Visual Misperception in Aviation: Glide Path Performance in a Black Hole Environment

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Objective: We sought to improve understanding of visual perception in aviation to mitigate mishaps in approaches to landing. Background: Research has attempted to identify the most salient visual cues for glide path performance in impoverished visual conditions. Numerous aviation accidents caused by glide path overestimation (GPO) have occurred when a low glide path was induced by a black hole illusion (BHI) in featureless terrain during night approaches. Method: Twenty pilots flew simulated approaches under various visual cues of random terrain objects and approach lighting system (ALS) configurations. Performance was assessed relative to the desired 3° glide path in terms of precision, bias, and stability. Results: With the high-ratio (long, narrow) runway, the overall performance between 8.3 and 0.9 km from the runway depicted a concave approach shape found in BHI mishaps. The addition of random terrain objects failed to improved glide path performance, and an ALS commonly used at airports induced GPO and the resulting low glide path. The worst performance, however, resulted from a combination ALS consisting of both side and approach lights. Surprisingly, novice pilots flew more stable approaches than did experienced pilots. Conclusions: Low, unsafe approaches occur frequently in conditions with limited global and local visual cues. Approach lights lateral of the runway may counter the bias of the BHI. The variability suggested a proactive, cue-seeking behavior among experienced pilots as compared with novice pilots. Application: Visual spatial disorientation training in flight simulators should be used to demonstrate visual misperceptions in black hole environments and reduce pilots’ confidence in their limited visual capabilities.

INTRODUCTION

The black hole illusion (BHI) is a specific type of illusion in featureless terrain. According to the U.S. Department of Transportation (2002), “An absence of ground features, as when landing over water, darkened areas, and terrain made featureless by snow, can create the illusion that the aircraft is at a higher altitude than it actually is. The pilot who does not recognize this illusion will fly a lower approach” (p. 8-1-6).

Dating back to the 1950s, aviation safety has been concerned with the BHI and visual spatial disorientation contributing to accidents caused by misperception of altitude and distance (Calvert, 1954; Civil Aeronautics Board, 1960). The National Transportation Safety Board (NTSB, 1977) formally recognized the BHI in accidents as far back as 1974 in the analysis of the Pago Pago, American Samoa, crash in which only 5 of the 101 people on board survived. More recently, the BHI was cited in a commercial aircraft accident at Tallahassee, Florida, and the final approach was characterized by the classic concave shape prior to terrain impact (NTSB, 2002). Despite the presence of precision approach path indicator lights (called PAPIs, similar to visual approach slope indicator lights, VASIs), the pilots still experienced glide path overestimation (GPO).

The U.S. Air Force (USAF) Accident Investigation Board reported in 1999 on a C-130 accident in Kuwait and in 2002 on a C-17 mishap in Afghanistan. The C-130 mishap occurred during a night approach over featureless terrain and resulted in a short landing that was partly attributable to a lack of ambient visual cues. The C-17 mishap occurred during a night approach that landed short, and the BHI was cited as a contributing factor to
the accident. In 2006, an F-16 came within 6 m of the ground 0.9 km from the runway while flying a night visual approach (E. Cassingham, personal communication, October 27, 2006). The F-16 near mishap occurred despite the presence of PAPIs to the landing runway. As recently as February 2008, the USAF made changes to a runway in Germany to help alleviate visual misperception and obstacle hazards that had contributed to eight mishaps since 1985 (Schonauer, 2008). Clearly, the problem has not gone away.

Gibb (2007) described the visual misperception that occurs in a featureless environment when a pilot is induced into GPO (Figure 1). GPO results when a pilot develops a false sensation that the aircraft is too high, above the desired 3° glide path, which is described as “feeling steep.” Incorrectly trusting their perceptual capabilities, pilots initiate an aggressive descent and wrongly adjust to an unsafe position below the desired glide path. As defined previously, the BHI refers not to the runway but to the environment surrounding the runway. GPO, as shown in the figure, results in a concave-shaped approach, a below-glide path arc, which may result in impacting terrain or an obstacle ahead of the runway.

GPO appears to stem from misperception of altitude and distance arising from a lack of reliable visual information about these quantities. In the featureless environments typically associated with BHI accidents, the only visual cues available for estimation of altitude and distance are the shape and size of the retinal image of the runway. For example, the aspect ratio of the runway’s retinal image (e.g., the ratio of its medial and lateral visual angles) increases as a function of altitude and distance. Therefore, a long and thin retinal image is typically seen when a pilot is high and far from the runway; thus the runway appears more orthogonal than when a pilot is low and close to the runway. This perception of being high and far may induce a pilot into an overly aggressive descent.

Similarly, the visual angle subtended by either the medial or lateral axis of the runway will be inversely related to altitude and distance, so, for example, when the front edge of the runway subtends a larger visual angle, the pilot is typically low and close to the runway. This perception may induce pilots to lessen their descent rate. Nearly every aviation visual perception discussion includes the illusion of runway size and shape (e.g., Newman, 2005; Pitts, 1967). Pilots experience perceptual constancy problems in rich viewing environments when they encounter a runway different from those to which they are accustomed.

Given these relationships, it is not surprising that pilots seem to use these visual cues to control their approach in featureless terrain conditions. As discussed in the context of BHI (Perrone, 1984) and more generally in relation to distance and depth

![Figure 1](image_url). The black hole illusion induces pilots to fly unsafe, shallow approaches because of visual misperception. From “Visual Spatial Disorientation: Re-Visiting the Black Hole Illusion” by R. W. Gibb, 2007, *Aviation, Space, and Environmental Medicine, 8*, p. 802. Copyright 2007 by the Aerospace Medical Association. Reprinted with permission.
perception (Gregory, 1997), the shape and size of an object’s retinal image in isolation do not provide reliable cues to altitude and distance.

For one, the aspect ratio, medial visual angle, and lateral visual angle of the runway’s retinal image not only are related to distance and altitude but will also depend on the physical slant of the runway (i.e., whether it is on an up or down slope) and the physical aspect ratio (e.g., whether it is a 2,700-× 30-m or 1,500-× 90-m runway). If these physical characteristics are not known, the pilot could make a dangerous misjudgment: For example, the long and thin image produced by a narrow runway (or a runway that is physically sloped up) could be misinterpreted by the pilot as an approach from a high altitude, appearing more orthogonal and inducing GPO.

Although there is evidence that these factors are related to BHI accidents (e.g., up-sloped runway in Guam: NTSB, 1997; up-sloped runway and rising terrain prior to the runway in Germany: Schonauer, 2008), they do not seem to be the sole cause, given that many of the featureless terrain accidents have occurred on flat or down-sloped runways that have common aspect ratios (e.g., down-sloped runway and 47 ratio in St. Thomas [NTSB, 1998]; down-sloped approach and 53 ratio for the 2002 Florida accident [NTSB, 2002]).

Another problem associated with using the angular size and shape of an object’s retinal image as the sole cue to its distance is that humans have many estimation biases in environments with impoverished visual cues. When only the target object is visible, distance is consistently underestimated (Teghtsoonian & Teghtsoonian, 1969). It has also been shown, analogous to the 2-D horizontal-vertical illusion presented in many textbooks, that visual angles in the medial plane are overestimated relative to visual angles in the lateral plane (Crassini, Best, & Day, 2003).

Both of these biases are consistent with GPO and the pilot behavior observed in featureless terrain accidents. An overestimation of the runway’s medial visual angle (and consequently its aspect ratio) will lead to an overestimation of altitude, resulting in GPO and inducing the pilot to “correct low.” Because the approach angle associated with a given altitude is inversely related to the distance to the runway, GPO would be even further exacerbated by the pilot’s tendency to underestimate distance. Clearly this analysis of GPO and BHI suggests that additional sources of visual information in the landing environment (e.g., visible ground texture or landing lights) may help to disambiguate the cues provided by the runway’s retinal image and/or reduce the overestimation of distance and altitude.

Visual perception. Previc (2004a) defined a visual approach to landing as an ambient vision task. Ambient vision is concerned with orientation within the environment relative to earth-fixed coordinates (Parmet & Gillingham, 2002). This ambient environmental orientation is the unconscious portion of vision in terms of one’s lack of awareness regarding the assimilation and inference gained from peripheral cues toward overall perception. Ambient vision also provides an external viewpoint of one’s motion (Previc, 2004b). Previc (2004b) further described the function of ambient vision as the veridical perception of distance and ground plane slant. In contrast, focal vision is primarily involved with detail discrimination and color as well as an internal viewpoint in judging distance, size, and shape.

In an approach under rich viewing conditions, the ambient cues providing veridical perception of movement and spatial orientation are in the background (periphery) for the central task of landing. Consequently, the runway is the perceived primary visual cue and favored target during a visual approach (Riordan, 1974). The paradox is that in black hole conditions, the favored runway image is still present but the vital ambient cues are absent. Therefore, pilots may feel that they have the same information available as they do under rich viewing conditions. The missing ambient cues are not actively attended to when they are available, so they may seem unnecessary. The BHI clearly suggests otherwise.

Previous Research

An analysis of USAF spatial disorientation (SD) mishaps from 1990 to 2004 found that of all mishaps, 11% were attributed to SD. SD accounted for 23% of accidents occurring at night (Lyons, Ercoline, O’Toole, & Grayson, 2006). Benson (1999) defined SD as when a pilot fails to sense correctly the position, motion, or attitude of the aircraft within the fixed coordinate system provided by the surface of the earth and the gravitational vertical. Both Gillingham (1992) and Previc (2004a) estimated that visual SD contributes to nearly half of all SD mishaps. Two separate surveys of USAF pilots (Matthews, Previc, & Bunting,
2002; Sipes & Lessard, 2000) reported that in terms of visual SD, the BHI is a leading form of pilot misperception that is experienced during impoverished visual conditions.

Mertens and Lewis (1982, 1983) studied the BHI by manipulating runway shape and approach lighting systems (ALSs) during simulated night approaches. They found that the higher a runway’s ratio is, the greater the GPO will be (Mertens & Lewis, 1982), and the addition of an ALS increased a runway’s ratio and further induced GPO (Mertens & Lewis, 1983). Mertens (1981, p. 385) also recommended research into “extra-runway cues” for visual perception guidance.

Perrone (1984) developed a model of slant misperception in aviation to quantify the BHI, and it is still a leading theory on the phenomenon (Previc, 2004a). According to Perrone (1982), an observer will often underestimate slant (from vertical) by falsely perceiving the axis of rotation at the bottom of a figure rather than at its center. In impoverished viewing conditions during a landing, pilots focus on their target – the approach end of the runway – and this incorrect axis of rotation results in foreshortening of the rectangular image and an overestimation (from horizontal). Perrone (1984) explained that the lack of surface detail eliminated the monocular depth cue of linear perspective, leaving pilots with only runway edge lighting.

Perrone’s (1984) formula is founded on the theory that the higher the runway’s ratio, the greater the GPO. Pilots use runway width for perspective when landing at night. During rich viewing conditions, in contrast, cues extend out beyond the width of the runway, providing linear perspective, the primary visual cue to perceiving distance (Mertens, 1979; Previc, 2004b). Perrone (1984) also expressed the need to quantify the amount of textual information that is sufficient to assist pilots in properly perceiving linear perspective.

Lintern and Walker (1991) examined scene content and runway width in simulator landings, assessing pilot performance from 3.0 to 0.7 km from the runway. Scene content was categorized as reduced or normal, and as a factor it was significant: More shallow glide paths were flown in the reduced-content scenes because of GPO. Similarly, Galanis, Jennings, and Beckett (1998) concluded that texture reduced pilots’ uncertainty while they were attempting to maintain the glide path. Palmisano and Gillam (2005) also concluded that increasing information regarding the true orientation of the ground plane improved glide path judgments. See Gibb and Gray (2006) for further discussion of the role of structural and textural elements in perceived terrain orientation.

Aims of the Present Study

As discussed in detail previously, in a feature-less terrain environment the only visual cues available to the pilot are those provided by the retinal image of the runway, resulting in misjudgments of altitude and distance (i.e., the BHI). The GPO that can occur in this situation could potentially be remedied with the addition of other sources of visual information in the landing environment. The primary aim of the present study was to directly compare the effectiveness of different environmental cues (objects on the ground terrain, a standard ALS, and a reconfigured ALS) in reducing the incidence of GPO.

The following specific hypotheses were addressed in the research:

1. Relative to the runway alone, the presence of random terrain objects will reduce the magnitude of GPO (Perrone, 1984).
2. Relative to the runway alone, a standard ALS will increase the magnitude of GPO (Mertens & Lewis, 1983).
3. Relative to the runway alone, a reconfigured ALS (consisting of lights on the side of the runway) that has the effect of decreasing the perceived runway aspect ratio will reduce the magnitude of GPO.
4. The combination of a standard ALS with the reconfigured ALS provides an optimal landing light configuration for perception of the approach to landing and accurate glide path performance (Gibb & Gray, 2006).
5. Different visual cues influence pilot performance at different distances from the runway (Galanis et al., 1998; Lintern & Walker, 1991).

METHODS

Apparatus

Microsoft Flight Simulator™ (2004 version), was used to simulate the landing approaches. This system is often used as a research tool (Khan, Rossi, Heath, Ali, & Ward, 2006) and as a training system by the U.S. Navy for its future aviators (Brewin, 2000). Microsoft Flight Simulator was augmented by “add-on” software called FS Architect™ (2005 version), which created airfields at particular latitude and longitude positions. The two software packages allowed for the creation of
black-hole approach environments for runways of various shapes and sizes, ALSs, illuminated objects, and runway edge lighting. A Boeing 737-400 was flown by participants, with the gear down and flaps fully extended. However, no instrument displays were provided; the approach was purely visual.

The aircraft was controlled by a standard aviation computer game joystick, Logitech Attack3. The visual environment was projected on a large wall using a LCD projector (Hitachi CPX1200 SER) updated at a rate of 60 Hz to simulate the movement of the virtual aircraft. In order to reduce variability caused by lateral movement of the joystick, lateral control input was removed ($x$ axis), resulting in the participant controlling only the pitch movement ($y$ axis). The lateral position of the participant’s aircraft always remained aligned with the center of the runway. Thus, the pilot focused on controlling the rate of descent to fly a 3° glide path to landing. The participant sat 2.5 m from a wall that displayed the projected image. The total visual scene was 2.99 m horizontal and 2.26 m vertical, creating a horizontal visual angle of 30.5° and a vertical visual angle of 24°.

**Dependent Variables**

There were two dependent variables in this research. The primary dependent variable was altitude deviation, which consisted of precision and bias performance data. *Precision,* or accuracy, is the most common measure of performance, describing how close the pilot is to the desired 3° glide path target, whereas *bias* refers to the direction of the glide path flown, relative to the desired 3° glide path (i.e., above or below it; Lintern & Liu, 1991; Palmisano & Gillam, 2005). The second dependent variable, standard deviation, refers to the stability of the altitude deviation.

Glide path performance was obtained by distance and altitude data points collected approximately every second (0.99 s) throughout the entire approach. The approach started and data collection began at 9.3 km (5 nautical miles; NM), and data collection continued until the landing; however, only data between 8.3 km (4.5 NM) and 0.9 km (0.5 NM) from the runway’s threshold (the aim point) were analyzed. Data were not analyzed from 9.3 to 8.3 km to allow the pilot participants time to stabilize their control inputs, and data collected closer than 0.9 km to the threshold were not analyzed because of the large variability in the data found during pilot studies.

The horizontal distance from runway threshold (the start of the runway) and altitude at that distance were converted into a spatial position relative to the desired glide path, an angle to aim point. Altitude deviation from 3° was computed by taking the current altitude and subtracting the desired 3° altitude. For example, a position of 244 m (800 ft) in altitude and 3.7 km (12,152 ft) from the runway results in an altitude deviation of +48 m (+163 ft). Altitude deviation was used instead of the conventional glide path in degrees because the sensitivity of the degree measure changes dramatically as one approaches the runway. For instance, in the example at 3.7 km, the 48-m altitude deviation equates to 3.8°, but the same 48-m altitude deviation at 2 km equates to 6.9°. The altitude deviation measure reflects both precision and bias in that zero altitude deviation is the goal and the sign of the altitude deviation reflects the direction of the deviation (negative for below the glide path and positive for above the glide path).

The second dependent variable, standard deviation, allowed us to assess the stability of performance and was computed by averaging the standard deviation values within each distance interval range within each approach.

**Independent Variables**

The independent variables are listed in the following sections.

*Terrain density.* This variable was manipulated with three levels of randomly placed objects per square grid, based on Kleiss and Hubbard (1993). The objects within each level were illuminated rectangular solids of the dimensions 15.2 m (50 ft) side × 15.2 m side × 9.1 m (30 ft) tall. Each runway was situated within a 6 × 10 grid layout; each grid had the dimensions 3,048 m (1,000 ft) × 3,048 m, resulting in 3 grids each side of the runway and 10 grids in length (60 grids total). The three levels were (a) *Terrain Density 0* (zero objects); (b) *Terrain Density 5* (5 random objects per 60 grids); and (c) *Terrain Density 10* (10 random objects per 60 grids).

*Approach lighting.* This was manipulated with four levels of lighting system configurations. The first was (a) *no ALS:* This was the same condition as the zero-object condition for terrain density. The landing environment consisted of only the runway.
The second was (b) standard ALS: Here, a standard ALS system was present. The ALS used in this study was the ALSF2 (shown in the foreground of Figure 2; also used by Mertens & Lewis, 1983), which extended 732 m (2,400 ft) from the threshold (out from the approach end of the runway).

The third and fourth approach lighting arrays were new manipulations. (c) Reconfigured ALS: This was a novel-shaped ALS consisting of illuminated objects at the sides of the runway in a distinct pattern, the same type of illuminated objects used for terrain density (see Figure 2). No lights extended from the end of the runway, only side lighting. Twelve objects, three pairs on each side, were positioned starting at 152 m (500 ft) down the runway, then at 457 m (1,500 ft) and 762 m (2,500 ft) down. The pairs were 15.2 m (50 ft) from the side of the runway with 15.2-m gaps between them, resulting in a total of 61 m (200 ft) in width on each side. (d) Combination ALS: This array combined the standard ALS and reconfigured ALS, as shown in Figure 2.

Distance. Distance from the runway was assessed at eight intervals ranging from 8.3 to 0.9 km (4.5–0.5 NM) from the runway. Visual inspection of the levels revealed three distinct groupings: above, near, and below the desired glide path. Consequently, the eight intervals were collapsed into three based on those groupings. The distance ranges used were (a) distance far: 8.3–5.6 km (4.5–3.0 NM) from the runway; (b) distance mid: 5.6–3.7 km (3.0–2.0 NM) from the runway; and (c) distance near: 3.7–0.9 km (2.0–0.5 NM) from the runway.

Expertise. This was the only between-group factor, and categorization was based upon a post hoc grouping of the volunteer pilot participants.

Experimental Design

The experiment included two mixed designs. The first design, the terrain density analysis, examined natural aspects of the landing scene and was a within 3 (terrain density) × 3 (distance) between 2 (expertise) ANOVA. This manipulation added natural aspects to a black hole approach environment to improve visual perception. The second design examined approach lighting manipulations using a within 4 (approaching lighting) × 3 (distance) between 2 (expertise) ANOVA. These manipulations added manufactured lighting configurations to counter the bias of a BHI.

The runway for all conditions was 2,743 × 30 m (9,000 × 100 ft). This runway represented the more narrow (long, thin) runway encountered by pilots, having a ratio of 90. The condition with only the runway (shape illuminated with edge lighting) and no ALS and no terrain objects was the most impoverished visual scene and was part of both mixed designs (zero terrain objects condition and no ALS condition).

The ANOVA results were assessed using an alpha value of .05, and the post hoc tests were computed using an alpha of .10 divided by the number of tests using one-tailed probability values where directional hypotheses were in the expected direction. Sphericity was handled with the Huynh-Feldt correction to the degrees of freedom.

Participants

All pilot participants were paid volunteers ($15) who had actual flying experience to ensure they could accomplish a visual glide path to landing. The 20 volunteer pilot participants fell into two groups: 8 experienced and 12 novices. The 8 experienced pilots ranged in age from 34 to 48 years (mean = 42.1) and in flying hours from 2,000 to 15,000 hr (mean = 6,238, median = 4,000). The 12 novice pilots ranged in age from 18 to 27 years (mean = 19.9) and in flying hours from 40 to 1,100 hr (mean = 1,500, median = 100).
years (mean 21.4) and in flying hours from 75 to 527 hr (mean = 256, median = 284).

**Procedure**

The experiment began with instructions and three practice approaches with three different runway conditions. Each trial started 9.3 km from the runway threshold and at 485 m (1,500 ft) above the runway elevation. The simulator was taken off “freeze,” and the participants were instructed to fly straight and level until they felt they had intercepted the 3° glide path to landing. At that time, they vertically maneuvered the aircraft to the landing runway. Pilots had to visually capture and then maintain a 3° glide path using no instrumentation. The desired intercept point for a 3° glide path was at approximately 8.7 km (4.7 NM) from the runway. The only input was the control stick to either raise (to climb) or lower (to descend) the nose of the aircraft. The autot throttles maintained desired airspeed, 125 knots (64 m/s or 211 ft/s). Each trial was approximately 2 min 15 s in duration.

It should be noted that because of space constraints, this paper presents less than half of the data. In the actual experiment, each participant accomplished 18 randomly ordered conditions that consisted of all terrain and lighting conditions flown into runway ratios 17 and 90 with either a horizon present or absent. The data presented, however, concentrate on the conditions producing the BHI, namely flying into a high-ratio runway with no visible horizon. Thus the reported data come from six different manipulated conditions at ratio 90. It is important to note that the results should be interpreted from the perspective that the pilots, at the beginning of every condition, had not only random environmental cues either present or absent but also random runway ratios to perceive.

**RESULTS**

**Distance Levels**

The data were analyzed via the terrain density and approach lighting designs described previously at all eight distance levels. Then additional analyses were accomplished at collapsed distance levels, from eight down to three. When collapsed, the three distance levels were significantly different, \(F(1.9, 686.8) = 237.9, p < .001\). The average altitude deviation values for each distance were +25.3 m (standard deviation = 2.4) for distance far (Distance 1–3), −2.1 m (3.9) for distance mid (Distance 4–5), and −15.5 m (2.7) for distance near (Distance 6–8). Our data shown in Figure 3 depicts the classic concave approach shape described in previous mishaps (NTSB, 2002) and research (Kraft, 1978).

**Terrain Density Analysis**

The average altitude deviation values for the three levels of terrain density were, unexpectedly, less accurate for the higher number of random objects; 0 objects averaged −1.7 m (standard error 10.9), 5 objects averaged −16.8 m (9.7), and 10 objects averaged −23.9 m (10.0). As shown in Table 1, terrain density as a main effect was significant, and the post hoc assessment found that the changes from 0 to 5 objects and 0 to 10 objects were significant, \(t(19) = −2.35, p = .015\), and

![Figure 3. Altitude deviation performance over eight distance levels.](image)
Contrary to Hypothesis 1, random terrain objects as presented in this study degraded glide path performance, leading to lower approaches.

The altitude deviation performance between the two different expertise levels depicted more accuracy for the novice pilots, who averaged +10.3 m (11.4), as compared with the expert pilots, who averaged –38.6 m (14.0). This main effect was also significant, \( F(1, 18) = 7.35, p = .014 \).

Approach Lighting Analysis

Table 2 represents the average altitude deviation values of the four different approach lighting manipulations, and Table 3 shows the ANOVA results. Approach lighting, distance, and the interaction were all significant main effects. Expertise, however, was not significant.

As shown in Table 2, no ALS and the reconfigured ALS produced the most accurate pilot performance in terms of altitude deviation, and both were significantly different from the combination ALS, \( t(19) = 3.66, p = .002 \), and \( t(19) = 3.84, p = .001 \), respectively. The difference between the reconfigured ALS, +3.8 m, and the standard ALS, –16.8 m, was nearly significant, \( t(19) = 2.26, p = .018 \) (one-tailed, alpha level .017). The less accurate and low-biased standard ALS performance suggests support of Hypothesis 2, whereas the more accurate performance with the reconfigured ALS supports Hypothesis 3.

In terms of the significant interaction between approach lighting and distance, however, Figure 4 depicts the degrading performance of the combination ALS and standard ALS at distance mid and distance near. The poor pilot performance in the combination ALS condition failed to support Hypothesis 4, which proposed that this condition would lead to the best performance. Both no ALS and the reconfigured ALS produced more accurate, less biased approaches throughout the different distances. Hypothesis 5 was supported by the interaction of distance and approach lighting, showing that lighting affects performance differently at different distances.

Pilot Variability

In terms of standard deviation (stability of performance), there was a difference in expertise and, again, it favored the novice pilots. In analyzing both the terrain density and approach lighting manipulated conditions at the original eight distance levels, we found that the expert pilots’ mean standard deviation was 23.8 m (standard error 2.3), compared with the novice pilots, whose standard deviation turned out to be more stable at 15.3 m (1.9). The between-subject comparison revealed significance, \( F(1, 18) = 8.47, p = .009 \).

Ordinal Position

An analysis was conducted to determine if a learning effect was present for the pilots, who performed repeated, but random, trials within an impoverished visual environment. Figure 5 presents the ordinal sequence of the original 18 conditions flown by the pilots. The effect of the ordinal sequence was significant overall across the 18 approaches, \( F(12.6, 226.2) = 2.59, p = .003 \). The expertise factor was not significant. Removing the first 2 ordinal position conditions and performing another ANOVA failed to reveal significance.
The average altitude deviation of the first ordinal position was –36.0 m (standard error, 10.7) and the second position was –18.7 m (11.2). The remaining 16 random positions, Positions 3 through 18, averaged +4.9 m (8.9). These findings suggest that pilots tended to fly lower initially but corrected in subsequent approaches. Although the averages improved, there were still many occasions when very low approaches were flown throughout the series of conditions.

**DISCUSSION**

**Terrain Density**

Previous research had predicted that increasing the number of objects around the runway would increase performance accuracy, but this was not the case (e.g., Gibb & Gray, 2006; Palmisano & Gillam, 2005). It was puzzling that the addition of terrain objects would actually hinder visual perception to the point of degrading glide path performance. Possibly the “objects” were not of sufficient size or illumination to provide salient visual information, or the number of objects present was insufficient to provide adequate surface plane orientation. Future research ought to explore increasing the number of random objects as well varying illumination levels to ensure proper stimulus intensity to help with perceptual differentiation.

**Approach Lighting**

Consistent with Mertens and Lewis (1983), the standard ALS in the present study induced shallow glide paths, less accuracy, and low bias. The standard ALS increased the runway to a ratio of 114. This is somewhat troubling because that standard ALS is currently in use at airfields, perceptually increasing the already-high-ratio runways. Airports such as Los Angeles International (RWY 7L/25R, ratio of 81), New York JFK (RWY 13R/31L, ratio 97), Miami International (RWY27/09, ratio 87), and Dallas-Fort Worth International (three runways with a ratio of 89) are just a few examples of high-ratio runways with BHI potential. Schiff (1994) also warned that the Honolulu (RWY 8L/26R, ratio 82) and Las Vegas (RWY 7L/25R, ratio 81).

**TABLE 3:** Approach Lighting ANOVA on Altitude Deviation

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<th>Source</th>
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<th>F</th>
<th>p</th>
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<td>2.26</td>
<td>.046*</td>
<td>.102</td>
</tr>
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</table>

*Significant at .05 level.

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**Figure 4.** Altitude deviation at the four levels of approach lighting. ALS = standard approach lighting system (ALS) condition; RALS = reconfigured ALS condition; COMBO = combination ALS condition.
Figure 5. Ordinal position in the sequence of random conditions.
25R, ratio 97) airports had runway approach environments with BHI potential.

A reconfigured ALS (side-mounted lights) and its interaction with viewing distance improved glide path performance in terms of accuracy and bias if added to runways with no approach-end lighting systems. This finding suggests one avenue to offset the bias of a high-ratio runway: artificially widen the runway to lower the ratio. The addition of the side lights lowered the runway’s ratio to 18. Possibly this could be used for temporary, tactical runways and may assist with visual glide path perception better than the standard ALS.

Established runways, however, already have a standard ALS installed. Our findings indicate that a reconfigured ALS should not be added to that current configuration. It is acknowledged that the purpose of an ALS is to extend the runway out toward the incoming pilot during impoverished visual conditions, flying in weather on instruments. The quandary is that during night visual approaches, those same approach lights, which help pilots during weather/instrument approaches, induce pilots into dangerously low approaches during night visual conditions.

The significantly shallow glide path induced by the combination ALS was unexpected. Possible explanations relate to Freeman’s (1966) finding that slant is overestimated for relatively larger objects as compared with smaller ones. The combination ALS produced a denser, larger illuminated area as compared with other ALS configurations. Another explanation may relate to the observation that brighter levels of illumination may appear closer (Schiff, 1994), and if the runway is perceived as closer than it is (horizontally), the pilot is induced into an unwarranted, aggressive descent toward it.

**Expertise**

The expertise variable revealed unanticipated findings. In terms of precision and bias, a difference was found between expert and novice pilots in the random terrain manipulation but not in the approach lighting manipulations. Furthermore, expert pilots flew much lower below the desired glide path, as compared with novice pilots. One could argue that the experienced pilots were falsely confident in their ability and hence started down sooner. In contrast, the novice pilots were more uncertain of their position (both vertically and horizontally) with reference to the runway and delayed descent. We should also note that a possible confounding factor was that the more experienced pilots were older.

The pilots’ level of expertise played a significant role in terms of stability (standard deviation). Surprisingly, novice pilots were more stable. At first one may attribute this to generational differences in familiarity with Microsoft Flight Simulator and/or computer game joystick controls. Also, one could argue more experienced pilots may have felt uncomfortable flying the simulator without the lateral control inputs and throttles.

Closer examination, however, suggests a difference in performance strategy. When pilots fly in impoverished conditions, a great amount of uncertainty is present as they attempt to ascertain the saliency of cues. The experienced pilots may have been seeking information and proactively varying their pitch inputs to better comprehend the visual cues in the environment, thus accounting for the appearance of instability. Fajen (2005) argued that visually controlled action theories should move away from error-nulling concepts toward an acceptable “window of performance.” Also, Gibson’s (1966) ecological approach to perception emphasized cue-seeking behavior involved in “information pickup” – the eye resonating to needed information in terms of the pilot actively searching for environmental change (p. 266).

**General Discussion**

Visual glide path overestimation in an approach and landing is influenced by runway ratio, random terrain objects, and approach lighting systems. Attempting to determine which visual cue is best is difficult, as it was found that certain cues were more salient at different distances. The attempts to reconfigure approach lights to improve glide path performance found moderate success when the illuminated objects were systematically placed on the side of the runway in isolation. Whether this success is attributable to lowering the runway’s ratio, improving surface orientation, or enhancing linear perspective is unclear. Combining those side lights with a current (standard) ALS, however, produced dangerously low glide path performance.

Aviation accidents and incidents have demonstrated that pilots may ignore or fail to perceive precision approach path indicator lights (PAPIs;
e.g., NTSB, 2002, and the 2002 F-16 near-mishap), or visual approach slope indicator lights (VASIs). Thus, it is recommended that continued efforts be made to create an airfield environment that reduces the frequency of shallow glide path performance.

Although the BHI has the appearance of a well-researched and documented phenomenon, much work remains to eliminate visual misperception as a contributing factor in aviation mishaps. The runway ratio may still prove to be the most effective way to debias the black hole approach illusion. Possibly runway shape and size, referenced by Riordan (1974) and Mertens and Lewis (1982), holds the key as the single optical invariant for visual glide path estimation. The promising results of side-mounted runway lights, created on the ideas of increasing terrain orientation via linear perspective and decreasing ratio, should foster continued efforts into ALS redesign.

Conclusion. Simply knowing about the BHI is not sufficient to prevent either the illusion or the threat to safety it engenders. Harris (1977) and Wickens (1992) pointed to the unconscious nature of visual perception and the difficulties in debiasing perceptual illusions despite objective knowledge of certain visual environments. For over 50 years, visual SD has been a topic of great interest in pilot training (Chamberlain, 2006; Cocquyt, 1953; Vinacke, 1947). Many pilot participants in this study recognized the black hole environment but then flew an inaccurate, low-biased approach. The study demonstrated that no pilot was immune from visual SD. Pilots with more experience tended to fly even lower than those with less experience. Low approaches occurred throughout the series of approaches. Visual SD represents a perceptual limitation that needs to be actively demonstrated to pilots for them to respect night visual approaches. Pilots must learn that the safest manner in which to fly a night visual approach is not to go completely visual.

Visual SD has ecological perceptual underpinnings as well as a cognitive aspect regarding pilot overconfidence in visual perception during impoverished conditions (Gray, 2006). Consequently, it is recommended that pilots perform black-hole-type approaches during their annual flight simulator training to reduce their confidence in their visual system and to help them to appreciate the lack of ambient cues available. Classroom discussions on GPO do not tap into the appropriate perceptual process. Well-designed simulator training may help pilots become more aware of the dangers of the BHI.

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