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PERIPHERALLY-LOCATED VIRTUAL INSTRUMENT LANDING DISPLAYS

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We examined how the location and spatial extent of a peripherally-located virtual instrument landing system (ILS) head-up display (HUD) affects landing precision. Our experiment compared three spatial formats of a peripherally-located virtual ILS HUD: a) a *large-format display* located within rectangular regions defined relative to the center of the HUD, with the lateral flight indicator subtending +/-5 to 62.5° by +/-0 to 16.875° (HxV) and the vertical flight command indicator subtending +/-0 to 45° by +/-6.875 to 16.875° (HxV); b) *near-peripheral displays* comprised of roughly the inner half of the large format display; and c) *far-peripheral displays*, comprised of the remaining outer half. We found that restricting display locations and extents to either the near or far periphery provided landing precision statistically equivalent to the large-format displays, which suggests that HUD clutter could be reduced by moving virtual ILS displays into the far periphery without negatively impacting landing precision.

Non-alphanumeric displays incorporating more naturalistic and less symbolic representations of actual flight parameters—known as *virtual displays*—can enhance aircraft pilots' spatial orientation, increase overall performance, and reduce workload (Hettinger, Brickman, Roe, Nelson, & Haas, 1996). Bulkley, Dyre, Lew, & Caufield (2009) showed experimentally that an instrument landing system (ILS) using a peripherally-located head-up display (HUD) with virtual symbology composed of moving arrows has the potential to provide superior landing precision as compared to the military standard ILS symbology (MIL-STD-1787B) presented in its normal central location within the HUD. One unresolved question is whether the peripheral location and spatial extent of the ILS HUD developed by Bulkley et al. (2009) modulates participants' ability to use the display to minimize vertical and lateral errors during simulated instrument landing approaches. This question is particularly important for addressing issues of display clutter (Kaber, Alexander, Stelzer, Kim, Kaufmann, & Hsiang, 2008). Moving the virtual ILS symbology to smaller spatial extents within the far peripheral regions of a HUD makes it less likely to visually obscure other important flight information within the HUD or the visibility of environmental obstacles viewed directly through the windscreen or canopy. Our purpose here was to examine the effects of the location and spatial extent of the virtual ILS on the landing performance.

Even under the best circumstances, pilot fatigue and workload are highest during landing (Hart & Hauser, 1987). Final approach and landing phases of flight account for a disproportionately high number of accidents, particularly at night, despite instruments such as the ILS that are specifically designed to provide accurate information regarding deviations from the optimal approach path (Boeing, 2002; Khatwa, Collins, & Helreich, 1998; Ashford, 1998). To land safely, pilots must infer their position and movement by integrating the optical flow and horizon seen through the windscreen with symbolic representations of altitude, pitch, heading, and airspeed read from instruments, while simultaneously avoiding other aircraft and ground obstacles and verbally communicating with air traffic control. These activities place a high demand on focal visual and central processing resources (Wickens, 1991), which may be limited by fatigue. Indeed, Roscoe (1980) estimated that 90% of aircraft control is performed using the central visual field: 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.

However, a virtual display could present landing information to pilots without taxing overburdened central visual field and attentional resources by taking advantage of automatized orienting and motion coding processes that are particularly robust in peripheral vision. In the context of simulated flight, Cox (2000) showed that a virtual speed error indicator composed of moving fields of arrows projected to the visual periphery provided better flight path and airspeed control than a head-up display (HUD) speed indicator defined by MIL-STD-1787B, while simultaneously lowering subjective workload. In a follow-up study that measured eye and head movements, Schaudt, Caufield, and Dyre (2002) further showed that participants spent the greatest amount of time looking directly at the traditional MIL-STD HUD airspeed indicator during the simulation and that they rarely, if ever,

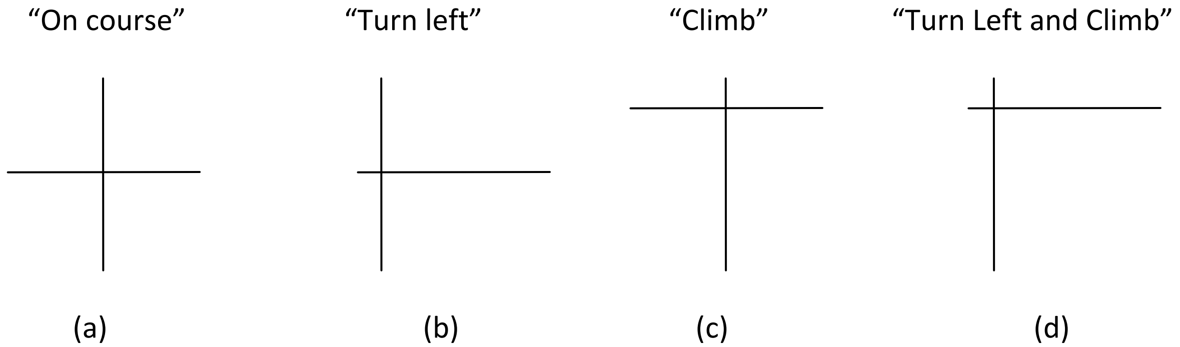

Figure 1. Format of MIL-STD 1387B HUD ILS command bars. The four panels show display configurations representing: (a) zero lateral and vertical error, on course, no control correction needed, (b) rightward lateral error, the aircraft needs to turn left to reestablish the optimal approach path, (c) downward vertical error, the aircraft needs to climb to reestablish the optimal approach path, and (d) both downward and rightward errors, the aircraft needs to turn left and climb to reestablish the optimal approach path.

looked directly at the peripheral virtual speed error indicator. These studies clearly demonstrated that the peripheral visual field can process the optical flow created by moving display elements and extract meaningful speed information with less attentional demand and central visual field resources than traditional symbolic displays.

More recently, Bulkley et al. (2009) found that a similar peripherally-located virtual display could be adapted to replace the flight command bars of a traditional ILS display, which are typically presented in the center of the HUD (as defined by MIL-STD 1787B). The ILS command bars instruct pilots to the direction the aircraft needs to be moved to attain proper lateral and vertical alignment with the optimal approach path during landing. The display contains a horizontally-oriented bar that moves up and down to indicate vertical angular errors from the ideal glide slope, and a vertically-oriented bar that moves left-to-right to indicate lateral angular errors from the ideal approach path (see Figure 1). When the bars form a symmetrical cross "+" the aircraft is optimally aligned with the ideal approach path. Movements of the bars from the "+" configuration indicate that control inputs are needed to regain the optimal path, and serve as command displays for how the pilot must maneuver the aircraft. In essence, pilots "chase the bars." When the vertical bar is left of the center, the pilot banks left to correct a rightward lateral error. When the horizontal bar is above the center, the pilot climbs to correct a downward glide slope error, and so on. Bulkey et al. (2009) adapted the peripherally-located virtual HUD format developed for representing airspeed by Cox (2000; see also Schaudt et al., 2002) to an ILS display by simply replacing the centrally-located flight command bars with fields of moving arrows located in the visual periphery (See Figure 2). When the arrows appear in the left visual field, the pilot responds by banking left to correct a rightward lateral error. When the arrows appear in the upper visual field, the pilot climbs to correct a downward glide slope error, and so on. The magnitude of lateral and vertical errors is redundantly coded by the speed of the moving arrows and their size, which both increase as errors increase up to a maximum limit. Importantly, size changes occur in discrete steps, creating transient events that can alert a pilot to increasing errors *pre-attentively* (Egeth & Yantis, 1997), even when the displays are presented in the visual periphery. Also, to help reduce display clutter, the arrows disappear completely when errors fall below a minimum threshold.

Indeed, the primary design goals of the virtual ILS were to reduce central visual field load, attentional demand, and display clutter within the HUD while still providing enhanced precision in maintaining glide path. Bulkley et al. (2009) demonstrated that a large-format virtual ILS can afford greater glide path precision than a traditional display, and other experiments underway in our laboratory are assessing whether central visual field load and attentional demand are reduced by such displays in a manner similar to that found for the virtual speed display examined by Cox (2000) and Schaudt et al. (2002). The focus of the research presented here was to evaluate different locations and spatial configurations of the virtual ILS display to examine whether display clutter can be reduced without negatively impacting landing performance. We report one experiment that examines three potential display configurations (see Figure 2): a) a *large-format display* identical to that tested by Bulkley et al. (2009), b) *near-peripheral displays* comprised of roughly the inner half of the large format display, and c) *far-peripheral displays*, comprised of the remaining outer half. Table 1 lists the specific spatial extents for each display configuration. These displays qualitatively varied central visual field load and display clutter as follows. Central visual field load and clutter was highest for the near-peripheral display because all display elements were presented within the

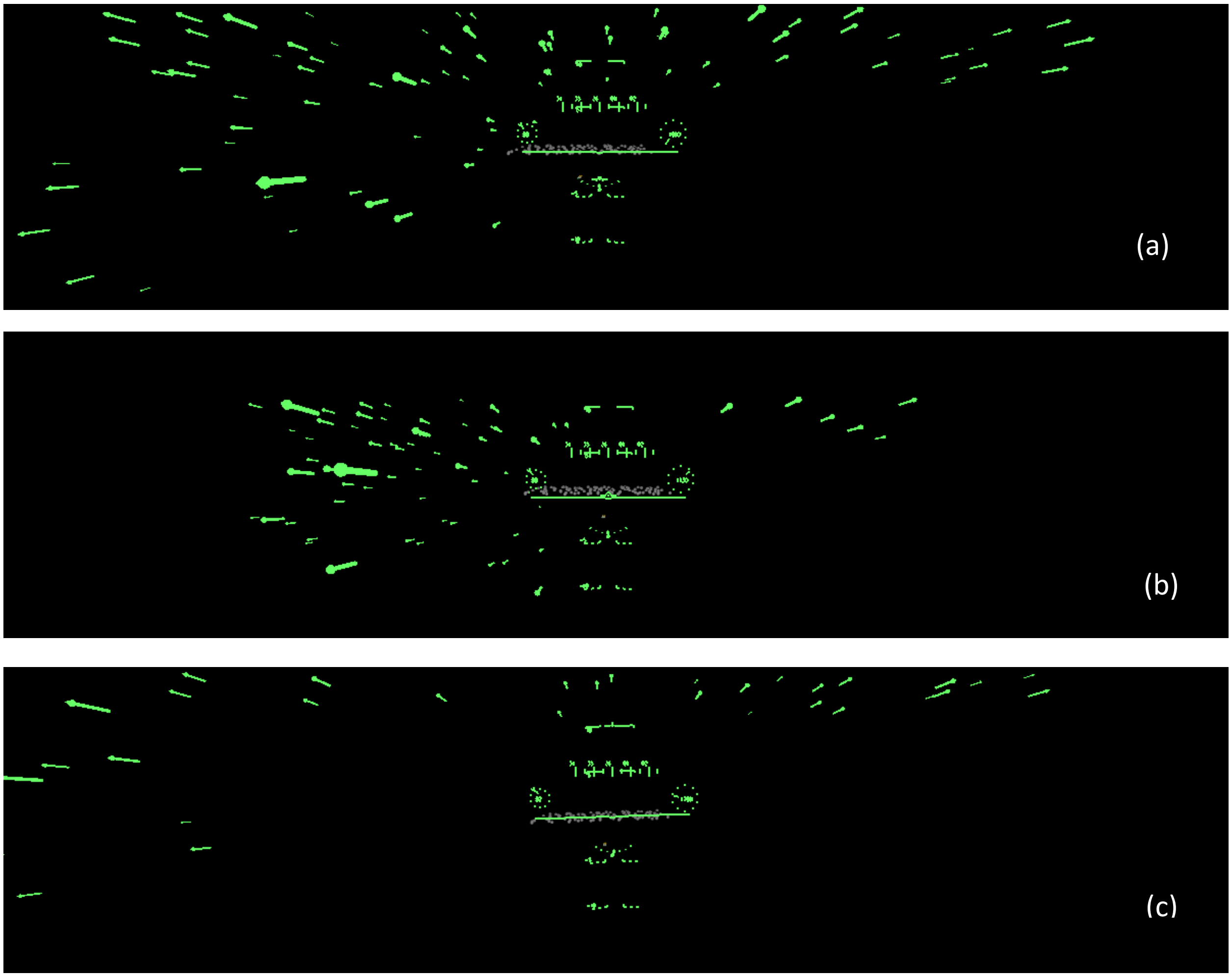

Figure 2. Screen shots of three spatial configurations of the virtual ILS HUD: (a) the large-format display equivalent to that developed by Bulkley et al. (2009), (b) the near-peripheral display, and (c) the far-peripheral display. All three panels represent both downward and rightward errors, the aircraft needs to turn left and climb to reestablish the optimal approach path.

relatively small areas surrounding the traditional HUD symbology. The large-format display represented intermediate central visual field load and clutter because the display elements were spread out into the periphery. The far-peripheral display represented the least central visual field load and display clutter because the virtual symbology was limited to areas of the visual field furthest from the traditional HUD symbology.

Method

Participants

The experiment tested 12 volunteer participants from the undergraduate, graduate and faculty population of the University of Idaho. Undergraduate participants were compensated with course credit. Participants reported normal or corrected-to-normal acuity and no previous aviation piloting experience. Bulkley et al. (2009) showed that non-pilots using simplified flight controls fly similar flight paths to those flown by pilots for simulated visual approaches under “blackhole” conditions (Gibb, Schvaneveldt, & Gray, 2008), which suggests that pilots and non-pilots are able to perceive their dynamic spatial orientation relative to the runway in a similar manner. Hence, we believe that our sample of non-pilots validly represents the same visual processes that pilots use to control their aircraft during landing.

Stimuli and Apparatus

Visual displays simulating flight were created by a set of four personal computers running ViEWER v2.23 (Dyre, Grimes, & Lew, 2009). One computer served as the simulation host, which coordinated the activity of three graphics computers over a local area network. Each graphics computer rendered to one of three display projectors, which front-projected images with a spatial resolution of 1024 x 768 pixels (H x V) at a refresh rate of 60 Hz onto three large screens arranged as three sides of an octagon with the design viewpoint at the center of the partial-octagon, 1.8 m from the center of each screen. Together, the three screens subtended 135 x 33.75 degrees of visual angle (H x V).

The simulated environment consisted of a large island extending 288,000 m in width (x) and 72,000 m in depth (z). A 30m wide runway started at the center of this island [x, y, z] = [0, 0, 0] and extended 950 m in depth [0, 0, -950]. Green, white, and red lights were spaced every 50m along the sides of the runway in a standard runway lighting configuration. The runway was texture-mapped with a pavement texture and the surrounding ground surface was texture-mapped with a high spatial frequency seamless texture resembling dirt and grass. At the far end of the runway the ground began to slant upward at 5 degrees for 18,000m before leveling off at a maximum elevation of 1600 m. To simulate the lights of a small city lying beyond the runway, white dots were randomly dispersed on this slanted area covering an area of 4000 x 8000 meters (width x depth) starting at 650m past the end of the runway and centered on the runway. Simulated ambient lighting was equivalent to an overcast, moonless night such that only the runway marker lights and city lights were clearly visible. Mild haze modeled as exponential fog was added to the displays to provide a sense of distance through aerial perspective. This haze did not affect the visibility of the runway or city lights.

The simulated view from the vehicle was open, no windscreen frame or other artifacts were used to create a simulated cockpit. The vehicle started 9889m short of the runway at an altitude of 720m, aligned laterally with the center of the runway and moving forward on a level trajectory at 45 ms^{-1}. The target glide-slope angle of 7.3 degrees was defined via two invisible waypoints. The first was located at the vehicle starting point [0, 720, 9889], and the second was centered on the runway, 2m from its near end [0, 0, -2].

Simulated lateral and vertical wind disturbances were produced by translating the vehicle along the lateral (x) and vertical (y) axes independently. Each disturbance was defined by a sum-of-sines with five prime frequencies. Amplitudes were chosen such that the maximum acceleration did not exceed 1 G (9.8 ms^{-2}). The disturbance frequencies for the x- and y-axes were 0.055, 0.085, 0.145, 0.185, 0.215, and 0.035, 0.065, 0.115, 0.155, 0.205 Hz, respectively; amplitudes were 10.47, 2.34, 1.37, 1.08, 0.93 and 25.85, 7.49, 2.39, 1.32, 0.75 m, respectively.

Since participants were non-pilots, simplified flight controls were used to control the lateral and vertical positions of the simulated aircraft. Left-right movements of a CF-F-16 joystick with the right hand controlled lateral velocity with a transfer function defined by first-order with gain = 25 ms^{-1} at maximum stick deflection and exponential lag constant = 1.0 s^{-1}. For simulation of banking while moving laterally, left-right stick movements also produced a zero-order roll with a gain = 15° at maximum deflection and exponential lag constant = 0.5 s^{-1}. Movements of a CF Pro Throttle configured as a first-order controller with gain = 25 ms^{-1} and exponential lag constant = 1.0 s^{-1} with the left hand controlled vertical velocity. Forward movement of the throttle caused the vehicle to go up (simulating more thrust), backward movements caused the vehicle to go down (less thrust).

Similar to Bulkley et al (2009), monochromatic green HUDs were superimposed over the terrain and environmental objects on the display and. included the following indicators from MIL-STD-1787B: aircraft pitch reference symbol, climb/dive marker, climb/dive ladder, airspeed indicator, target airspeed indicator, altitude indicator, heading indicator, and bank indicator. The ILS was implemented within the HUD as a peripherally-located virtual display of fields of moving arrows, which replaced the MIL-STD flight command bars. Fields of moving arrows randomly arranged within a volume of space appeared in the upper, lower, left or right peripheral areas of the HUD to provide control commands to overcome lateral and vertical deviations from the optimal flight path (see Figure 2). Similar to the MIL-STD ILS, the virtual ILS used a command format that informed pilots which direction to move to correct their course—in effect participants needed to “chase the arrows” to maneuver toward the optimal glide path. The arrows coded lateral and vertical deviation error magnitudes redundantly using both speed of movement and size. Zero course error resulted in zero speed and size--nothing was displayed. Small course errors resulted in small arrows moving slowly. As course errors increased, the speed of the arrows would increase proportionately, and the size of the arrows would increase in step-wise increments to produce sudden size-changes that naturally captured attention. The location and spatial extent of the fields of moving arrows varied across three conditions as listed in Table 1.

Table 1
Spatial Extents of Virtual ILS HUDs

	Horizontal Extent	Vertical Extent
Large-format		
Lateral Command	+/- 5.0 to 67.5	+/- 0.000 to 16.875
Vertical Command	+/- 0.0 to 45.0	+/- 6.875 to 16.875
Near-Peripheral		
Lateral Command	+/- 5.0 to 36.25	+/- 0.000 to 11.875
Vertical Command	+/- 0.0 to 36.25	+/- 6.875 to 11.875
Far-Peripheral		
Lateral Command	+/- 36.25 to 67.5	+/- 0.000 to 16.875
Vertical Command	+/- 0.0 to 45.0	+/- 11.875 to 16.875

Note. All units in degrees of visual angle from the HUD center

Table 2
Altitude Errors by Condition

Display	Mean Error (m)
Large-format	-1.62 (0.85)
Near-Peripheral	-0.39 (0.85)
Far-Peripheral	-0.65 (0.85)

Display	SD Error (m)
Large-format	13.40 (0.76)
Near-Peripheral	13.00 (0.76)
Far-Peripheral	12.29 (0.76)

Display	RMS Error (m)
Large-format	15.06 (0.84)
Near-Peripheral	14.57 (0.84)
Far-Peripheral	14.03 (0.84)

Note. Numbers in parentheses represent within-subject standard errors of the mean for the comparison of display configurations.

Experimental Design and Procedure

A 3 x5 within subject factorial design tested the effects of HUD format (large-format, near-peripheral, and far-peripheral) and block (1-5). The order of HUD formats was randomized within each block. Each non-crashing trial lasted approximately 3 minutes and 40 seconds and participants were able to complete all 15 trials, plus instructions and debriefing within a single 90 minute session.

The experimental session proceeded as follows. After obtaining informed consent, participants were instructed to land the plane along a linear glide slope connecting their starting position to the end of the runway. They received 2 training trials to learn how to land the simulated aircraft. First, to familiarize participants with the display of the ground and runway and to show them how the controls moved the vehicle laterally and vertically the experimenter demonstrated a visual approach, with environmental lighting turned on to reveal the terrain and runway and ILS indicators turned off. Participants then completed one practice visual approach using the same visual conditions, during which the experimenter provided additional instruction only if extreme deviations from the optimal approach path where observed. Following these training trials, participants were instructed that the experimental trials would simulate night landing using virtual indicators that would appear to help direct them to the optimal approach path and that these indicators would be made up of moving arrows in the display. In addition, they were informed that crashes were possible and to not be alarmed if they were to crash. If participants impacted the ground at any time the trial ended. After the experimental trials, participants were debriefed and informed of the purpose of the experiment.

Results

Altitude errors were defined as the difference between actual altitude and the target altitude defined by the linear glide slope at a particular point along the approach. Lateral errors were defined as the difference in position of the simulated aircraft relative to the runway centerline. Mean errors in altitude and lateral position computed over the entire trial duration represented constant error, or accuracy of control. Standard Deviations (SD) of altitude and lateral position errors computed over the entire trial duration represented variable error, or precision of control. Root-mean-squared (RMS) errors represented overall error.

All types of lateral and altitude errors were analyzed using 3x5 within-subjects analysis of variance (ANOVA) with display configuration (large-format, near-periphery, and far-periphery) and block (1-5) as the two variables. For altitude errors, no reliable differences were found between display configurations or blocks for mean, SD, or RMS errors ($p > .05$, see Table 2). These results show that all three display configurations afforded statistically equivalent control over glide slope—there was no reliable performance cost to moving the virtual display into the far periphery, indeed the non-significant trend was toward better performance with the more peripherally-located display. A similar lack of effect for display configuration was found for lateral errors. Overall, error magnitudes were quite similar to those found by Bulkley et al. (2009) for the virtual ILS display.

Discussion

While considerable caution is needed whenever interpreting a null result, we believe that the null effect found in the present study when considered together with the results of Bulkley et al. (2009) can be taken as evidence that the three virtual display configurations afforded equivalent perception and control of glidepath. The experimental measures used in this study were identical in all respects to those used by Bulkley and his colleagues who found a statistically reliable advantage for the same large-format virtual ILS examined here as compared to the MIL-STD 1387B ILS in its traditional central field location. This demonstrates that the error measures are reliable enough to detect differences in performance when they exist and that it is unlikely that our null result was due to unreliable measures of error. This point is further underscored by the fact that the present study tested a larger sample of participants than Bulkley et al. (2009) and thus had potentially greater statistical power for detecting reliable differences between the display conditions.

These results have important implications for the design of HUDs. Clearly, the peripheral visual field—even the far periphery—is 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 ILS control of landing approaches. Peripheral virtual displays of ILS commands appear to provide pilots with information in a more natural, pre-attentive manner that has the potential to lessen attentional demand, central visual field load, and display clutter, while still affording performance that is equal to or better than traditional ILS displays. Further research is needed to assess these claims, particularly with pilots as participants to see if this potential can be realized.

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