REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 10-12-2021	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* Oct 2014 - Sep 2021

4. TITLE AND SUBTITLE
Aviator Black Hole Illusion: Validated Training Countermeasures for Newly Identified Causal Factors

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Wright-Patterson Air Force Base, OH 45433

8. PERFORMING ORGANIZATION REPORT NUMBER
NAMRU-D-21-152

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Air Systems Command, PMA 205
47123 Buse Road
Building 2272, Suite 540
Patuxent River, MD 20670

10. SPONSOR/MONITOR'S ACRONYM(S)
NAVAIRSYSCOM (PMA-205)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Conventional Black Hole Illusion (BHI) avoidance training emphasizes flying into airfields at night increases susceptibility to runway depth illusions. This research hypothesized BHI episodes may also be caused by perceptual problems unrelated to variances in runway size or slope. To mitigate BHI, a customized BHI flight simulation scenario and customized training video were used to inform pilots about dynamic visual interactions of primary and secondary spatial cues. Analysis revealed revised BHI training significantly ($t(25) = -4.6$, $p < .01$) reduced BHI glide path errors. Pre-training simulated nighttime conditions caused pilots to fly landing approaches significantly lower than glide slopes observed during daytime trials. Of 26 pilots tested, 24(92%) demonstrated BHI approach characteristics (approach path < 2.5°) during night pre-training conditions. Among the 24 subjects who committed BHI errors, 21(88%) eliminated or reduced their errors after receiving spatial strategy based BHI recognition and avoidance training. BHI errors occur at distances where unfamiliar runway dimensions have little or no effect on approach performance. Educating pilots about appropriate spatial strategies involving primary and secondary cue dynamics can help reduce BHI risk.

15. SUBJECT TERMS
spatial disorientation, black hole illusion, aviation safety, night landing approaches, aerospace physiology training, degraded visual environments (DVE)

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Frederick R. Patterson, Ph.D.
UNCLAS	UNCLAS	UNCLAS	SAR	40	**19b. TELEPHONE NUMBER** *(Include area code)* (850) 572-4265

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

`   Sept-2021

NAMRU-D-21-152

NAVAL MEDICAL RESEARCH UNIT DAYTON

Aviator Black Hole Illusion: Validated Training Countermeasures for Newly Identified Causal Factors

by

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STATEMENTS

Disclaimer

Source of Support

This work was supported and funded by Naval Air Systems Command PMA-205.

Human Research/Institutional Review Board (IRB) statement

The study protocol was approved by the Wright-Patterson Air Force Base Institutional Review Board in compliance with all applicable federal regulations governing the protection of human subjects.

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Abstract

Problem: Pilot surveys and accident statistics document Black Hole Illusion (BHI) is a leading form of aviation spatial disorientation. *Background*: Conventional BHI avoidance training often emphasizes flying into unfamiliar airfields at night increases susceptibility to runway depth illusions. Previous research has confirmed the link between visual illusions and BHI; however, these studies suggest BHI is unlikely to occur at distances greater than 4.5 nm from the runway. Since mishap data indicate BHI errors often occur at runway distances greater than 4.5 nm, this research effort hypothesized BHI episodes may also be caused by perceptual problems unrelated to variances in runway size or slope. *Method*: To mitigate BHI, a customized BHI flight simulation scenario and classroom training module were used to inform pilots about the dynamic visual interactions of primary (runway image) and secondary (glareshield image) spatial cues. *Results:* Statistical analysis revealed the revised BHI training significantly ($t(25) = -4.6$, $p < .01$) reduced BHI glide path errors (i.e., glide path less than 2.5°). Pre-training simulated nighttime with horizon and no horizon conditions caused pilots to fly landing approaches significantly lower than glide slopes observed during simulated daytime trials. Of the 26 pilots tested, 24(92%) demonstrated BHI approach characteristics (approach path < 2.5°) during simulated night pre-training conditions. Among the 24 subjects who committed BHI errors, 21(88%) eliminated or reduced their errors after receiving spatial strategy based BHI recognition and avoidance training. *Conclusion:* BHI errors can occur at distances where unfamiliar runway dimensions have little or no effect on approach performance. Also, educating pilots about appropriate spatial strategies involving primary and secondary cue dynamics may help reduce BHI risk.

Introduction

Problem: Aircraft accident investigators frequently cite Black Hole Illusion (BHI) as a primary causal factor for excessively low night landing approaches (7). Conditions typically associated with BHI are nighttime straight-in visual approaches over dark featureless terrain with the horizon often obscured by clouds or fog. Conventional definitions further summarize BHI conditions as follows:

> "Without peripheral visual cues to help orient relative to the earth, the pilot tends to feel that the aircraft is stable and situated appropriately but that the runway itself moves about or remains malpositioned (is down sloping, for example)" (2).

Pilot surveys and mishap statistics indicate BHI occurs frequently among military pilots. Navy and Marine Corps flight crews report BHI is the second most commonly encountered visual problem, surpassed only by misinterpretation of fixed horizon cues (6). Air Force surveys reinforce the severity of this cognitive threat by citing BHI as the leading visual problem for flight crews of multi-engine aircraft and among all types of USAF pilots, the third most commonly reported form of spatial disorientation (SD) (15). Sipes and Lessard published a more alarming analysis that found of 141 pilots surveyed, with an average flight time of 2,886 hrs, 79% had experienced BHI, averaging 12 times each (32). In the civilian aviation community BHI is also recognized as a significant reoccurring problem. Low visibility during landing approaches has been identified as a causal factor in over 70% of commercial airline accidents, and further analysis by the National Transportation Safety Board documented accident rates during night landings are three times more frequent than mishaps occurring with daytime conditions (1).

Background: Although BHI characteristics were initially identified in 1947, research aimed at providing a better understanding of BHI did not emerge until the late 1960's (35). In 1969, Kraft and Elworth utilized flight simulation technology to test their theory that pilots succumbing to BHI inadvertently maintain a constant visual angle of the runway perimeter lights during night landing approaches (12). Since a visual angle comprised of near and far runway ends will slowly expand during normal fixed angle approaches, Kraft and Elworth surmised BHI errors occur when pilots "fly the null". Kraft and Elworth further explained the "null" is an unintended low curvilinear approach path that creates a constant runway visual angle which subsequently generates an illusion that the aircraft approach path is also constant (Figures 1a and 1b). Since early BHI investigators assumed this action was an undetected cognitive error, it provided Kraft and Elworth (as well as a host of more recent researchers) a seemingly credible explanation as to why pilots sometimes fly low and fast BHI approaches (4, 5, 23, 24, 33). Although conventional BHI explanations continue to emphasize runway visual angle misperceptions as the root cause of BHI errors, ongoing SD research has produced several variations of Kraft's original hypothesis. In 1981, Mertens' proposed the angular relationship, or splay, of the runway side perimeter lights may also contribute to BHI susceptibility (20). More recently, Galanis, et al. suggested pilots compensate for diminished or obscured horizon views by using the angular splay of runway perimeter lights to estimate the real horizon location (4). In conjunction with these complex BHI theories, a number of supporting mathematical formulas have been created to delineate algorithms of low curvilinear approach paths associated with misinterpretations of runway angle, size, slope, or shape (4, 5, 30, 33).

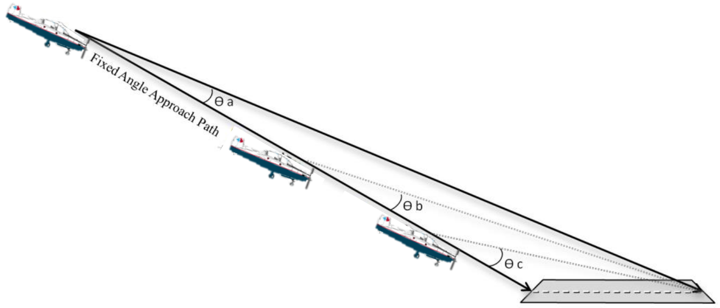


Figure 1a: In the above example, flying a fixed approach path will cause the runway visual angle to expand as the distance and altitude decreases. Kraft and Elworth believed this angular expansion would cause pilots to believe they were rising above the desired fixed glide path. In the above illustration "Θ a" equals 7.5°, "Θ b" equals 12°, and "Θ c" equals 17.5 degrees.

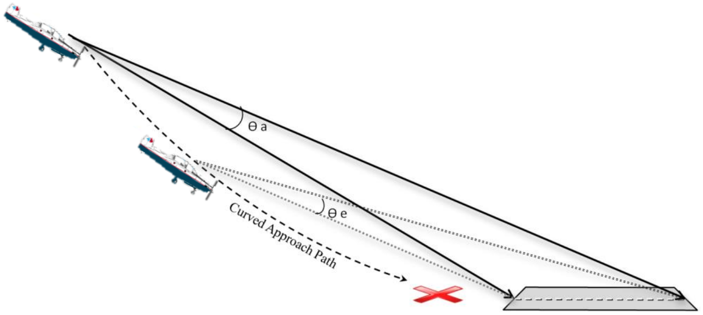


Figure 1b: Kraft and Elworth postulated that instead of flying a safe fixed angle landing approach, pilots committing Black Hole approach errors unintentionally flew low curved approaches that kept the runway visual angle constant (i.e., null angular change). Their theory was based on the assumption that keeping the runway visual angle constant would create the illusion that an aircraft's approach angle was also constant. In the above illustration, following a curved approach path: both "Θ a" and "Θ e" are equal to 7.5 degrees.

In 2007, Gibb conducted an in-depth analysis of aviation visual spatial problems and found that among the most common BHI theories there exists a total of nine different explanations (7). He concluded both the diversity and number of these explanations has confounded the search for practical solutions and suggested the following decades old statement by Hasbrook still describes the current situation:

> "…it appears that pilot perception of the approach path is often seriously in error. Whether such error is due to a lack of needed visual cues (particularly at night), visual illusions, lack of knowledge of available cues, potential error-producing visual concepts or a combination of these, it is a question that has been studied many times, but still awaits an answer" (10).

Conventional BHI theories cited by Gibb appear to have two common threads that tie these multiple explanations together. The first is the belief BHI is a problem that typically begins within a few miles of the runway and the second is an assumption that BHI errors are exclusively related to outside cockpit visual references. Regarding BHI onset, recent studies have described 4.5 nm from the runway as the most likely long-range starting point, with shorter distances causing an increase in susceptibility (8, 23). The estimated maximum onset range of 4.5 nm has been consistently incorporated into past BHI studies that utilized this distance, or even shorter distances, as an appropriate starting point for simulated BHI flight trials (14, 18, 19, 21, 22).

A second factor common among many existing BHI theories is the concept that misperception of outside visual cues is a primary causal factor and peripherally viewed cockpit structures have little if any impact on BHI susceptibility. Peripheral images of the cockpit or airframe, defined as secondary spatial cues (25, 26), were initially reported by Mertens as having no significant relationship with BHI (19). However, data used for Mertens' conclusion were generated from a series of flight experiments that kept subjects' heads immobilized on a chin rest as they peered (with one eye) through a 12 mm aperture at a reflected image of a miniature movable runway (17). To replicate cockpit secondary cues, Mertens modified his apparatus by installing, "…a [stationary] light box… to produce a luminous square frame enclosing a dark area, in the center of which the [reflected runway] model was seen during experimental trials" (19). Although Mertens considered these modifications sufficient for replicating peripheral views of the glareshield and windscreen, the subject's inability to control visual cue position, coupled with restrictive head movements and limited field of view (FOV) suggests this protocol had little in common with normal cockpit secondary cues.

Since current research indicates well defined pilot spatial strategies are essential for both recognition and prevention of BHI (or other types of SD), it is important to define the dynamics of spatial strategies within the context of aviation nomenclature (27). In general terms the word strategy refers to having a plan of action aimed at achieving a particular goal. When applied to spatial problems, a spatial strategy may be defined as a cognitive process that allows one to sense spatial patterns for the purpose of predicting and manipulating future spatial positions. When describing in-flight spatial relationships, the term "sight picture" is often used to explain how visual cues interact within a pilot's FOV. To better characterize this descriptive term, pilot "sight pictures" have been described as having specific retinal images defined as primary and secondary spatial cues. Patterson et al. previously classified primary spatial cues as stabilized retinal images that remain centered on or near the pilot's central (foveal) FOV (25, 26, 29). Secondary spatial cues were further defined as un-stabilized peripheral images perceived as being in motion relative to the primary cue during aircraft maneuvers. With flight involving visual meteorological conditions (VMC), distant aim points situated on or near the outside horizon typically serve as a pilot's primary spatial cue. Since perception of aircraft position relative to the primary cue is crucial for maintaining spatial orientation, peripheral views of aircraft structures such as glareshield, canopy bows, or wings play a vital role as secondary cues that allow pilots to gauge aircraft attitude relative to the horizon (primary cue). When outside visual references are present, pilots can accurately determine aircraft orientation by comparing retinal distances and angles of their primary and secondary spatial cues (Figure 2).

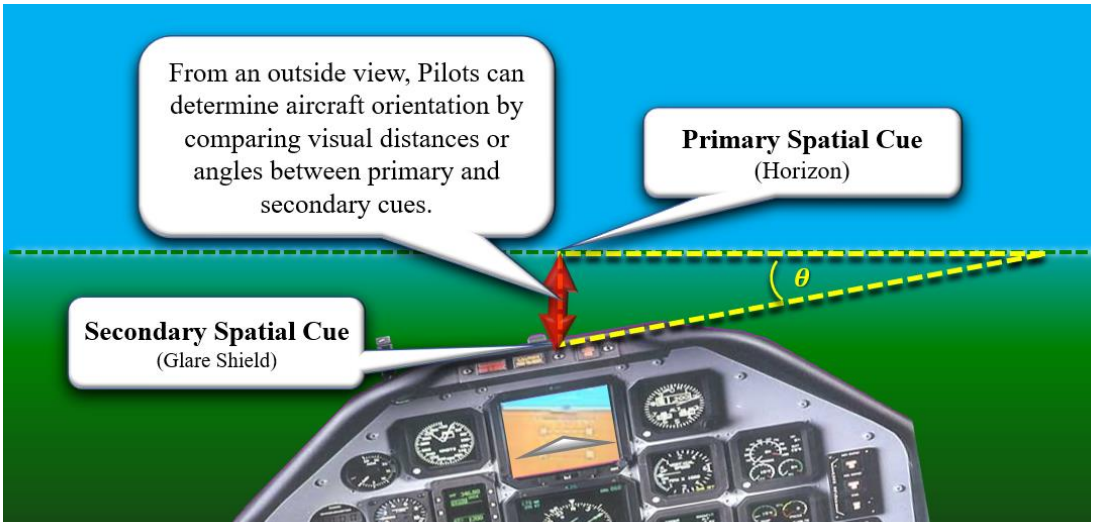


Figure 2: To maintain spatial awareness, a pilot's spatial strategy must include primary and secondary spatial cues. The relationship between primary and secondary cues provides feedback for position, velocity, and acceleration spatial information used for control input decisions.

Understanding the visual dynamics of sight picture cues is critical for developing an effective spatial strategy, since changes in visual cues provide immediate feedback indicating the aircraft response to pilot control inputs. As an example, during a normal descent, if a pilot uses a real horizon as a primary spatial cue with the aircraft glareshield serving as a secondary spatial reference, a sight picture depicting increasing separation between these two cues would indicate the aircraft nose was dropping in response to forward control stick movements. Conversely, a decrease in separation between primary and secondary cues would provide visual feedback indicating the aircraft negative pitch angle was decreasing in response to pulling back on the control stick. An important aspect of this spatial strategy is: visual feedback from the secondary spatial cues will move in the same direction as the stick control movements. This characteristic has been identified as a critical aspect of human controlled systems and is often referred to as the "principle of the moving part" (31).

During day VMC landing approaches, the horizon image and peripherally viewed glareshield provide primary and secondary cues during initial airfield lineups; however, once the approach is stabilized, the runway landing point becomes the foveal aim point (primary spatial cue). Although, the horizon continues to serve as an important spatial reference during an approach; when the center foveal position shifts to the runway aim point, the off-foveal horizon becomes a tertiary rather than primary spatial cue (Figure 3) (27). With fixed angle approaches, perceived visual separation of the horizon, runway aim point, and glareshield will remain constant until round-out and flare is initiated shortly before touchdown (3). In contrast, as the airfield distance decreases during a stabilized approach, the changing visual angles of the runway will cause the threshold image to drift lower within the sight picture as the far end runway image moves higher, at a slower rate (13) (Figure 3). During daytime VMC, clear visibility of the horizon (tertiary cue) and runway aim point (primary cue) increase spatial awareness and help prevent spatial misperceptions that can occur with changing visual angles of the runway. However, when darkness obscures both the horizon and runway aim point, pilots are forced to transition to less precise spatial cues within their sight picture. With a dark runway surface and no visible horizon, pilots must estimate their landing (aim) point using visual angle interpretations of the runway perimeter lights and glareshield. Under these conditions, researchers have suggested some pilots may use the runway threshold lights as a horizontal reference that by default becomes their primary spatial cue (29).

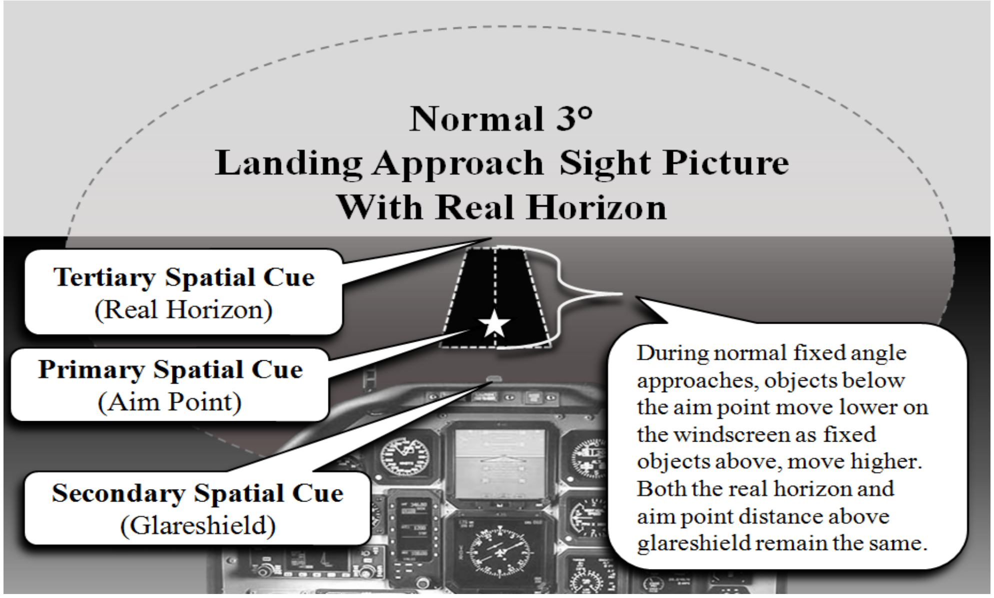
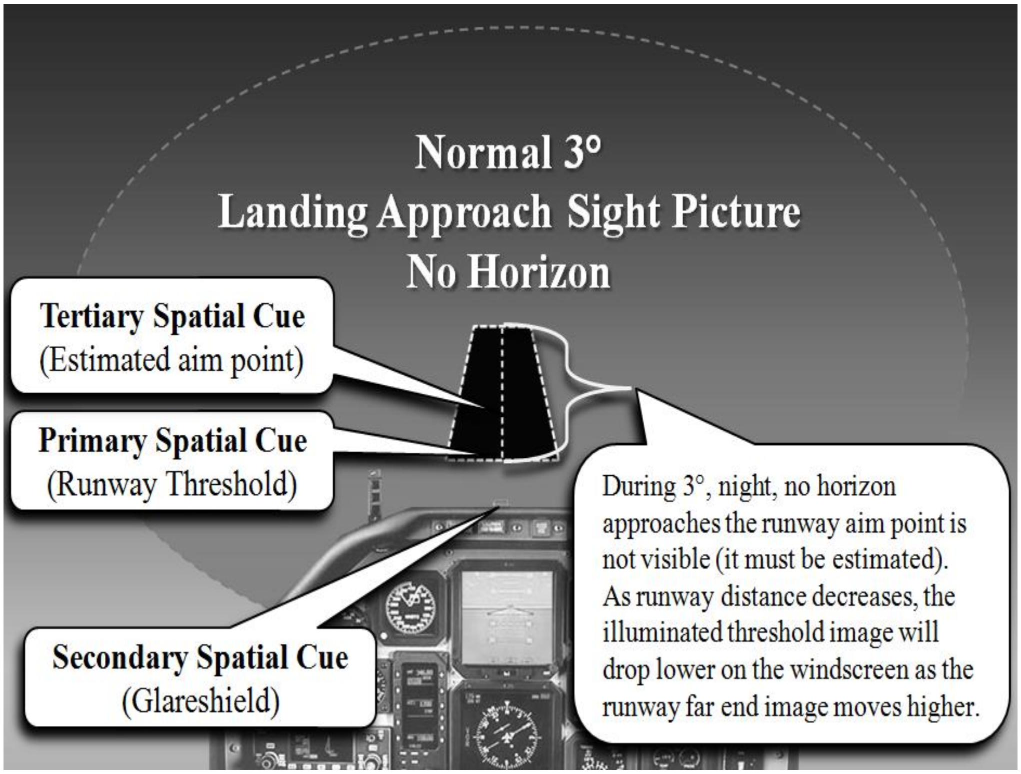


Figure 3: If an aircraft remains on a fixed 3.0° glide slope toward a runway aim point, closure with the runway will cause expansion of the runway visual angle. The runway threshold image below the aim point will steadily move lower on the windscreen and the distant runway end will move higher at a slightly slower rate. If the glide path remains constant, both the real horizon image and aim point will remain at fixed distances above the glareshield.

With night approaches, using the runway threshold as a primary spatial cue can be problematic. Unlike a real horizon image that remains visually stable on the windscreen as it moves backward in space (as the aircraft moves forward), the threshold image is a fixed ground point that will slowly drift downward toward the glareshield as the distance to the runway landing point decreases (Figure 4). Since pilots are often correctly taught that keeping the horizon image a fixed distance above the glareshield will ensure a constant glide slope during day VMC approaches (13), on a dark night with no visible horizon it would be understandable as to why some pilots might use a similar spatial strategy by substituting the runway threshold as a horizontal reference. Unfortunately, with a proper 3° runway lineup, as the descent continues, the only way a pilot can maintain a constant "sight picture" (using the runway threshold as a primary cue) is to slightly increase the aircraft's downward pitch angle as the distance to the runway decreases. Since this action would likely occur as an undetected reflexive response, rather than a well thought out process, it provides a credible alternative explanation as to why pilots occasionally enter into unintentional low and fast BHI approaches during dark night landings.



During 3°, night, no horizon approaches the runway aim point is not visible (it must be estimated). As runway distance decreases, the illuminated threshold image will drop lower on the windscreen as the runway far end image moves higher.

Figure 4: As an aircraft approaches a runway on a 3.0°, fixed glide slope, with no horizon, and no visual landing aids, the runway threshold will likely become the primary spatial cue, when the optimum runway landing point is obscured by darkness. If a pilot is able to maintain a true aim point (TAP) on the runway, it will cause the image of the runway threshold (primary cue) to drift downward in the sight picture toward the glareshield. In contrast, if a pilot in this situation attempts to keep the runway threshold/glareshield distance constant, it will set the TAP short of the threshold.

Hypotheses - Based on the premise that some pilots are unaware of the risks associated with maintaining a fixed threshold-glareshield sight picture during night approaches, two hypotheses were formulated for evaluating this potential BHI causal factor. The first hypothesis proposed low and fast BHI approaches are caused by spatial strategy errors that involve misinterpretation of primary (runway threshold) and secondary (glareshield) spatial cues: and it was further proposed that these errors can be reproduced in a non-motion-based flight simulator. The second hypothesis proposed teaching pilots about the dynamics and correct interpretation of primary and secondary spatial cues (spatial strategy theory) will help reduce or eliminate BHI errors.

Methods and Materials: All experimental protocols conducted for this study were completed at the Naval Medical Research Unit-Dayton, WPAFB, Dayton, OH, in accordance with Department of Defense (DOD) and U. S. Navy directives governing ethical research standards and protection of human subjects (DoD Inst 3216.02, November 8, 2011).

Subjects – Twenty-six subjects were recruited using local announcement posters, email, and verbal notification. Each participant in this study reported having achieved some level of piloting experience, ranging from "civilian pilot under instruction" to fully "certified military instructor pilot". The average number of pilot flight hours was 1,204 hrs (median = 305 hrs), with a range extending from 20 to 7,000 hrs. All but one subject reported having flown at night and for the entire group, nighttime flight hours ranged from 0 -1,890 hrs with an average of 264 hrs (median = 24 hrs). Eleven of the 26 pilots held instrument ratings, six were rated military pilots, and 10 were qualified commercial pilots. The average age was 40 and three of the 26 volunteers were female.

Subject tasks – For familiarization with the BHI flight simulator controls and displays, all participants completed a "hands on" 4.0 min, day VMC, loose formation flight prior to initiation of the landing trials. During this practice flight, the aircraft was initially set up in a "clean" configuration with an airspeed of 165 knots indicated airspeed (KIAS) at an altitude of 9,500 ft above mean sea level (MSL). After this familiarization flight, subjects began a series of nine landing trials, all of which began with the simulator paused and the aircraft in a wings level attitude, on a centerline course to the runway, with half flaps and gear down. The aircraft was positioned at 2,550 ft above field elevation, 8.0 nm from the touch down zone, which placed it at a 3.0º angle to the optimum landing point, 1,000 ft past the runway threshold. The runway used for this simulation was 14,000 ft long, 200 ft wide, and remained clearly visible during all trial conditions with threshold and edge lighting for night approaches.

The first landing trial was an autopilot-perfect VMC day approach designed to demonstrate what a 3.0º glide slope sight-picture looked like in this simulator. All subsequent landing trials were manually flown by subjects, who were instructed to fly a 3.0º glide slope at 110 KIAS. After watching the autopilot approach, subjects flew two day VMC "baseline" approaches (trials 2 & 3), followed by two night VMC approaches (trials 4 & 5) with dimly lit terrain and a starlit sky that helped define the true horizon. Two more night approaches under instrument meteorological conditions (IMC, trials 6 & 7) were flown next, with no visible terrain features and an overcast that completely obscured the stars and horizon. While still seated in the cockpit, subjects then watched a 5 min video that provided instruction on spatial strategy theory and described techniques for recognizing and coping with BHI. Following completion of the BHI training video, subjects flew two additional night approaches (trials 8 & 9) that were identical to trials 6 & 7. Due to technical limitation of the simulator programing system, the night and day flight trials were not randomized and were instead conducted in the order described.

For all landing approach trials the runway visual approach slope indicator and the cockpit vertical speed indicator were inoperable. No instrument landing system, distance measuring equipment, or radar altimeter information was provided. The flight instruments that were available included the attitude director indicator, airspeed indicator, barometric altimeter, horizontal situation indicator, and engine performance gauges. Light turbulence was also included with the flight simulation trials. Each trial took just over 4 min to complete and the total time subjects spent in the lab was approximately 55 mins.

Flight Simulation Apparatus –The design criteria for the fixed based BHI flight simulation system included high fidelity imagery of runway primary cues and a realistic glareshield representation that provided secondary cue information (Figure 5). The simulator utilized a T-6A flight model with out-the-window (OTW) views and cockpit display imagery generated with Laminar X-Plane® version 10.2 software. Head-down cockpit instruments were displayed on a 26 inch diagonal ELO® monitor located just beneath the fabricated metal glareshield and OTW imagery was presented on a 60 inch diagonal Samsung® LED high definition TV that provided an 87º wide by 49º high FOV, relative to the simulator design eye point. A custom built gaming computer was used to augment rapid generation of OTW scene graphics. Cockpit flight controls consisted of a Thrustmaster Warthog® throttle module for controlling power and a modified extended shaft Thrustmaster Cougar® joystick mounted on the center cockpit floor for controlling pitch and roll. For yaw control, fore-and-aft adjustable Flight Link® USB rudder pedals were installed. During flight simulation trials, subjects were seated in a padded SPARCO® seat that allowed vertical viewing angle adjustments to the simulator design eye height limits.

Figure 5: NAMRU-D fixed-base BHI flight simulator system.

Throughout the trials, subjects’ roll, pitch, and yaw head positions were monitored using an ISCAN® ETL-600 eye and head tracking device. In addition to head tracking, this system also tracked eye movements for the purpose of generating point-of-gaze data with respect to a head-mounted scene camera. The ETL-600 was able to calculate line-of-sight vector information using combined eye and head position data to display a line-of-sight intersection point, which was then stored in the database and superimposed over a global view scene display on the instructor operating system (IOS). The eye tracking system was capable of determining fixation points to within +/- 2.0 º, which provided ample resolution for determining when subjects were looking outside the cockpit or focused on the inside instrument panel.

IOS – To record data and control functions within the BHI training simulator, an IOS utilizing LabVIEW® software was integrated into the flight simulation system. The IOS provided experimenters with real-time graphic displays of the subjects’ flight path, animations of the subjects’ head movements, OTW scenery, and live video capture of subjects’ viewpoints with overlapped eye tracking information.

Through the IOS interface, data points were collected at a rate of 10 Hz and then synchronized with the flight performance data for temporary storage in the IOS buffer memory. At the end of each trial the buffer memory data were written to the computer hard drive for permanent storage in ASCII CSV format.

Statistical analysis – This study used a repeated measures design that exposed the sample population of 26 subjects to all experimental conditions. The design allowed participants to serve as their own controls for comparisons of different landing environments and the BHI pre-training and BHI post-training conditions. For the first hypothesis, which proposed BHI occurs when pilots apply a day VMC spatial strategy to nighttime no-horizon conditions, the independent variable was the availability of outside visual cues. The dependent measures used to evaluate the first hypothesis were deviation from the 3.0º glide slope, eye tracking position relative to the cockpit instruments, and deviation from the normal 110 KIAS approach speed. The second hypothesis, which proposed teaching pilots the differences between daytime and nighttime spatial strategies would help mitigate BHI, utilized pre and post BHI training conditions as the main independent variable. Dependent variables for this part of the experiment were the same as those used with the first hypothesis.

To determine the number of participants necessary for evaluating the defined variables, a power analysis was completed using G* Power statistical software. Since previous studies have reported BHI can readily occur in flight simulation settings, a medium effect size was incorporated into the power calculation. Based upon the results of this calculation, a sample size of 26 subjects was identified as the necessary population size for generation of an acceptable 0.80 power value.

Results

Runway glide slope comparison: all 26 subjects successfully completed one “hands-off” (autopilot) and eight “hands-on” (pilot controlled) BHI simulated airfield approaches using the BHI training flight simulator. At the beginning of each trial the simulator was paused at the starting position with subjects viewing a stationary OTW view that became active when the trial simulations began. Since the startup of each trial required subjects to transition from a wings level “frozen” scene to an active flight simulation, and at the same time initiate a push-over descent maneuver to set up their runway glide path, data for the first 0.5 nm of the approach (which lasted approximately 16 sec) were considered part of a control adjustment period. Because this period had large subject induced pitch variations attributed to the required push-over maneuver, data samples collected during the first 0.5 nm of the approach were excluded from the runway approach angle calculations and were instead analyzed separately. Similarly, samples from the final 0.5 nm of each flight were also excluded from the glide path calculations because: at this point in the approach, pilots were less concerned about maintaining the required 3.0˚ glide slope and were instead focused on making throttle and pitch adjustments while preparing to flare prior to touchdown. After the first and last 0.5 nm segments were removed from the processed data, samples from the remaining 7.0 nm of the approach path (7.5 – 0.5 nm) were used for defining pilot glide slope performance. Of the 26 subjects tested, 24(92%) demonstrated BHI approach characteristics (approach path < 2.5°) during simulated night (pre-training) conditions. Among the 24 subjects who committed BHI errors, 21(88%) were able to eliminate or reduce occurrences of BHI after receiving a spatial strategy based BHI avoidance training presentation.

Across all four hands-on trial conditions, the average time required for completion was 3.0 min: 30.0 ± 3.2 sec. To determine variations in glide path performance over the designated approach segment (7.5 – 0.5 nm), a runway glide slope calculation was made for every 10 Hz data point. Since two trials were completed for each of the four hands-on conditions, glide slope values for duplicate trials were combined and averaged to help normalize the data. The combined calculated glide slope values for all four experimental conditions are listed in Table I. The average day VMC glide path of 2.93° ± 0.41° verified that within the T6-A BHI flight simulator, subjects were capable of flying a daytime runway approach path within the established FAA standard of 3.0° ± 0.5° (30). In contrast to daytime approaches, averages for both night pre-BHI training conditions were well below the briefed optimum flight path and according to FAA regulations, below a safe glide path trajectory. After subjects received their video BHI training, the average performance for nighttime no horizon conditions returned to within an optimum level and was nearly identical to the average approach angle observed during simulated daytime conditions.

Visual Condition During Approach	Average Glide Path in Degrees
Day VMC.	2.93 ± 0.41
Night VMC with horizon, stars, and cultural lighting.	2.46 ± 0.34
Night IMC illuminated runway only.	2.55 ± 0.43
After receiving BHI training Night IMC no horizon.	2.92 ± 0.33

Table I: Average runway glide slope angles to optimum aim point (1,000 ft past threshold) for the four experimental conditions (n=26). Glide slopes for day VMC and night IMC post BHI training were statistically the same. VMC and IMC night pre BHI training glide slopes were statistically the same and both were significantly ($t(25) = 5.6$, $p < .001$) lower than glide slopes observed during day VMC or night IMC post BHI training approaches.

A one-way repeated measures analysis of variance (ANOVA) was conducted to compare glide slopes completed under the four experimental conditions. The experiment main effect for the four conditions had a significant ($F(3, 75) = 10.5$, $p < 0.001$) impact upon the observed glide slope angles. In addition to the ANOVA, a series of post hoc t-tests, conducted using a Bonferroni adjusted alpha level of 0.0125 (.05/4), indicated both night VMC and night IMC (pre-BHI training) conditions caused pilots to fly simulated landing approaches significantly ($t(25) = 5.6$, $p < 0.001$) lower than glide slopes observed during simulated daytime conditions. The corrected t-tests further revealed that after pilots received their BHI recognition and avoidance training, night approach performances significantly improved ($t(25) = -4.6$, $p < 0.001$) to the extent that night IMC post BHI training glide slopes were statistically the same as those observed with day VMC conditions.

Pilot total flight hours comparison: since pretrial interviews indicated a wide range of piloting experience among the experimental group, an effort was made to determine whether BHI susceptibly was influenced by the total number of hours flown. To evaluate this variable, the 26 subjects were ranked according to their number of total flight hours. Using the flight hour median as a dividing point, subjects were divided into two groups with subjects having the lowest number of flight hours (n=13) placed in the low flight time (LFT) subgroup and subjects (n=13) with the greater number of hours placed in the high flight time (HFT) subgroup. Descriptive statistics indicated flight hour averages for the two subgroups were 138 ± 85 hrs (range 20 – 301 hrs) for the LFT and 2,271 ± 1,955 hrs (range 400 – 7,000 hrs) for the HFT subjects. To evaluate BHI glide slope performances between these two subgroups, a series of Bonferonni adjusted t-tests [alpha level = 0.0125 (.05/4)] were used to compare LFT and HFT results across all four experimental conditions (Table II). Although there appeared to be a trend toward better glide slope performance with the HFT subgroup, especially in the day and post-training conditions, the difference between HFT and LFT subgroups was not significant (Figure 6).

Visual Condition During Approach	Low Flight Hour Subgroup Glide Slope (N=13)	High Flight Hour Subgroup Glide Slope (N=13)	T-test Results
Daytime VMC	2.8 ± 0.4	3.1 ± 0.4	*t*(12) = -1.7, *p* = 0.06
Nighttime VMC with horizon, stars, and cultural lighting	2.4 ± 0.4	2.5 ± 0.3	*t*(12) = -0.65, *p* = 0.26
Nighttime IMC illuminated runway only	2.5 ± 0.5	2.6 ± 0.3	*t*(12) = -0.75, *p* = 0.23
After receiving BHI training Nighttime IMC no horizon	2.8 ± 0.4	3.0 ± 0.3	*t*(12) = -1.5, *p* = 0.09

Table II: Glide slope comparisons between the Low Flight Time (LFT) and High Flight Time (HFT) pilot groups.

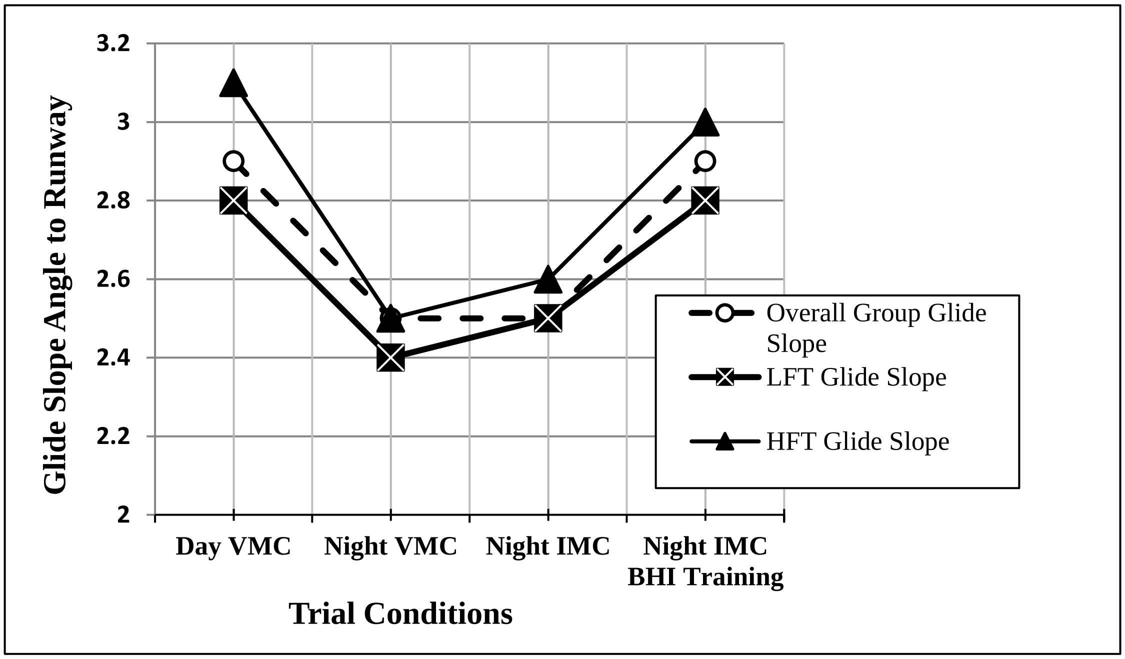


Figure 6: Illustration comparing overall group performance with low flight time (LFT) and high flight time (HFT) subgroups. Data points represent average glide path angles to optimum aim point (1,000 ft past threshold) for each of the four visual approach conditions.

Nighttime flight hours comparison: an additional variable existing within the experimental group was the number of logged nighttime flight hours. To evaluate the impact of this variable on BHI susceptibility, a statistical assessment was completed in a manner similar to that used for examining the total flight hour variable. All subjects (n=26) were ranked according to their number of logged nighttime flight hours and the group was divided by the night flight hour median into two equal subgroups. The night lowest flight time (N-LFT) subgroup (n=13) averaged 7.6 ± 5.6 hrs (range 0 – 20 hrs) and the night highest flight time (N-HFT) subgroup (n=13) averaged 520.9 ± 592.1 hrs (range 27.6 – 1,890.0 hrs). Between the two subgroups, t-test comparisons of glide slope performances indicated no significant differences between the N-LFT and N-HFT subjects; however, similar to the total flight time analysis, the N-HFT subgroup demonstrated a possible trend toward more positive performances across all four trial conditions (Table III, Figure 7). For each of the N-LFT and N-HFT glide slope comparisons, the probability values were well above 0.05, with the exception of the night IMC illuminated runway only approaches. Although, the probability value for this t-test comparison was 0.04, with the Bonferroni corrected value of 0.0125, this calculated probability value was not considered statistically significant.

Visual Condition During Approach	**Night Low Flight Hour Subgroup Glide Slope (N=13)**	**Night High Flight Hour Subgroup Glide Slope (N=13)**	**T-Test Results**
Day VMC	2.8 ± 0.4	3.0 ± 0.4	*t*(12) = -1.1, *p* = 0.15
Night VMC with horizon, stars, and cultural lighting	2.4 ± 0.4	2.6 ± 0.2	*t*(12) = -1.4, *p* = 0.09
Night IMC illuminated runway only	2.4 ± 0.5	2.7 ± 0.2	*t*(12) = -2.0, *p* = 0.04*
After receiving BHI training; Night IMC no horizon	2.8 ± 0.4	3.0 ± 0.2	*t*(12) = -1.0, *p* = 0.16

Table III: Glide slope comparisons between the night low flight time (N-LFT) and night high flight time (N-HFT) pilot subgroups. Student's t-test analysis indicated no significant differences between subgroups across all four trial conditions.
*With Bonferroni correction calculation, the *p* value difference for nighttime IMC illuminated runway was not significant.

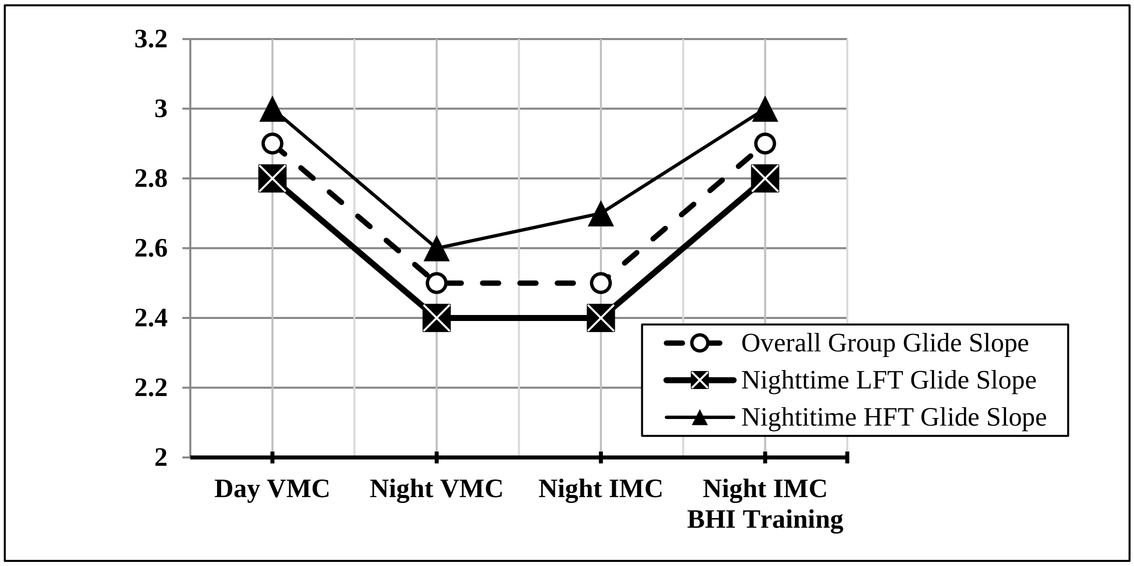


Figure 7: Illustration comparing the overall group performance with the night low flight time (N-LFT) and night high flight time (N-HFT) subgroups. Data points represent average glide path angles for each of the four visual approach conditions:

True aim point errors: the FAA Airplane Flying Handbook states that during landing approaches, "The point toward which the airplane is progressing is termed the "aiming point", which is also described as "…the point on the ground at which, if the airplane maintains a constant glide path and was not flared for landing, it would strike the ground" (3). The FAA handbook also emphasizes that, "one of the most important skills a pilot must acquire is how to use visual cues to accurately determine the true aiming point [TAP] from any distance out on final approach". During landings where the pilot's perceived aim point location is the same as the TAP, the pilot's control inputs are correct, and the aircraft is following the desired approach angle. However, if location of the perceived aim point is different from the TAP location, it indicates the pilot has committed an unrecognized aiming error that has placed the aircraft on an incorrect approach path (3).

In order to identify and quantify potential approach path aim point errors during the four trial conditions, glide slope TAPs were calculated for each 1.0 nm increment, beginning at 7.5 nm and ending 0.5 nm from the runway. The sectional slopes were determined using the differences in altitudes between the beginning and end of each 1.0 nm segment (Figure 8: night VMC example slope calculations). The incremental changes in altitude gave the "rise" needed for calculating the flight path angle using a constant "run" value of 1.0 nm. Dividing the rise by the run provided the slope (i.e., tangent) for each 1.0 nm approach segment and from this value, variations in TAP slope angles were extrapolated for each trial condition (Table IV). Table V provides data describing the group's average range of altitudes below the ideal 3.0° flight path at the beginning of each trial condition (7.5 nm), near the halfway point (3.5 nm), on final (1.5 nm), and approximately 15 sec before touchdown (0.5 nm). Consistent with the glide slope analysis described in Table II, observations collected across the four trial conditions indicated altitude errors (Table V) were prevalent during night VMC and night IMC (pre BHI training) approaches; however, after receiving BHI recognition and avoidance training, subjects' average night IMC altitude discrepancies were reduced to the same minimal level observed during day VMC (Figure 9).

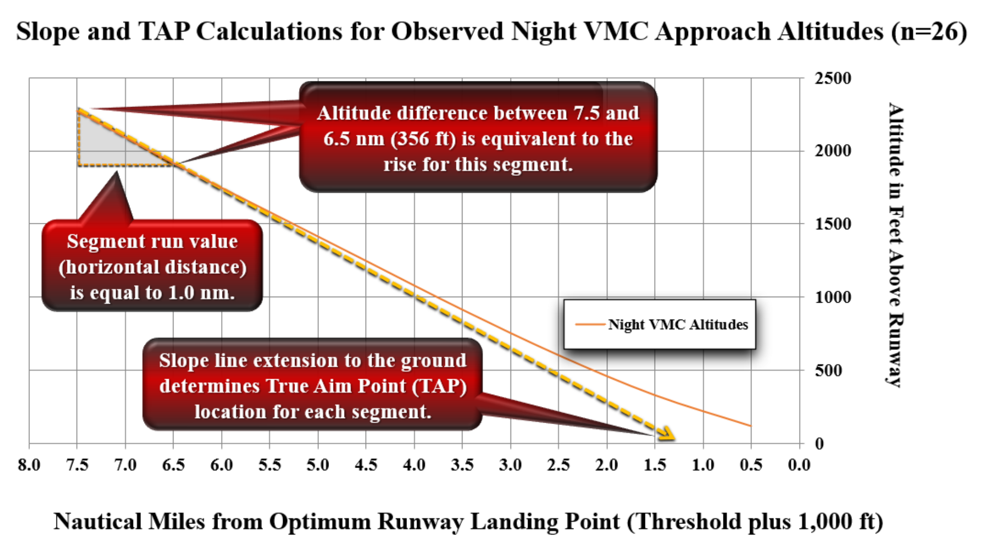


Figure 8: For night VMC pre-training trials, slope values and glide path angles were calculated for each 1.0 nm segment beginning with 7.5 nm and ending at 0.5 nm. By using the slope angles of each segment, TAPs were calculated to determine where ground contact would occur if the TAP for a specific 1.0 nm segment remained constant. The example in this figure illustrates the calculation method for the first (7.5 – 6.5 nm) approach segment.

nm	**Day VMC 1.0 nm segment angles**	**Night VMC 1.0 nm segment angles**	**Night IMC 1.0 nm segment angles**	**Night IMC post training 1.0 nm segment angles**
6.5	2.71	3.34	3.19	3.09
5.5	3.02	3.15	3.11	2.93
4.5	2.89	3.14	2.99	2.86
3.5	2.90	3.14	2.91	2.80
2.5	2.87	2.90	2.96	2.85
1.5	2.79	2.57	2.81	2.86
0.5	2.85	1.99	2.44	2.80

Table IV: The slope angle for each 1.0 nm segment for all four trial conditions was calculated by dividing each segment change in altitude by the horizontal distance (which was a constant 1.0 nm for each segment). The slope angle of each segment determined the respective TAP for that segment. By extending the segment slope vector to the ground altitude, it was possible to calculate where ground contact would occur if the TAP angle, for a particular segment, were to remain constant for the remainder of the approach.

Visual Condition	Average Feet Below 3.0° Glide Slope at 7.5 nm	Average Feet Below 3.0° Glide Slope at 3.5 nm	Average Feet Below 3.0° Glide Slope at 1.5 nm	Average Feet Below 3.0° Glide Slope at 0.5 nm
Day VMC.	79 ± 121	32 ± 144	0 ± 129	0 ± 54
Night VMC with horizon, stars, and cultural lighting.	114 ± 66	200 ± 142	148 ± 107	41 ± 55
Night IMC illuminated runway only.	87 ± 62	112 ± 173	88 ± 126	29 ± 62
Post BHI training; Night IMC illuminated runway only.	64 ± 53	31 ± 121	3 ± 113	0 ± 32

Table V: Average number of feet below 3.0° runway glide slope at critical points along the flight path (n=26). For runway distances listed, desired 3.0° glide slope target altitudes are 2,384 ft at 7.5 nm, 1,113 ft at 3.5 nm, 477 ft at 1.5 nm, and 159 ft at 0.5 nm.

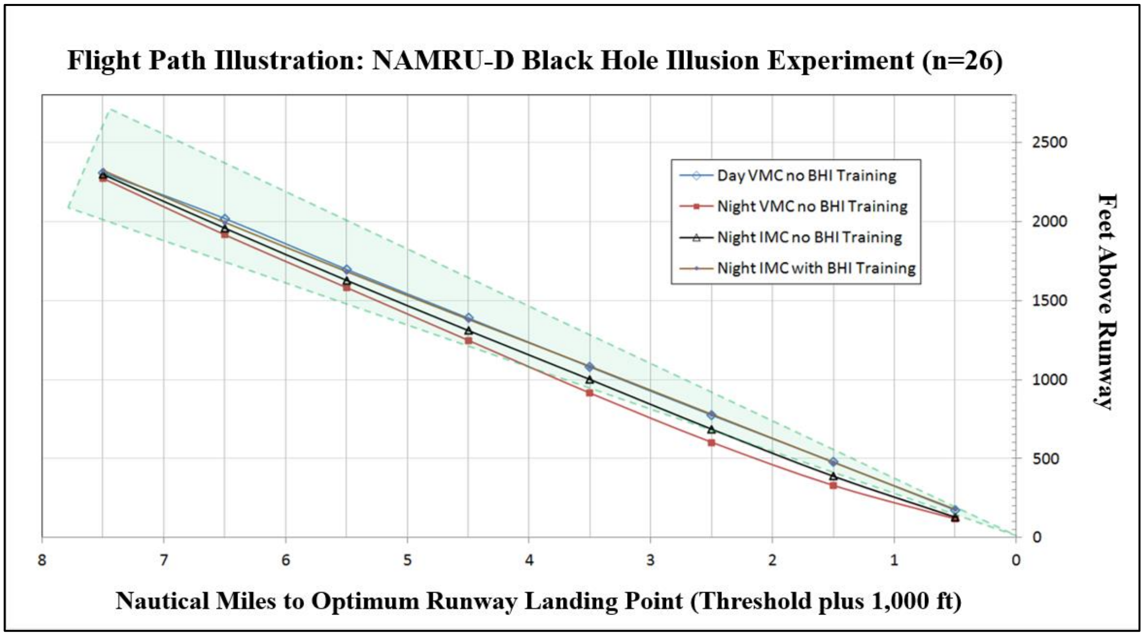


Figure 9: The above chart illustrates at one-mile increments, average approach altitude variations for all four experimental conditions. The shaded area represents acceptable FAA glide path ranges (3.0 ± 0.5°). The data for day VMC and night IMC with BHI training were nearly identical, which make these two lines on the graph difficult to distinguish.

Given the parameters of this experiment, during a perfect 3.0° approach the optimum runway TAP position was located 1,000 ft past the runway threshold; however, observed variations with runway glide slope performances indicated the TAP position selected by the subjects was continuously shifting with variations in pitch control input. After each 1.0 nm segment slope angle was determined, the respective TAPs (which can also be described as the trajectory toward a specific ground point) were calculated. This calculation made it possible to determine each segment TAP location relative to the optimum runway landing point (Table VI). During day VMC approaches, the average TAP was 522 ± 1,306 ft past the optimum landing point. In contrast, for night VMC and IMC (pre-training) trials the average TAPs were respectively 3,640 ± 2,330 ft and 2,102 ± 1,448 ft short of the optimum landing point. Since the optimum landing point was 1,000 ft past the threshold, the night VMC and IMC average TAPs were respectively, 2,640 ft and 1,102 ft short of the runway threshold. After receiving their BHI avoidance training, the subjects' average night IMC TAP placement was 83 ± 1,119 ft from the optimum runway landing point, which demonstrated a dramatic improvement and was the best performance of all four trial conditions.

nm	Day VMC distance (ft) optimum landing point	Night VMC distance (ft) optimum landing point	Night IMC distance (ft) optimum landing point	Night IMC (post training) distance (ft) optimum landing point
6.5	3,119	-6,795	-4,364	-2,594
5.5	-1,233	-4,708	-3,455	-555
4.5	173	-4,629	-2,243	261
3.5	73	-4,622	-1,576	857
2.5	289	-3,306	-1,906	457
1.5	736	-1,784	-1,189	394
0.5	497	358	13	601

Table VI: The values represented in this table are 1.0 nm segment TAP averages relative to the optimum runway landing point (located 1,000 ft past the runway threshold). Negative values indicate a TAP position in front of the optimum landing point and positive values indicate a TAP beyond the optimum point. Since the runway threshold was 1,000 ft in front of the optimum landing point, shaded negative values that exceed -1,000 ft indicate the TAP was short of the runway.

When subjects initially took control of the aircraft at the beginning of each simulated landing trial, they started from a wings level position (zero pitch and roll), which meant they had to immediately execute a nose down pitch control input to begin their descent toward the airfield. Among the four conditions, there was no significant difference between the average nose down start times, which ranged from 1.1 sec for the night IMC post BHI training approaches to 3.26 sec for night IMC pre BHI training trials. The averaged group data indicated the initial pitch down input (push-over maneuver) for all four trial conditions resulted in excessive forward stick inputs that were quickly followed by pitch up corrections to what was perceived as a proper 3.0° glide slope (Figure 10). During day VMC conditions, negative pitch peaked at -3.3° within 3.0 sec of trial initiation and was quickly followed by pitch-up inputs that stabilized the aircraft trajectory on a 3.0° runway glide path within the first 22 sec of simulated flight. With pre-BHI training night trials, t-tests with a Bonferroni corrected alpha value of 0.0125 indicated initial excess pitch down maneuvers were significantly ($t(25) = 4.6$, $p < 0.01$) greater than day VMC or night post-training conditions. During the first 4.5 sec of the pre-training night approaches, with and without a horizon, average group (n=26) push-over maneuvers respectively peaked at -4.7° and -4.3° (Table VII). Similar to day VMC trials, nighttime excess downward pitch was quickly reversed; however, unlike daytime trials, subjects consistently recovered to an approach path angle well below the desired 3.0° runway glide path. After recovering from their initial push over maneuvers during night VMC and IMC pre-training trials, subjects stabilized on TAPs that were respectively located 5,795 ft (0.95 nm) and 3,364 ft (0.55 nm) short of the runway threshold (Figure 11). From 7.5 - 3.0 nm, glide path angles for all four conditions appeared relatively stable; however, during the first half of the night VMC and IMC approaches, TAPs for both conditions continued to fall short of the runway threshold (Table VI and Figure 12). With night VMC trials, group averages indicate at approximately 3.0 nm from the runway, subjects began to recognize and recover from their BHI errors by incrementally shifting their TAPs further forward onto the runway.

Visual Conditions During Nose Over Maneuver (8.0 to 7.5 nm)	**Average (n=26) pitch angle in degrees**	**Maximum (-) pitch angle in degrees**
Day VMC.	-1.4 ± 1.1	-3.3
Night VMC with horizon, stars, and cultural lighting.	-2.7 ± 1.4	- 4.7
Night IMC illuminated runway only.	-2.3 ± 1.3	- 4.3
After receiving BHI training night IMC no horizon.	-1.7 ± 1.1	-3.5

Table VII: Average (n=26) pitch angle values for the first 0.5 nm (8.0-7.5 nm) of the runway approach during the four trial conditions. Pitch angles for day VMC and night IMC with training were not significantly different; however, both nighttime VMC and IMC (no BHI training) pitch down maneuvers were significantly greater ($t(25) = 4.6$, $p < 0.01$) than either day VMC or night IMC with BHI training.

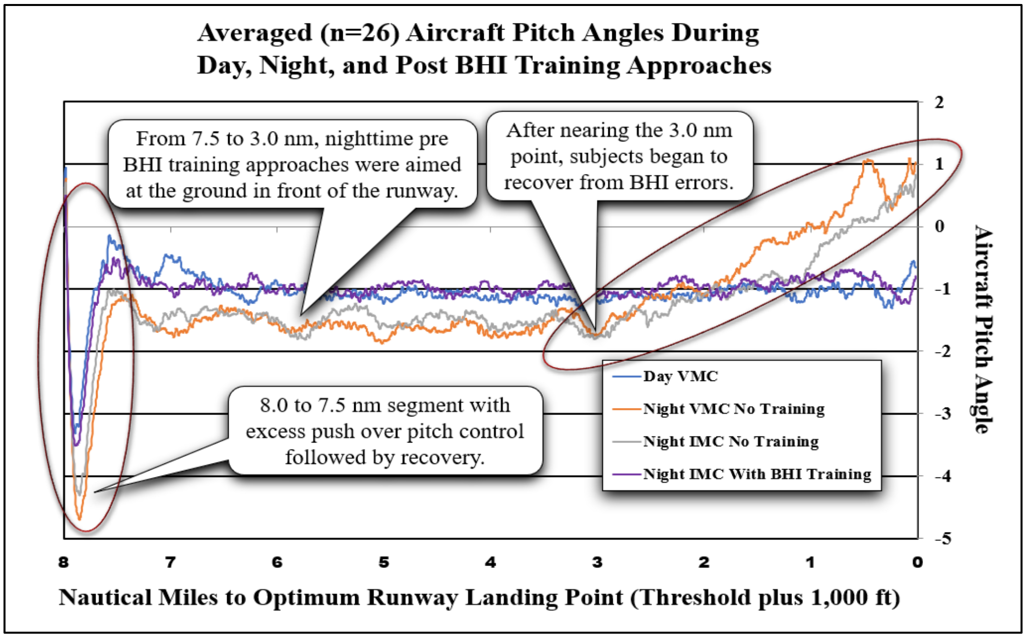


Figure 10: Aircraft pitch angles during day VMC, night with horizon, night without horizon, and night post BHI training. The grouped averages (n=26) for night VMC and IMC (without BHI training) push over maneuvers were significantly greater than either daytime or post training nighttime trials and night VMC and night IMC aircraft pitch angles were also significantly lower. However, after committing night VMC and night IMC BHI errors during the first half of the approach (7.5 – 3.0 nm), subjects began shifting their TAP's back onto the runway.

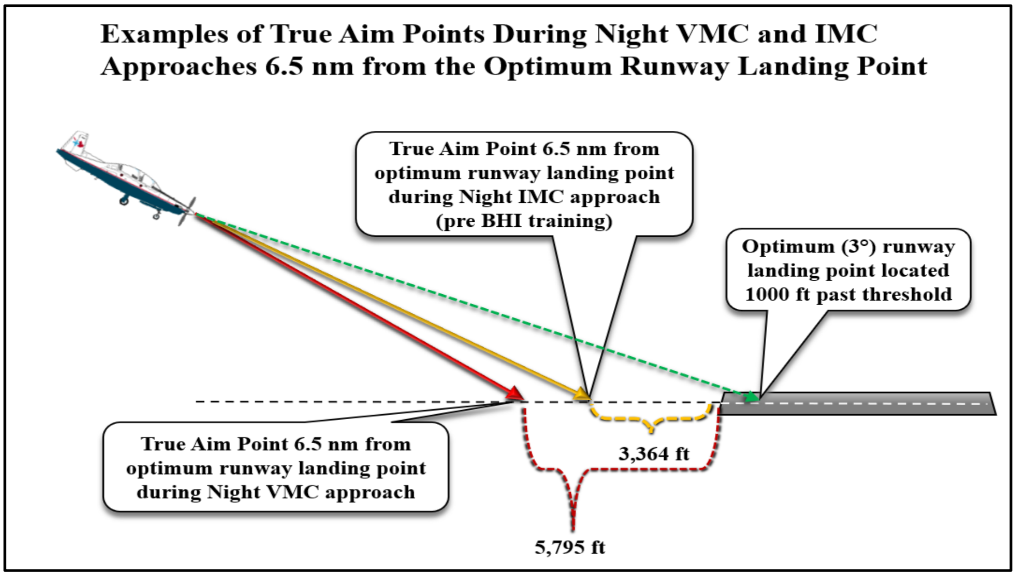


Figure 11: Illustration of improper TAP selection following excess push over (8.0 -7.5 nm) and recovery to a stable glide slope. In the above examples, after transiting from 7.5 - 6.5 nm, trajectory for the nighttime conditions (prior to BHI training) was toward ground points well short of the runway threshold.

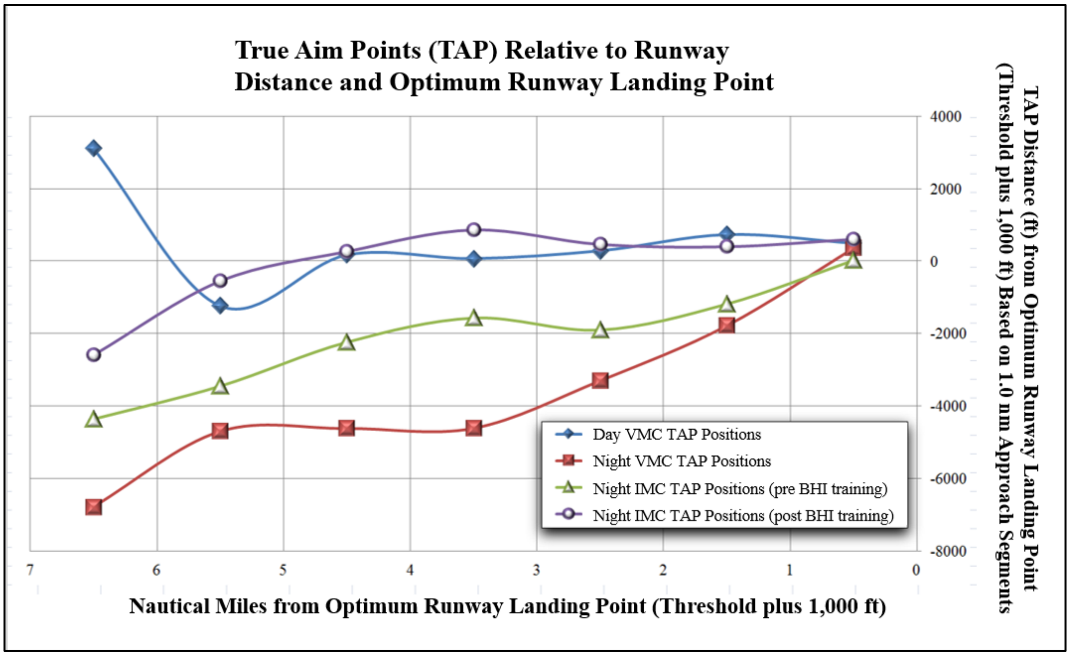


Figure 12: Illustration of the relationship between landing approach distance from the runway and TAP during day VMC, night VMC, night IMC, and night IMC with BHI training trials. For each 1.0 nm segment from the runway, beginning with 7.5 nm, the TAP ground impact point was calculated using the slope angle for each segment (Figure 9). As an example, data points aligned with the 6.5 nm marker on the horizontal axis were calculated using 7.5 – 6.5 nm slope trajectories for each respective trial condition. Data points with vertical axis values of less than zero indicate the TAP was in front of the optimum touchdown point (located 1,000 ft past the runway threshold) and values that fall below -1,000 ft on the vertical axis indicate the TAP was in front of the runway threshold. All data points on or above the vertical axis zero line indicate the TAPs for these points were on the optimum landing point or positioned further down the runway.

Airspeed Comparison: airspeed averages for each trial were analyzed using ANOVA and post hoc t-tests (Table-VIII). An ANOVA comparison of average approach airspeeds indicated the experimental conditions had a significant effect ($F(3,100) = 5.6$. $p < 0.01$) on performance. Post hoc t-tests with Bonferonni adjusted alpha levels of .0125 (.05/4) document there were no significant airspeed differences between day VMC and night IMC post BHI training trials and airspeeds for both conditions were consistent with the briefed target airspeed (110 KIAS). In contrast, t-tests with a Bonferonni adjusted alpha level of .0125 indicated pre-BHI training night VMC and night IMC approaches were significantly ($t(25) = 5.4$, $p < 0.003$) faster than either day VMC or night IMC post BHI training trials.

Visual Condition During Approach	Average Airspeed (KIAS)
Day VMC	110 ± 1.5
Night VMC with horizon, stars, and cultural lighting	111 ± 1.4
Night IMC illuminated runway only	112 ± 2.0
After receiving BHI training Night IMC no horizon	110 ± 3.2

Table VIII: Average glide slope airspeed values in knots indicated airspeed (KIAS) for each of the four experimental conditions (n=26). Day VMC and night post BHI training approach airspeeds were statistically the same and close to the briefed airspeed of 110 KIAS. Pre BHI training VMC and IMC night approaches were also statistically the same; however, both were significantly faster than either day VMC or post BHI training IMC night approaches.

Eye gaze comparison: eye tracking data were analyzed using the same statistical methods described for glide slope and airspeed evaluations. A comparison of "outside" vs. "inside" the aircraft eye gaze indicated no statistical differences among the four conditions tested (Table IX); however, the large variances observed across all four trial conditions may have contributed to the lack of statistical significance.

Visual Condition During Approach	Outside the Aircraft Eye Gaze Percentage
Day VMC	64.5 ± 19.0
Night VMC with horizon, stars, and cultural lighting	65.5 ± 17.4
Night IMC illuminated runway only	60.7 ± 20.2
After receiving BHI training Night IMC no horizon	59.8 ± 28.6

Table IX: Percent of average "outside" the aircraft eye gaze values for each of the four approach conditions (n=26).

Discussion: Results from this experiment suggest there are three sequential components to BHI errors. These components are defined as *BHI I - excess push-over*, *BHI II - improper TAP selection*, and *BHI III - failure to recognize incorrect TAP position* (Figure 13)**.** The observed BHI I and BHI II errors were most likely caused by a combination of factors related to loss of visual foreground texture and the absence of visible TAP cues. Both BHI I and BHI II errors were of short duration (approximately 4.5 and 9.0 sec) and typically involved large pitch control inputs within the first few seconds of approach initiation. In contrast, the observed BHI III errors took place over a period of several minutes and when recognized, appeared to involve slow, rather than rapid recoveries. The experimental data indicates for night VMC and IMC (pre-training) trials, BHI III lasted an average of 2 min:10 sec and extended over a runway approach distance of approximately 7.5 - 3.0 nm. After subjects arrived within 3.0 nm of the runway threshold, they began to correct their BHI III approach errors by shifting their TAP positions forward onto the runway, which subsequently caused an unstabilized concave approach path.

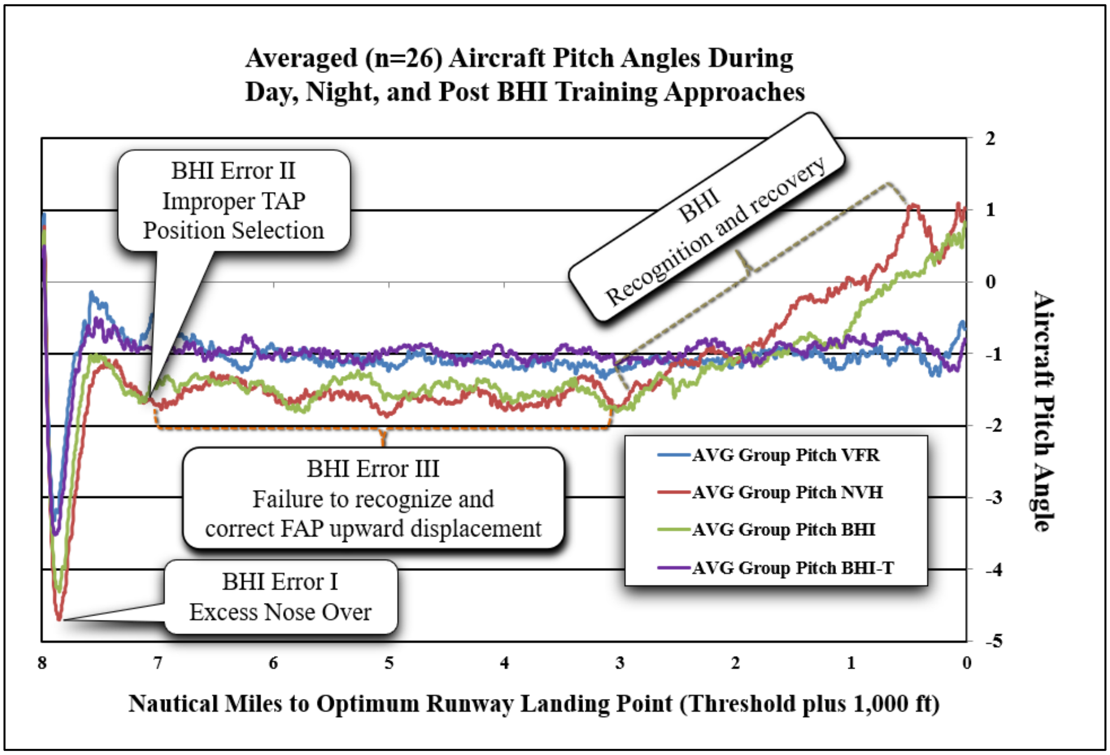


Figure 13: Aircraft pitch angles during day VMC, night with horizon, night without horizon, and night post BHI training. The pre-training group averages (n=26) for night with and without horizon approaches resulted in BHI errors I, II, and III. Recognition and recovery initiation typically occurred approximately 3.0 nm from the designated runway landing point.

BHI Error I (Excess Push-over): subjects began each BHI simulation in a wings level configuration that required pitch down control inputs to initiate descent to the runway. The data confirm excess push-over maneuvers occurred at the beginning of each trial, regardless of visual conditions (Figure 10, Table VII). With all four trial conditions, excess pitch-down was quickly followed by pitch-up corrections; however, day VMC pitch-down errors were significantly less than those observed during night VMC and IMC (pre-BHI training). Since day VMC allowed for a visible horizon and ground texture cues, the availability of these cues may be the reason why daytime conditions had significantly less push-over errors in comparison to night pre-BHI training trials. Because ground texture cues were not clearly visible for any of the nighttime trials, the push-over error reductions observed during night IMC (post-BHI training) were most likely caused by the BHI countermeasure instruction, training effects from the preceding trials, or a combination of these factors.

BHI Error II (Improper TAP position selection): after recovering from their day VMC excess push-over maneuvers, subjects made accurate and safe TAP selections that established runway glide paths within acceptable FAA parameters (3.0°± 0.5°). In contrast, during night approaches (VMC, IMC and IMC with BHI training), subjects initially stabilized their glide paths on TAP trajectories that fell short of the runway (Tables V & VI, Figure 11). One explanation for this disparity between initial day and night TAP selections is, in addition to having visible ground texture with day VMC, subjects also had the advantage of being able to view the runway optimum TAP touchdown point relative to a clearly visible horizon. Since the touchdown zone, as well as the entire runway surface, was not illuminated during night trials, selecting the proper 3.0° runway TAP position was more difficult because subjects had to estimate their runway landing point using visual angle interpretations of the glareshield and runway perimeter lights.

BHI Error III (Failure to recognize incorrect TAP position): although variations in aircraft pitch and power will cause the TAP ground position to change, it is important to emphasize that within a pilot's sight picture the TAP windscreen location relative to the glareshield remains constant, even when darkness renders the TAP image invisible. Since pilots know they must cross over the threshold lights to land on the runway, without a well-defined horizon or visible runway touchdown point, the illuminated runway threshold is likely to become a default horizontal reference (primary spatial cue). Consequently, visual placement of the threshold image on the windscreen relative to the cockpit glareshield becomes a critical spatial factor for setting both the TAP and glide path angle. During night approaches, any failure to recognize the correct sight picture dynamics of the runway threshold lights will contribute to TAP misplacement and sustained BHI III errors.

Night Approach Sight Picture Dynamics: if lift and pitch remain stable during a fixed angle landing approach, a visible TAP ground image will maintain a constant vertical height above the glareshield. However, regardless of whether the TAP is positioned correctly or incorrectly (on or off the runway) as distance from the TAP trajectory ground point decreases, the changing sight picture angles will cause ground images positioned on the windscreen below the TAP, to shift downward toward the glareshield as images above the TAP will appear to drift upward. These shifts in peripheral image positions, relative to the glareshield and the TAP, play an important role toward enhancing pilot spatial awareness because they create a dynamic sight picture that provides critical visual feedback for spatial interpretation of aircraft ground trajectory (Figures 3 and 4).

When attempting to establish a proper approach angle at night, by using only the runway lights for spatial reference, positioning the runway threshold image above or below the windscreen TAP position will determine whether the aircraft lands on the runway or crashes short of the airfield. To help illustrate this concept, during a fixed angle approach, if the runway threshold appears on the windscreen below the TAP, the continuously contracting visual angle of the threshold-glareshield will cause the threshold image to slowly shift downward toward the glareshield as altitude and runway distance progressively decrease. In this situation, downward shift of the threshold image indicates the TAP is set on the runway and confirms the aircraft is on an approach that will pass over the threshold. In contrast, if the aircraft pitch angle places the TAP position below the windscreen threshold image, the sight picture visual dynamics will cause the threshold to drift upward, which is a clear indication the aircraft is headed to a ground point short of the runway (Figure 14).

The risk for encountering BHI III errors *(Failure to recognize incorrect TAP position)* is highest at the beginning of an approach because sight picture differences between correct or incorrect TAP settings become smaller with increased distance. As an example, if a pilot begins a runway approach descent from a distance of 8.0 nm, the sight picture difference between setting the windscreen TAP position on the runway touchdown zone, or 1,000 ft short of the threshold, is less than 0.1 inch. Consequently, without proper glide slope information (Instrument Landing System or Precision Approach Path Indicator) a small error in initial TAP placement (BHI II error), would be difficult to recognize (BHI III error) during the first few minutes of a visual night landing approach. Initially placing the TAP slightly below the optimum point on the windscreen does not create an immediate problem because from a far enough distance, the aircraft will still be within an acceptable FAA 3.0° ± 0.5° flight path cone (Figure 15). From a runway distance of 8.0 nm, aircraft altitude can vary by 424 ft above or below the optimum 3.0° approach path and still remain within the FAA glide path limits; however, the diameter of an acceptable flight path cone contracts linearly with decreased distance, which causes the range of acceptable altitude limits to become progressively narrower. When an aircraft on a 3.0° approach reaches a runway distance of 4.0 nm the vertical limits will contract to ± 212 ft, and at 2.0 nm the range is further reduced to ± 106 feet.

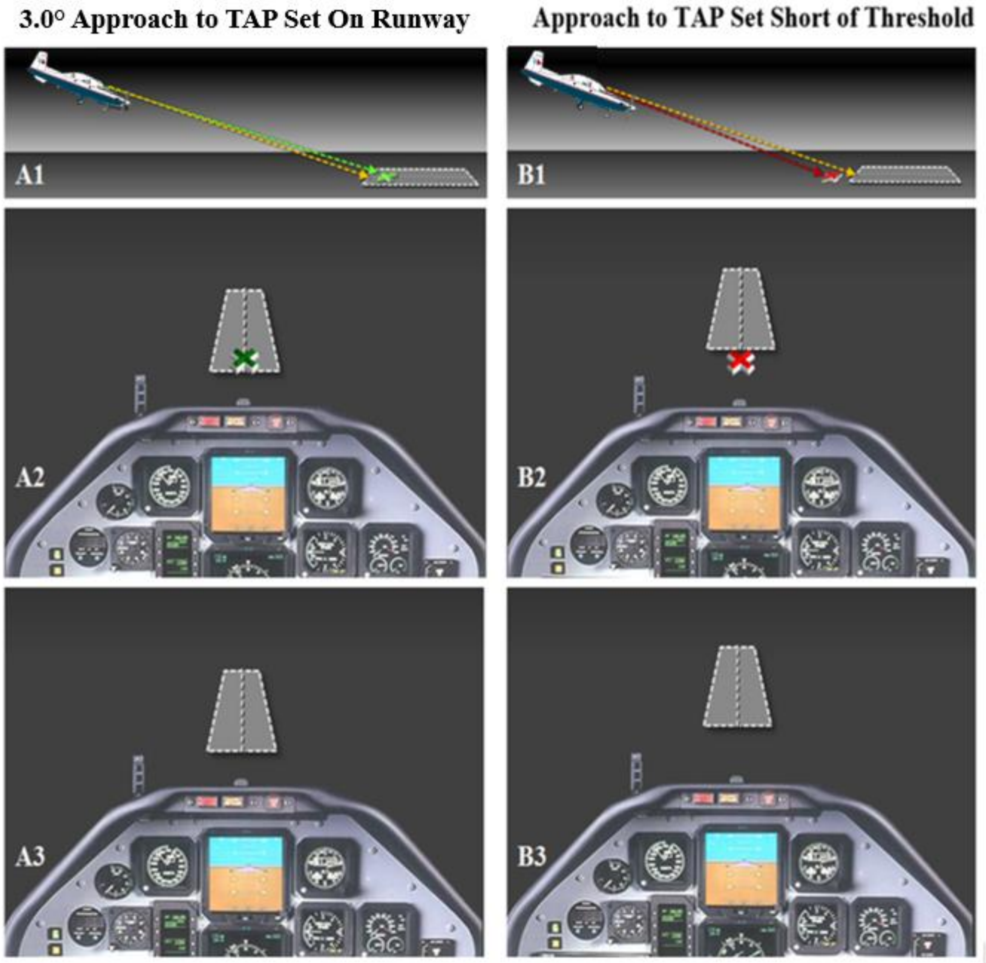


Figure 14: Series A1–A3 illustrations depict the glide path and sight picture dynamics (not to scale) encountered during a 3.0° approach to the touchdown zone. Illustration A2 includes a green "X" that represents the approximate TAP location during a successful 3.0° approach. When a pilot sets the TAP past the threshold lights, it ensures that initial ground contact will be on the runway; if the TAP remains in front of the threshold (illustrations B1-B3), a ground strike will occur short of the runway. The red "X" in illustration B2 represents a TAP location set in front of the threshold, which is a common error associated with BHI approaches. When the TAP is not visible during night approaches, pilots may choose to use the threshold lights to estimate their TAP location. Unfortunately, when starting out on a 3.0° glide path from a distance of 8.0 nm, the sight picture difference between setting the windscreen TAP position on the runway optimum landing point, or 1,000 ft short of the threshold, is less than 0.1 inch, which may cause pilots to initially fail to recognize onset of BHI errors. In illustrations A2 and B2, the TAP "X" symbols are the same distance above the glareshield; in these illustrations, it is the runway image that has moved within the sight picture.

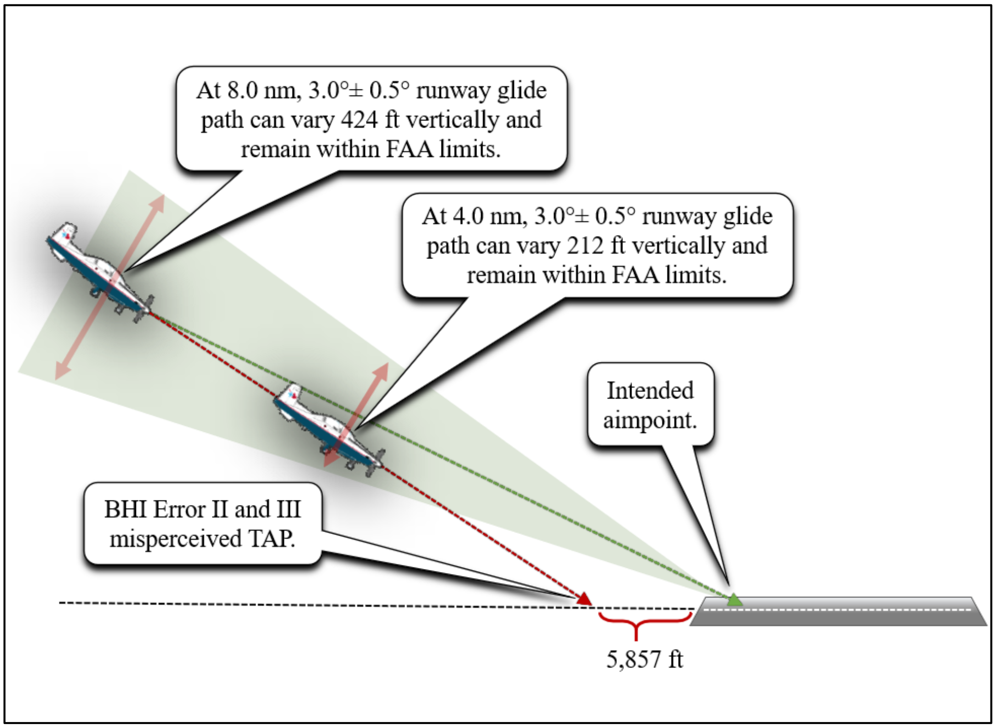


Figure 15: Illustration of vertical variation limits for 3.0° landing approaches. In this example an aircraft begins a night approach 8.0 nm from the runway on a 3.0° glide slope to the optimum landing point. A pilot who experiences excess pitch-over while initiating a night descent (BHI Error I) from 8.0 nm can inadvertently shift the TAP up to 5,857 ft in front of the threshold (BHI Error II), and at 4.0 nm still remain within acceptable FAA limits for a 3.0° ± 0.5° glide slope.

For this experiment, during night VMC and IMC (pre BHI training) trials, the average TAP trajectories selected during the initial approach segment (7.5 - 6.5 nm) were respectively 0.9 nm and 0.5 nm short of the runway (Figure 11). Neither the correct (runway) nor incorrect (short of runway) TAP ground positions were illuminated during night trials, which forced subjects to estimate their landing aim points using the runway threshold lights as a primary spatial reference. Since windscreen sight picture differences between the correct and incorrect night (VMC and IMC) TAP positions were only 0.24 and 0.15 inches respectively at a distance of 6.5 nm, it is not surprising that 24 of the 26 subjects failed to recognize their TAP placement errors during the initial approach phase.

If a pilot experiencing BHI Error II inadvertently sets the TAP 6,000 ft short of the runway at the beginning of an 8.0 nm 3.0° night approach, the aircraft will remain within acceptable FAA glide slope limits until reaching a point 4.0 nm from the runway. From 8.0 - 4.0 nm the threshold image will shift upward on the windscreen as the distance and altitude decrease; however, this movement will be small, slow, and difficult to perceive (BHI Error III). After arriving within 4.0 nm of the runway, the upward movement of the threshold image will rapidly accelerate due to exponential expansion of the glareshield-threshold visual angle and thereby increase perceptibility of TAP misplacement. The sudden recognition of upward runway threshold motion at 4.0 nm may have helped subjects initiate the observed pitch-up recoveries that moved the threshold image down toward its original windscreen position, which would have the effect of gradually shifting the TAP forward onto the runway.

The combined group data documents 24 of the 26 subjects consistently flew the first half of their night (pre-training) approaches below the desired 3.0° flight path. Although the first half of their night approaches were too low (BHI III error), subjects did inadvertently remain on an approximate 3.0° (3.2° ± 0.1°) flight path to an unintended aim point (TAP) located 0.9 (night VMC) to 0.6 nm (night IMC) in front of the runway threshold (Figure 16). Once they arrived within 3.0 nm of the optimum runway landing point, subjects began to correct their BHI III errors by moving their aim points forward toward the runway. The combined segments (7.5 - 0.5 nm) glide path angles for night VMC and IMC (pre-training) trials were typically well below the optimum 3.0° runway glide slope with respective group average runway approach angles of 2.46° ± 0.34° and 2.55° ± 0.43°. The lowest observed 1.0 nm segment glide slope averages, for night VMC and IMC (pre-BHI training), occurred on final approach at 1.5 nm, with respective angles of 1.9° and 2.3 degrees. The aim point shifting was accomplished by incrementally decreasing the aircraft nose down pitch angle, making for a shallower (unstabilized) approach, which also had the effect of nudging the TAP forward while simultaneously reducing the flight path angle (Tables V and VI). This behavioral pattern of TAP error recognition and incremental flight path recovery offers a credible alternative explanation as to why pilots experiencing BHI often end up flying a curved approach to the runway.

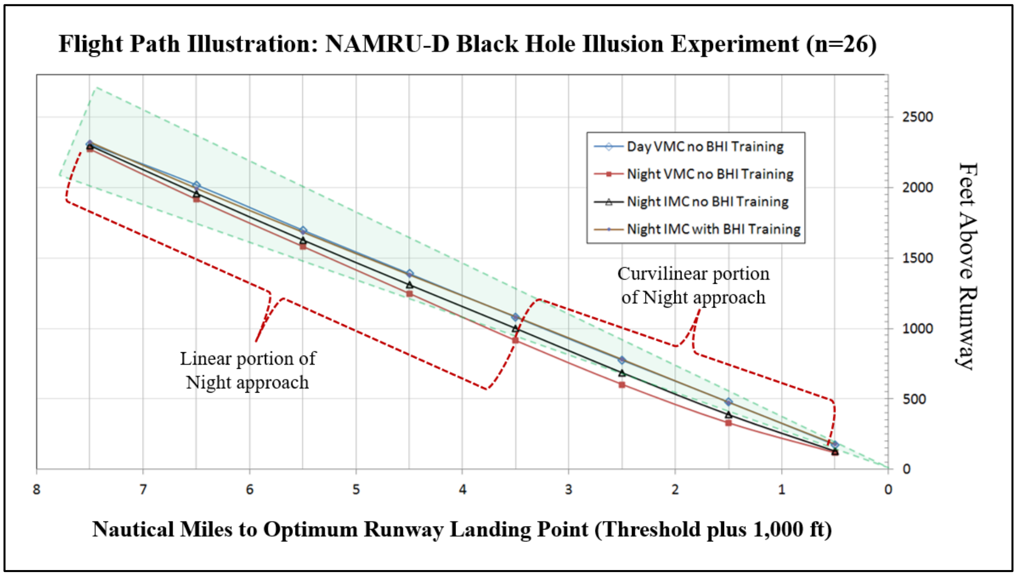


Figure16: During the first half of the night (pre-training) approaches, 24 of the 26 subjects flew a relatively linear approach to an aim point located in front of the runway threshold. After reaching a point approximately 3.0 nm from the runway, subjects experiencing BHI began to correct their error by flying a shallower (unstabilized) approach.

When both visible (day) and estimated (night) ground TAPs are correctly positioned on the runway, the windscreen TAP location relative to the glareshield remains stationary; however, as altitude and distance decrease during a stable runway approach (with the TAP set on runway) the visual angle of near and far ends of the runway increases (Figure 17). During night approaches, the threshold perimeters lights in front of a correctly positioned runway TAP will appear to move lower on the windscreen as images of the runway lights beyond the TAP move higher. Because the far end runway lights move upward on the windscreen at a slower rate than the threshold lights move downward, runway landing point estimates become progressively more difficult since near and far runway proportions (relative to the TAP) change at an increasing rate with reductions in altitude and distance. As an example of this perceptual anomaly, calculated sight picture models with runway dimensions used with this experiment indicate from 8.0 nm, an aircraft on a perfect 3.0° glide slope to the designated runway touchdown point will have a 1:10 TAP ratio (between near and far ends of the runway). During the first half of the approach, as the aircraft reaches 4.0 nm, the TAP runway ratio will be reduced to 1:8.1 and after passing the 4.0 nm mark, the ratio will begin a non-linear contraction down to 1:3.8 at 1.0 nm (Table X). Unfortunately, for pilots trying to recover from BHI III errors that become perceivable at runway distances of less than 4.0 nm, spatial estimates of the correct TAP position are made more difficult by the sudden non-linear changes of the runway/TAP proportions.

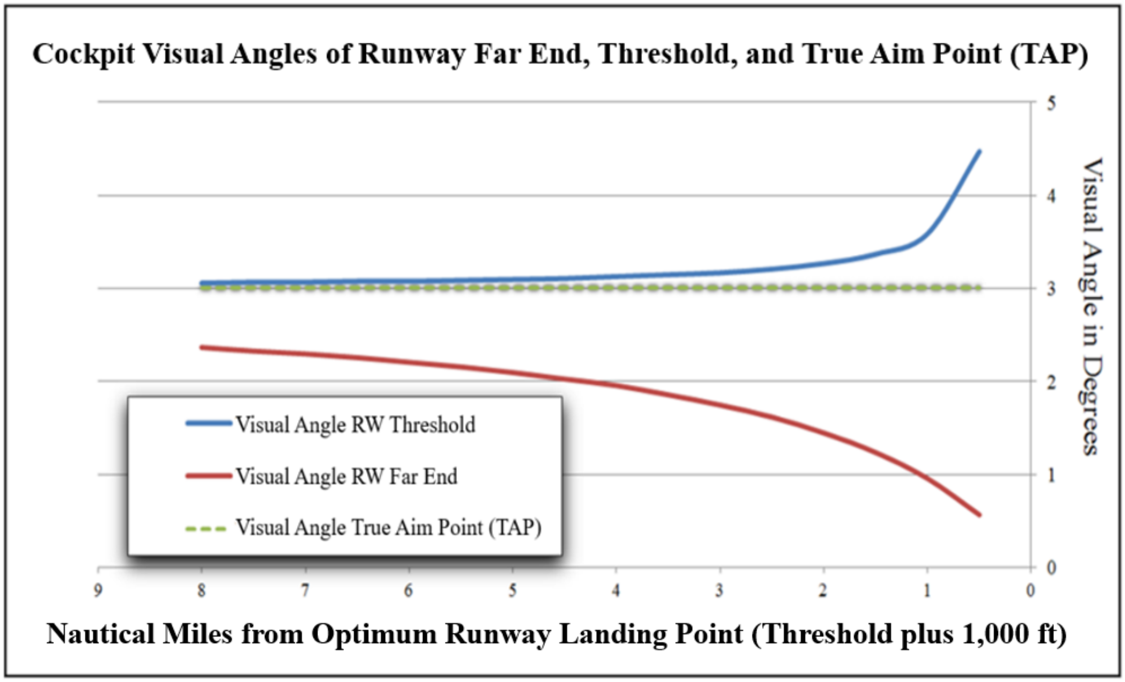


Figure 17: Illustration of runway visual angles and TAPs encountered during a fixed 3.0° approach. When the TAP is located between near and far ends of the runway, the far end visual angle will decrease as the near end (threshold) visual angle increases. The nonlinear expansions of the runway visual angles will cause a proportional shift between runway segments in front of and beyond the TAP.

Distance (nm) to Runway Optimum Landing Point	Ratio of Runway Segments in Front of and Beyond the True Aim Point (TAP) during a 3.0° Approach
8	1 to 10
7	1 to 9.7
6	1 to 9.3
5	1 to 8.8
4	1 to 8.1
3	1 to 7.2
2	1 to 5.8
1	1 to 3.8

Table X: Table of visual angle ratio relationships between portions of the runway in front of and beyond the True Aim Point (TAP) during a normal 3.0° landing approach.

Perception thresholds for sight picture dynamics: perception of spatial cue changes within a pilot's sight picture is dependent upon limitations of Visual Short Term Memory (VSTM) and the human threshold for detection of angular variations (referred to as the High Contrast Visual Angle threshold or HCVA) (11). To evaluate how these two factors impact BHI susceptibility during night approaches, an analysis was made to determine whether or not the initial sight picture changes encountered during the first half of the night approaches were within the limits of human perception. Since VSTM storage decays by 50% within 4.0 sec, and unrefreshed VSTM images essentially disappear after 10 sec, in order to detect changes in spatial cue positions; visual angle variations causing retinal shifts must be above the optimum HCVA threshold of 0.017° and a perceptible angular change must occur within 10 sec or less (16, 36). To illustrate these sight picture dynamics; if an aircraft travelling at 110 KIAS began a 7.5 nm 3.0° glide slope to a landing point 1,000 ft past the runway threshold, with primary (landing point) and secondary (glareshield) cues vertically spaced 6.0 inches apart on the windscreen, the runway threshold image would initially shift downward on the windscreen approximately 0.002 inches, every 10 sec. From 7.5 to 3.5 nm, the threshold image rate of motion would slowly increase; however, the threshold downward movement would still remain below the limits of human perception (less than 0.017º over 10 sec). Consequently, from approach distances of 3.5 nm or more, with airspeeds of 110 KIAS or less, a pilot is likely to misperceive the threshold image as remaining stationary on the windscreen, even though it is slowly shifting downward. In contrast, under the same flight parameters, when the TAP is set on the runway, once an aircraft arrives within 3.5 nm of the airfield, there will be a sudden exponential expansion of the threshold/glareshield visual angle that will cause an accelerated and easily detectable downward shift of the threshold image (Figure 17). If the TAP is placed incorrectly in front of the threshold at the beginning of an 8.0 nm night approach (BHI II error), instead of the threshold image shifting downward toward the glareshield, the image will slowly drift upward at an undetectable rate. When the aircraft arrives within 3.5 nm of the airfield, the accelerating upward movement of the threshold will make the TAP placement error more apparent, at which point BHI recognition and a curved approach recovery becomes more likely to occur.

Conclusion: Consistent with the sight picture dynamics described above, the observed experimental data for nighttime trials documents an improvement in glide slope tracking performance once subjects arrived within 3.0 nm of the runway. An examination of subject data from those who appeared most susceptible to BHI errors reinforces the concept that pilots appear to recognize and recover from the effects of BHI, once closure with the landing point causes spatial cue motion to accelerate above human perceptual thresholds. One subject, an instrument rated military pilot with over 3,000 flight hours, was among those who demonstrated a high susceptibility to BHI. His performance closely tracked a linear BHI approach path until he reached a point approximately 3.5 nm from the runway. After closing to this distance, the data indicate he began to correct his glide slope error by gradually reducing the aircraft downward pitch angle (Figure 18), which subsequently decreased his flight path error from -343 ft at 4.0 nm to -26 ft at 0.5 nm. An important consequence of this corrective action was it caused the TAP to gradually shift forward onto the runway. Since data from this experiment indicate a similar pattern for the combined subjects' night approach trajectories, the results support the proposed theory that curvilinear BHI flight paths begin when the primary cue (threshold image) rate of upward motion reaches a perceptual threshold that allows for sight picture error detection and correction. Although conventional BHI theories assume pilots commit BHI errors when they choose to fly the "null" of the runway visual angle, the results of this study suggest BHI errors are more likely caused by inappropriate TAP placement and failure to recognize the risks associated with keeping the runway threshold and glareshield sight picture constant.

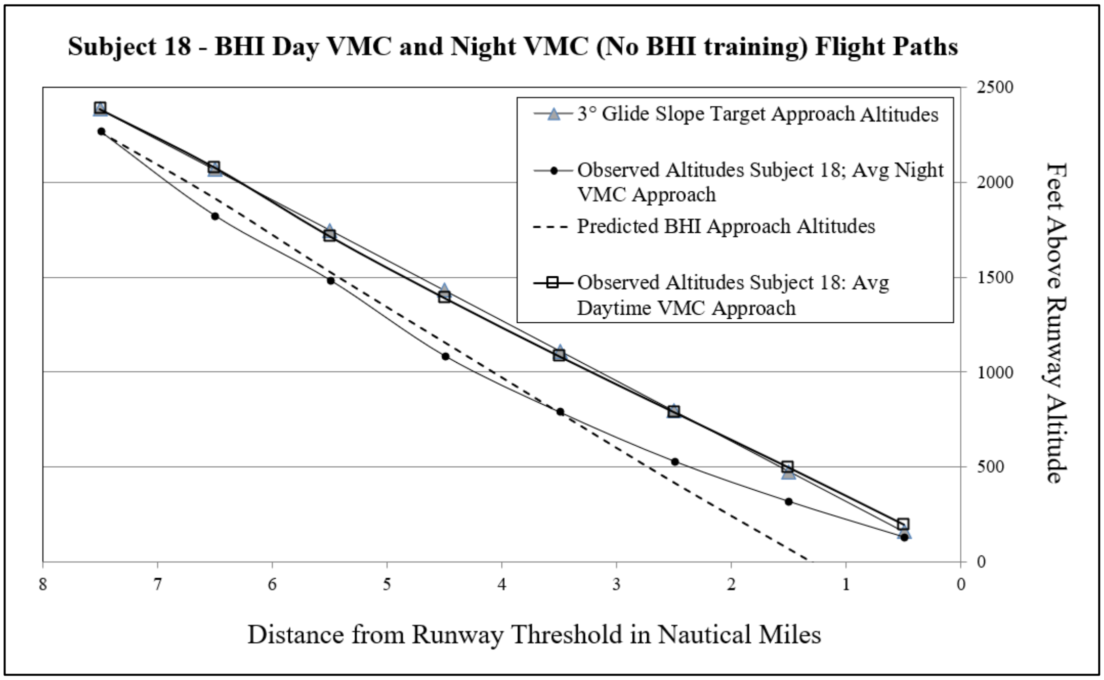


Figure 18: Subject 18 BHI day VMC and night VMC (no BHI training) flight paths with target 3.0° glide slope altitudes and predicted BHI approach data generated from the BHI spatial strategy model.

Based upon the experimental results, the first stated hypothesis appears to be valid with regard to confirming the possibility that BHI errors are caused by misinterpretation of primary (runway threshold) and secondary (glareshield) spatial cues. The experimental data also documents this type of spatial disorientation can be readily induced in a properly designed non-motion-base flight simulator. The second hypothesis, which proposed teaching pilots how to correctly interpret primary and secondary spatial cues will reduce BHI risks, also appears to be true since there was an 88% reduction in nighttime low altitude approaches after subjects received their five-minute BHI countermeasures training. However, since practice effects with repeated trials may have influenced pilot performance, the results of this study should be confirmed using a counterbalanced design.

Recommendations: For preventing future BHI accidents and improving night landing approach performance, providing pilots with instruction that covers the following training objectives may help reduce the risk of BHI:

1. When initiating a night approach, during transition from level flight to a descent attitude, there is often a tendency to use excessive pitch down control inputs that are followed by inadequate pitch up recovery. This error often results in stabilizing the glide slope on an aim point that is short of the runway threshold (BHI Error I).
2. During night approaches, the TAP position is frequently set short of the runway during the initial approach phase (BHI Error II). The visual difference between having the TAP set in the correct or incorrect position may not be perceivable until the aircraft is approximately 4.0 nm from the airfield, depending upon the approach airspeed (faster speed will increase detection distance and slower speeds will shorten it).
3. Any upward movement of the runway threshold on the windscreen is a clear indication the TAP is set short of the runway and ground impact will occur if flight path corrections are not made.
4. If the TAP is set on the runway, the threshold visual image will steadily move downward on the windscreen (toward the glareshield) and the far end of the runway will appear to slowly move upward.
5. If the TAP is set short of the threshold, depending upon the runway length, the runway will suddenly appear to flatten out approximately 2.0 nm from the threshold. Any appearance of runway “flattening” is a clear indication the aircraft is below glide slope and will land short if corrections are not made.

Documenting the BHI sight picture dynamics that occurred during this study has been an important first step toward better understanding this common form of spatial disorientation. Additional studies should be conducted for the purpose of refining, training, and designing methods for avoiding, recognizing, and recovering from BHI I, II, and III errors.

Acknowledgements

The authors of this study wish to acknowledge and thank both Mr. Dain Horning and Mr. Charles Powell for their outstanding technical support that helped make this research possible. Mr. Horning provided insightful and valuable statistical applications that enhanced development of the experimental design and contributed greatly to the analysis of collected data. Mr. Powell's specialized expertise with designing and operating advanced simulator systems made it possible to create a realistic pilot in-the-loop BHI simulation that was critical to the success of this research.

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