABLE 8
Importance Behavior Regression Analysis

	a	*b*	*c*
Base	27.56	–219.96	472.35
Turn	24.81	–209.99	471.24
Approach	4.38	–51.36	177.86

Note. y = max head movement range scalar; x = effective field of view; a, b, and c are second order polynomial coefficients.

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ioral change responses measured while varying the pilot's effective field of view. An important behavior change to consider is the measured AOI behavioral change results. During the course of pilot training, a pilot develops a normal scan pattern for either visual meteorological conditions or instrumented flight. For instrumented flight, the pilot does not normally use the OTW AOIs. The AOI behavioral change results indicate that the limited effective field of view forced an unnatural scan pattern behavior for simulated visual conditions, which is counterproductive in a training environment.

Based on measured pilot RAE and VTE, performance results indicate that pilot basic task performance decreases significantly as the effective field of view is decreased. This supports our original hypothesis. The RAE became relatively large at less than 40% effective field of view. However the VTE linearly increased as the effective field of view was decreased. As a pilot's field of view was constrained, it appears that the primary focus of the pilot was to ensure they were lined up properly after their turn phase, and a steady rate of descent was a secondary concern. By limiting the pilot effective field of view, additional workload and stress were also assumed to increase for the pilot, measured by AOI, effort, and importance behavioral changes. As the effective field of view was decreased, head movement range (in degrees) and head rate of movement (in degrees per second) increased to compensate for the reduced peripheral visual data. However, eye movement velocities did not indicate a significant change; only pilot scan pattern changes were significant.

It was also demonstrated, while decreasing the effective field of view, that pilots had a noticeable threshold where they could no longer compensate sufficiently to maintain an adequate cognitive mental image due to a decreased amount of OTW visual information.

Our cooperating organization was very gracious in providing access to flight simulation facilities, the FNPT II. No charge was made to conduct these experiments. It is important to reiterate that the simulator was inherently restricted to a 170° horizontal × 75° vertical field of regard, which prevented a true 100% effective field of view condition. This limitation justifies why the only effective field of view conditions used were 80%, 60%, 40%, 20%, and 10%. It would be most helpful to repeat this procedure using a full field of regard simulator, or even more beneficially, during an actual flight. The field of view masking process was actually similar to instrument flight rules check flight procedures where student pilots wear a mask that allows them to see only the instrument panel during navigation and approach, while the instructor pilot observes and can take over the controls during flight for safety. One limitation on this work was testing time. Although the pilots graciously volunteered, again free of any charge, it was only possible to test during time off from their regular schedule. Therefore, the five simulation runs had to be brief, which limited the pilots' time in the simulator. Although the basic landing task using a familiar airport visual landing pattern collected valuable field of view

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effect data, further work is clearly needed on important performance tasks such as navigation, where previous experiments have indicated that a wide field of view is required. For this experiment design, a low-level navigation task over land could be an important candidate scenario.

Application

The results from this experiment can be used in developing models to predict user behavior and performance when designing, implementing, and evaluating head-worn displays of a given effective field of view for training applications and also operational situation awareness. For example, new night vision goggle prototype designs need to consider the significant behavior and performance degradation effects with fields of view less than 80° horizontal × 54° vertical prior to development and validation against similar operational tasks. Additionally, the process and methods used in this experiment can be used in evaluation of head-worn displays or optical devices for different and more complex tasks. Additional behavior and performance model development is needed with a larger sample of experienced pilots for a wider range of tasks.

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