Foyle, D.C., Kaiser, M.K. and Johnson, W.W. (1992). Visual Cues in Low-level Flight: Implications for Pilotage, Training, Simulation, and Enhanced/Synthetic Vision Systems, American Helicopter Society 48th Annual Forum, Vol. 1, 253-260.

Visual Cues in Low-level Flight: Implications for Pilotage, Training, Simulation, and Enhanced/Synthetic Vision Systems

David C. Foyle Research Psychologist
Mary K. Kaiser Principal Scientist
Walter W. Johnson Research Psychologist

Rotorcraft Human Factors Research Branch
NASA Ames Research Center
Moffett Field, California

ABSTRACT

This paper reviews some of the sources of visual information that are available in the out-the-window scene and describes how these visual cues are important for routine pilotage and training, as well as the development of simulator visual systems and enhanced or synthetic vision systems for aircraft cockpits. It is shown how these visual cues may change or disappear under environmental or sensor conditions, and how the visual scene can be augmented by advanced displays to capitalize on the pilot's excellent ability to extract visual information from the visual scene.

INTRODUCTION

During low-level flight, the visual transformations of the out-the-window scene yield an abundance of information. These transformations are determined entirely by the physical geometry of the objects in the world through which the pilot and the aircraft are transversing. Examples of the information available from these visual transformations include ground speed, altitude, ground slant angle, and distance.

IMPLICATIONS OF VISUAL CUE RESEARCH

Determining the visual "out-the-window" cues that pilots actually use, and the limitations associated with the use of those cues has implications for current applications (e.g., normal pilotage, training and simulator research) and for the development of advanced systems (e.g., enhanced or synthetic vision systems).

Normal Pilotage

Visual "out-the-window" cues are used to control and maintain craft state during normal "eyes out" flight by experienced pilots. Even though the reliability of different visual cues varies, pilots often rely on cues that are highly salient, but of low reliability, leading to flight performance errors. For example, Johnson and Phatak (Ref. 1) examined performance in a pseudo-hover task and found that pilots attempted to maintain altitude by holding a ground location at a fixed optical location; a strategy that led to inappropriate altitude corrections in response to fore/aft vehicle movements.

Training Implications

Visual cues may not necessarily be intuitive and immediately apprehended. Instead, they require training to use, and, even more importantly from a safety view, may be used incorrectly in the early stages of training. Pilots tend to "latch on" to the most salient cues for a given task, although these cues are misleading or not optimal. For example, the visual shape of the runway is a salient visual cue often used to estimate and maintain glideslope. Consequently if novice pilots have learned to land at normal-width, small-airport runways, it is common for them to make excessively steep approaches when landing at a large airport with a wider runway. To perform well, pilots must learn to use different visual cues, or use them in a different manner, as the circumstances change.

Simulator Displays

Some of the visual cues in aircraft simulators are not identical to those in actual flight. Consider the case when the pilot approaches texture-mapped terrain. In the physical world, "micro-texture" emerges in a continuous fashion (increasingly smaller objects become visible) as one approaches an object. For example, gross texture, such as the helipad and markings, is first visible upon landing; then increased detail, such as large cracks in the helipad material can be seen; finally, very small cracks and debris are seen. In simulators, however, this increase in micro-texture emergence is rarely simulated (and even then in one or two discrete steps), Accordingly, as pilots approach the texture-mapped ground in the simulator, the texture detail and density decrease and blurs. This is in contrast to the physical world, where blurring occurs as altitude <u>increases</u>. Clearly, the impact of this simulator limitation on pilots' performance depends on his understanding of the importance of the use of that visual cue. When possible, important visual cues should be maintained in the simulator environment to allow positive transfer to actual flight (if used for training) and for validation (if used for research and design).

Enhanced/Synthetic Vision Systems

Enhanced or synthetic vision is the term used to describe those advanced technology systems that will present or augment out-the-window information. Near-term designs (i.e., enhanced vision systems) propose presenting sensor imagery with superimposed flight symbology on a head-up display (HUD), and may include such things as runway outlines and other display augmentations (e.g., obstacles, taxiways, flight corridors). Longer-term designs (i.e., synthetic vision systems) may include complete replacement of the out-the-window scene with a combination of sensor imagery and database information (as proposed in one version of the High-Speed Civil Transport, HSCT). In these systems, the pilot would control the aircraft based on a <u>representation</u> of the world displayed in the cockpit, and may not see the actual out-the-window visual scene. Such systems present visual information that is needed but would not otherwise be visible (e.g., increased runway visibility in poor weather). Also likely, however, is that some visual information will be lost, due to such limitations as resolution, field of view, or spectral sensitivities. Clearly, the most important and salient visual cues for pilotage must be maintained veridically in the display.

This paper will review the results of several studies focused on the ways in which pilots extract information from the out-the-window visual transformations for flight, with special emphasis on low-level flight. Research will be reviewed that addresses: (1) the visual cues used under normal, optimal visual flight conditions; (2) the visual cues available and their usage under such degraded conditions as night flight, weather, or sensor usage; and, finally, (3) the enhancement of visual cues through advanced technology.

VISUAL CUES UNDER NORMAL FLIGHT CONDITIONS

Under normal, high-visibility daytime flight conditions there are many out-the-window visual cues that pilots use to control the aircraft. Some of the visual cues available to guide altitude, heading, and ground speed control are texture density (i.e., the visual angle compression of objects and distances near the horizon) and the shape and rate of the visual flow field (i.e., the relative movement of ground objects). Visible texture density, and its changes, have been proposed as a cue for altitude awareness, with increasing density associated with higher perceived altitudes. The dynamic optical changes (sometimes called optic flow) present during flight also hold information useful for flight control. For example, the track vector of a vehicle creates a visual outflow, or expansion, centered in the direction of movement. Also, changes in terrain object density, and vehicle speed and/or altitude, modify the average angular speed and frequency of passage of scene elements. The visual flow field also characterizes the terrain structure that is overflown. Motion parallax (the relative movement of ground objects) determines the relative distances of those objects. From those distances, the structure of the terrain is determined.

Cues for Speed and Altitude Control

Optical flow and texture rate have been proposed as quasi-independent sources of infor

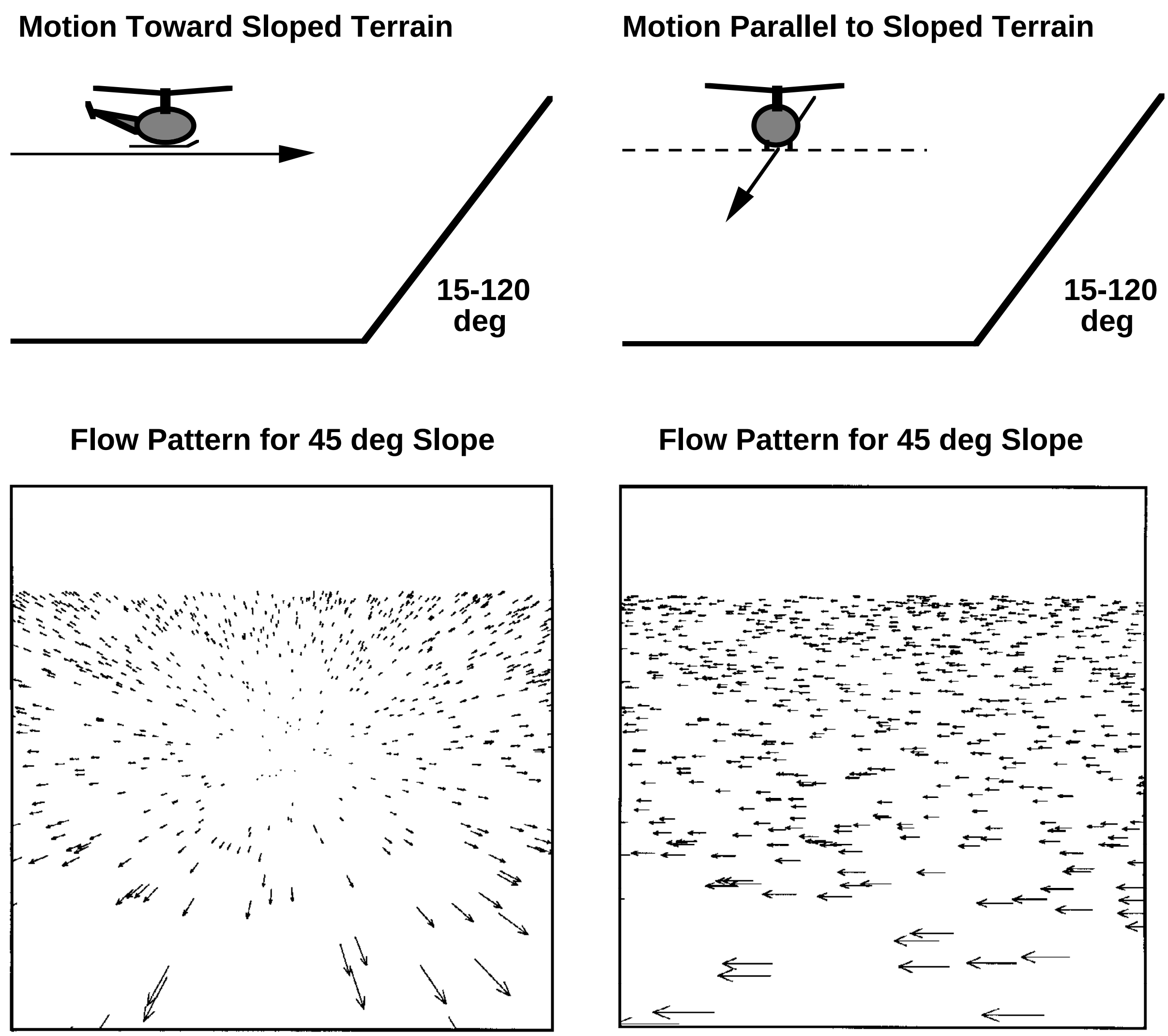

Figure 1. Flow patterns generated by motion toward the slope (x-motion, left panel) and parallel to the slope (y-motion, right panel). The 45 deg slope case is shown for both motion conditions.

mation about speed and altitude as well (Refs. 2-4). Flow rate is a measure related to the angular speed of terrain elements (trees, fields, etc.) as one moves through a visual scene, and increases as speed increases or altitude decreases. Texture rate (also called edge rate) is a measure of how many such elements pass through the visual scene per unit time. Texture rate yields a good estimation of ground speed when the spacing between these elements remains relatively constant. Thus, changes in flow rate can veridically signal altitude deviation when texture rate is constant. When terrain element spacing changes over time, however, this strategy leads to control difficulties.

Cues for Terrain Slant Determination

Under both laboratory and field test conditions, the slant of a surface is usually misperceived as being closer to the observer's frontal parallel plane than its true angle. Kaiser, Perrone, Andersen, Lappin and Proffitt (Ref. 5) conducted a part-task study to examine the extent to which observer motion mediates error in slant estimation. Observers estimated the slope of a surface relative to a horizontal ground plane under three motion conditions: no motion (static), motion toward the surface (x-motion), and motion parallel to the surface (y-motion). The surfaces were defined by point lights with a uniform random distribution, with slopes ranging from 15 to 120 deg. The length of the slope surface was varied randomly. All observers' slope estimates were most accurate in the y-motion condition, with no significant difference between the x-motion and static conditions. These findings suggest that the visual information specifying slant in the y-motion condition (i.e., motion parallax) has greater utility than that in the x-motion condition (i.e., differential optical expansion rates) (see Fig. 1 for a depiction of the flow patterns). Hence, pilots can judge the slope of terrain parallel to the track vector more accurately than the slope of terrain straight ahead. Such performance differences can impact pilots' navigation and control strategies.

Cues for Glideslope Control

Visual cues for glideslope acquisition and control have been investigated in a number of studies. The primary cues pilots use have been identified as the visual form ratio (the ratio of the visual angular length of the runway to the visual angular width of the far end of the runway, Ref. 6), and the visual depression angle between the horizon and the runway threshold (Ref. 7).

Cues for Depth Perception

Low-level rotorcraft flight is unique in that the conditions of flight allow pilots to use stereopsis, the recovery of depth/distance information from retinal disparity. Functional stereopsis has been shown to be a useful depth cue for distances up to approximately 30 meters (Ref. 8). The main utility and importance of this visual cue for rotorcraft operations is that it is functional within the ranges of close-in operations, and is a likely additional cue for the maintenance of close-in clearances.

VISUAL CUE DEGRADATION UNDER NON-OPTIMAL FLIGHT CONDITIONS

Not all flights are undertaken with optimal conditions for extracting the visual cues from the environment. A variety of flight conditions exist that result in a degradation of the visual scene. For direct viewing of the out-the-window scene, meteorological conditions (e.g., fog or haze), lighting conditions (night or moon phase), and terrain/vegetation conditions (featureless rolling sand dunes of the Persian Gulf theater versus the forests of Ft. Rucker, AL) will affect pilots' abilities to extract the visual cues from the environment. For enhanced or synthetic vision systems, the world is no longer viewed directly; the pilot views a representation through sensors and/or computerized databases. In these cases, it is important to determine the extent to which the enhanced/synthetic vision system accurately transduces or represents the visual cues. If visual cues required for pilotage are not accurately or reliably represented to the pilot, pilotage performance may suffer and safety considerations may ensue.

In this section, research demonstrating the degradation of visual cues and its consequences will be discussed. Topics include: (1) stereopsis with night-vision goggles (NVGs); (2) flight control with restricted field of view (FOV); (3) distance estimation with reduced resolution and FOV; and, (4) object recognition with infrared (IR) imagery.

Stereopsis With NVGs

Recent research on the use of night-vision goggles has demonstrated the potential pitfalls associated with complex visual systems. For example, Wilkinson and Bradley (Ref. 9) conducted an experiment that measured the amount of stereopsis (stereoscopic vision) available when using ANVIS-6 NVGs. Compared to unaided vision under comparable illumination levels, he found that subjects achieved a lesser degree of stereopsis when viewing with the goggles. He suggested that this decrease in stereopsis was due to degradation of visual cues (possibly increased signal/noise ratio or decreased resolution), or to conflicts between visual cues.

Flight Control With Restricted Field of View (FOV)

Brickner and Foyle (Ref. 10) conducted a simulation of a slalom course task with a forward-looking sensor. Three FOV values were tested: 25, 40 and 55 deg. Slalom course performance was measured by tallying number of slalom course pylon hits and averaging altitude and course deviations. Not surprisingly, the data indicated that flight control was best in the 40 and 55 deg FOV conditions, but an increased number of pylon hits occurred in the 25 deg FOV condition. An unexpected result was obtained when the flight paths were analyzed: The turns around the pylons were closest to the pylons in the 25 deg FOV condition, and largest for 55 deg FOV. This was explained by suggesting that the subjects adopted a flight control strategy in which they attempted to maintain the image of the pylons at the edge of the visible display.

A recent study by Grunwald and Kohn (Ref. 11) compared the relative impact of FOV and field of regard (FOR) on the estimation of flight path trajectories. Performance with a wide (103x90 deg) FOV fixed-forward FOR panel-mounted display was compared to a narrow (23x18 deg) FOV, wide (head-tracked) FOR helmet-mounted display (HMD). For curved flight paths, reduced FOR was the most detrimental, yielding increased path estimation error. For straight flight paths, reduced FOV yielded increased path estimation error. Additionally, increased flow and texture rate (increased speed for a constant altitude) reduced the time required to determine the flight path trajectory and, in general, decreased the path estimation error. This suggests that the accurate localization of path trajectory is aided by the ability to view the path along which one is going and to sample a wide visual area around it. Thus, for straight trajectories, the path tends to remain in front, and only the FOV is important. Alternatively, for curved trajectories, the ability to look off the instantaneous track vector and along the path is required, and thus FOR is more important.

Distance Estimation With Reduced FOV and Resolution

Foyle and Kaiser (Ref. 12) conducted a static distance estimation task in which helicopter pilots estimated the distance to two targets of unknown size located 20 to 200 ft in front of their positions. Seven viewing conditions were tested: (1) Unaided day vision (unrestricted FOV); (2) Unaided day vision (40 deg FOV); (3) Unaided night vision (unrestricted FOV); (4) Unaided night vision (40 deg FOV); (5) ANVIS-5 NVGs; (6) ANVIS-6 NVGs; and, (7) Infrared imagery (the AH-64 Apache PNVS IR sensor). The data indicated that distance estimation with unaided vision was the most accurate, with all other viewing conditions approximately equal. An analysis of the four unaided vision conditions indicated that distance estimation was not affected by the reduction in FOV (from approximately 160 deg to 40 deg), but was greatly affected by the day/night difference. One explanation for this is that the reduced resolution at night (1.0 min arc for day, 7.5 min arc for night) may have yielded poorer distance cues (the most likely distance cue in this study was the presence of minor ground texture).

Object Recognition With Infrared (IR) Imagery

Infrared imagery transduces thermal energy into a visible image. These sensors have been used by the military and others for night flight, since they are do not require any visible light to produce imagery. There are numerous differences between the images presented by these systems and the normal visual scene viewed during normal daytime flight, each having a consequence on flight performance. These include display-device related factors (e.g., monocular imagery, helmet-mounted displays with associated transport delays, FOV and FOR restrictions), and the inherent perceptual difficulties associated with flight based on imagery generated from thermal differences rather than reflected light. Foyle, Brickner, Sanford and Staveland (Ref. 13) conducted a study in which subjects identified terrain-type targets (e.g., trees, canyons) and non-terrain type targets (e.g., roads, vehicles) under television and IR imagery. As can be seen in Fig. 2, non-terrain objects were recognized faster with IR imagery, but terrain targets were recognized faster with television imagery. An analysis of the display parameters (i.e., contrast, luminance) associated with the targets indicated that for the non-terrain objects, the difference in recognition time varied as a function of the display parameters. This did not hold for the terrain targets: Recognition time was not related to the display parameters. It was hypothesized that cognitive factors determined the performance for the terrain targets. That is, under IR imagery, the terrain targets did not appear as expected.

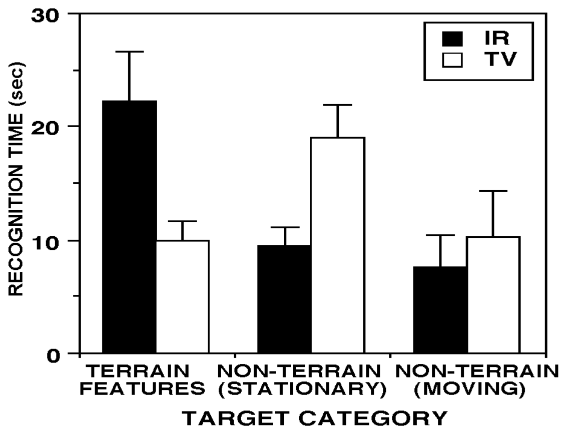

Figure 2. Recognition time for terrain and non-terrain objects viewed with television (TV) or infrared (IR) imagery.

ENHANCEMENT OF VISUAL CUES

Given the fact that not all flights are flown under optimum conditions for extracting the visual cues needed for low-level flight, the design challenge that faces the human factors and engineering communities is to design visual displays that preserve the most useful and unambiguous visual cues pilots naturally use. One way to accomplish this is through the development of designs that augment or enhance the visual cues. By augmenting the visual out-the-window scene under reduced-visibility conditions, the pilot can use these new, augmented cues in place of the missing or degraded cues available under better visual conditions. In the near-term, this augmentation may be done through symbology on head-up or helmet-mounted displays, or more realistically, in the long-term, in a synthetic vision system. Some examples of these augmentations range from the addition of a conformal horizon line, image processing to increase contrast (e.g., of runways), enhancing subthreshold information (e.g., distant runways, optical flow information), all the way to "making the invisible visible," such as showing graphically and spatially wind shear zones or taxiways and flight paths.

Forty years ago, there were two separate sources of flight information: the instruments and the out-the-window scene. Both were used and cross-checked. Today's technology has blurred the separation between these two sources of flight information. Superimposed flight symbology, whether on a HUD or on a panel- or head-mounted display of sensor imagery now allows a level of integration that was not possible previously. One example is a velocity vector that can be maintained on the runway aimpoint for landing. Another example, which has changed with the technology, is the artificial horizon. Originally presented as the ADI ball on the instrument panel, this can now be presented with superimposed symbology as a conformal, artificial horizon with additional pitch markings. This has the obvious added advantage in that not only is the information presented with an "eyes-out" capability, but that it augments the visual scene in a natural, intuitive, conformal manner. One additional characteristic of the conformal mapping is that the relationships of items in the world can be easily judged against the artificial horizon. Previously, this required scanning and mental transformations when the information was presented on the conventional ADI ball.

In this section, research investigating flight displays in which visual cues are enhanced or augmented will be discussed. Topics will include: (1) augmentation of the visual scene with grid references; (2) attentional fixation problems associated with superimposed symbology; and, (3) a proposed advanced display design, scene-linked HUD/HMD displays.

Grid Reference Augmentation

Bennett, Johnson and O'Donnell (Ref. 14) tested the concept of attaching a virtual grid system under a helicopter in a simulation study. When viewed through a panel-mounted display, HUD, or HMD, pilots saw both the out-the-window scene as well as the virtual, computer-generated grid-referencing platform under the helicopter. The research indicated that this type of augmentation did indeed allow the pilots to relate the scene information to the grid, and to note changes in aircraft state more accurately. In a hover

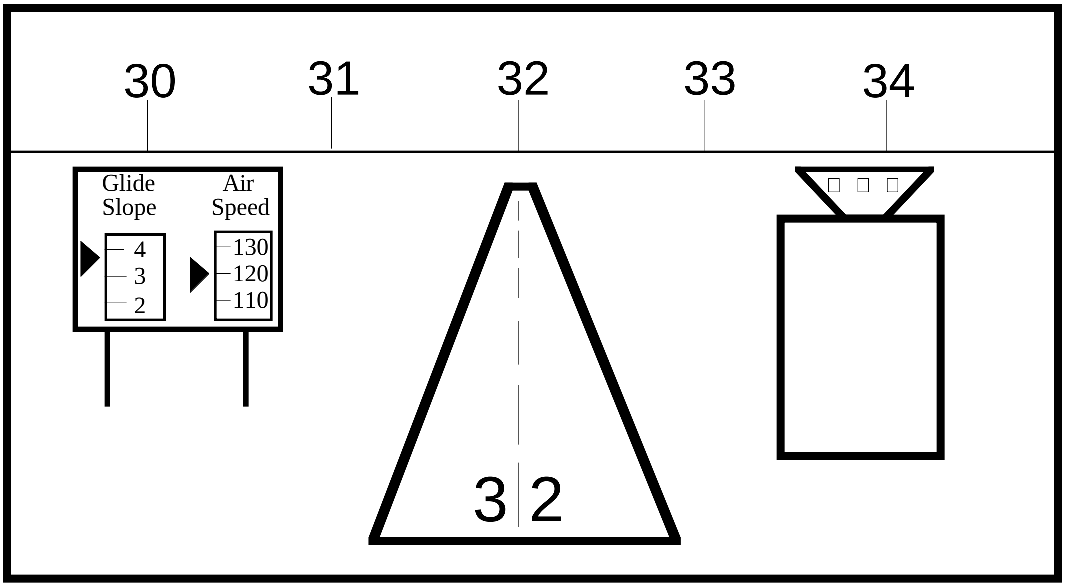

Figure 3. Schematic of a runway landing area demonstrating the "scene-linked HUD/HMD display" concept. The tower and runway represent real objects in the out-the-window scene. The compass rose attached to the horizon and the billboard with instrument displays represent virtual, computer-generated images.

task, the grid decreased altitude error for the narrow FOV conditions, in which pilots' abilities to determine the relationships among scene objects had been reduced.

Attentional Problems with Superimposed Symbology

Superimposed symbology, whether on a HUD or HMD, has been demonstrated to lead to visual fixation. Under visual fixation, pilots are less likely to process other symbology information, and/or the world seen through the HUD or the imagery presented on the HUD/HMD (Fischer, Haines & Price, Ref. 15). Foyle, Sanford and McCann (Refs. 16, 17) demonstrated that this fixation may be due to attentional issues rather than to visual factors, as suggested by Iavecchia, Iavecchia and Roscoe (Ref. 18) (also, see Sheehy & Gish, Ref. 19). Foyle et al also found that when augmented information is integrated into the visual scene, it does not suffer from the same attentional fixation problems that it does when presented through superimposed symbology.

Scene-linked HUD/HMD Displays

Advanced display media such as HUDs or HMDs, in combination with highly accurate positioning systems (e.g., Global Positioning System, GPS) allow for the possibility of placing information into the visual scene and stabilizing it with respect to the out-the-window scene (Ref. 17). On the basis of the results of Foyle et al (Ref. 16), this should allow for the processing of the displayed information without any of the attentional problems mentioned above. That is, such a display may allow for the parallel processing of both the displayed information and the out-the-window information without fixation and without large attentional switching delays.

Fig. 3 shows an example of such a scene-linked display. In the figure, the tower and runway represent actual items in the out-the-window image (either viewed through the HUD, or via sensor imagery on the HUD or HMD). The compass rose and horizon line, represent virtual, computer-generated imagery that is drawn as if it were "attached" to the image. Likewise, the Glideslope/Air Speed instruments are displayed on a virtual, computer-generated billboard, placed to the side of the runway alongside a nominal aim-point. Benefits, in addition to that of decreasing attentional problems, may occur from augmenting the visual scene in this manner. The addition of items of known size and consistent location allows the pilot to use the scene-linked display as a reference, using pictorial relationships, in the same manner as the grid reference described above (Ref. 14). For example, the billboard could be constructed so as to appear to have a height equal to the decision height for landing. Adding this redundant pictorial and perspective cue would allow quicker processing and lower workload for altitude assessment. The visual flow field would be augmented as well by the scene-linked additions. For example, the virtual displays (e.g., billboard) would grow larger as one approached the runway, and any pitch or yaw of the aircraft would be processed incidentally when viewing the display values. Research is underway to investigate the usefulness of the concept of scene-linked displays.

CONCLUSIONS

It has been shown that the out-the-window, low-level scene contains a variety of visual cues that pilots use when flying "eyes out." Under degraded conditions, such as weather or with sensor imagery, the visual cues may not be usable or reliable. To counteract such degradation, advanced displays in which the out-the-window scene is enhanced or augmented are proposed. Such enhancements may add the necessary visual cues back to the scene, which were removed or made unreliable by the degraded operating conditions.

REFERENCES

1. Johnson, W.W. and Phatak, A.V. "Optical Variables and Control Strategy Used in a Visual Hover Task," Proceedings of IEEE Conference on Systems, Man, and Cybernetics, Cambridge, MA, Nov 1989.

2. Wolpert, L. and Owen, D. "Sources of Optical Information and Their Metrics for Detecting Loss in Altitude," Proceedings of the Third Symposium on Aviation Psychology, Columbus, OH, May 1985.

3. Awe, C.A., Johnson, W.W., Perrone, J.A. and Phatak, A.V. "Inflexibility in Selecting the Optical Basis for Perceiving Speed," Proceedings of the Human Factors Society 33rd Annual Meeting, Denver, CO, Oct 1989.

4. Johnson, W.W., Tsang, P.S., Bennett, C.T. and Phatak, A.V. "The Visual Control of Simulated Altitude," *Aviation, Space, and Environmental Medicine*, Vol. 60, (2), Feb 1989.

5. Kaiser, M.K., Perrone, J.A., Andersen, G.J., Lappin, J.S. and Proffitt, D.R. "The Effect of Motion on Surface Slant Perception," The Annual Meeting of the Association for Research in Vision and Ophthalmology, Sarasota, FL, May 1990.

6. Mertens, H.W. and Lewis, M.F. "Effect of Different Runway Sizes on Pilot Performance During Simulated Night Landing Approaches," *Aviation, Space, and Environmental Medicine*, Vol. 53, (5), May 1982.

7. Lintern, G., Kaul, C.E. and Collyer, S.C. "Glideslope Descent-Rate Cuing to Aid Carrier Landings," *Human Factors*, Vol. 26, (6), Dec 1984.

8. Arditi, A. "Binocular Vision," in K.R. Boff, L. Kaufman and J.P. Thomas (Eds.), *Handbook of Perception and Human Performance*, Wiley, New York, 1986, Ch. 23.

9. Wilkinson, M. and Bradley, A. "Night-Vision Goggles: An Analysis of Dynamic Range and Visual Performance for the Unaided and Night-Vision Goggle-Aided Eye," Fifth Annual Joint Service Night Vision Conference, St. Louis, MO, Jun 1990.

10. Brickner, M.S. and Foyle, D.C. "Field-of-View Effects on a Simulated Flight Task with Head-Down and Head-Up Sensor Imagery Displays," Proceedings of the Human Factors Society 34th Annual Meeting, Orlando, FL, Oct 1990.

11. Grunwald, A. and Kohn, S. "Visual Field

Information in Low-Altitude Visual Flight by Line-of-Sight Slaved Helmet-Mounted Displays," Paper Submitted to *IEEE Transaction on Systems, Man, and Cybernetics*, 1992.

12. Foyle, D.C. and Kaiser, M.K. "Pilot Distance Estimation with Unaided Vision, Night-Vision Goggles and Infrared Imagery," *SID International Symposium Digest of Technical Papers*, Vol. 22, May 1991.

13. Foyle, D.C., Brickner, M.S., Staveland, L.E. and Sanford, B.D. "Human Object Recognition as a Function of Display Parameters Using Television and Infrared Imagery," *SID International Symposium Digest of Technical Papers*, Vol. 21, May 1990.

14. Bennett, C.T., Johnson, W.J., and O'Donnell, K.A. "Dynamic Perspective Displays and the Control of Tilt-Rotor Aircraft in Simulated Flight," American Helicopter Society 44th Annual Forum, New York, NY, Jun 1988.

15. Fischer, E., Haines, R.F., and Price, T.A. "Cognitive Issues in Head-Up Displays," NASA ARC TP 1711, Dec 1980.

16. Foyle, D.C., Sanford, B.D., and McCann, R.S. "Attentional Issues in Superimposed Flight Symbology," Proceedings of the Sixth International Symposium on Aviation Psychology, Columbus, OH, May 1991.

17. Foyle, D.C., McCann, R.S., and Sanford, B.D. "Superimposed Information Displays: Attentional Deficits and Potential Solutions," The 32nd Meeting of the Psychonomic Society, San Francisco, CA, Nov 1991.

18. Iavecchia, J.H., Iavecchia, H.P., and Roscoe, S.N. "Eye Accommodation to Head-Up Virtual Images," *Human Factors*, Vol. 30, (6), Dec 1988.

19. Sheehy, J.B. and Gish, K.W. "Virtual Image Displays: Is Redesign Really Necessary?", *SID International Symposium Digest of Technical Papers*, Vol. 22, May 1991.