

NIGHT-VISION GOGGLES IN HELICOPTER OPERATIONS: POTENTIAL CONTRIBUTION TO SPATIAL DISORIENTATION AND OPERATIONAL IMPLICATIONS

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Introduction: Night vision goggles (NVGs) extend the capability of helicopter crews to conduct night operations, but they do not reproduce daytime vision and may alter the visual conditions in which spatial disorientation (SD) develops. A historical helicopter study reported an approximately five-fold higher SD-related accident rate during night-vision device (NVD) operations than during daytime flight. This review examines how NVG/an night vision imaging system characteristics, degraded visual environments (DVE) and crew-system interactions may contribute to the development or delayed recognition of SD, and identifies practical safety barriers for helicopter operations.

Methods: This purposive narrative review integrates peer-reviewed aviation-medicine and human-factors literature with a structured analysis of seven publicly documented helicopter accidents or serious incidents involving NVG/NVD operations. The case analysis distinguishes official investigation findings from the author's interpretation and maps case evidence onto recurrent perceptual, cognitive and operational mechanisms.

Results: Across the seven cases, recurrent patterns involved low-contrast or featureless scenes, loss or degradation of visual references, blooming or incompatible lighting, delayed transition to instruments and attentional or crew-monitoring failures. Five proposed conceptual operational pathways summarise how these conditions may converge on SD.

Discussion and Conclusions: The principal hazard is not NVG use per se, but continued reliance on a partially reliable external image that may omit a stable horizon, surface texture, optical flow or valid depth cues. Mitigation therefore depends on predefined visual-reference minima and abort criteria, early transition to instruments, compatible lighting, radar-altimeter and flight-parameter monitoring, realistic DVE training, and assertive crew coordination.

Keywords: spatial disorientation, degraded visual environment, human factors, situational awareness, crew resource management

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INTRODUCTION

Spatial disorientation (SD) is an incorrect perception of the position, motion or attitude of the aircraft or pilot relative to the Earth's surface, the gravitational vertical or another relevant reference [13]. Three classical types of SD are defined [23]. In Type I, the pilot is unaware of the disorientation; in Type II, the pilot recognises a conflict but may not identify it as SD; and in Type III, the pilot recognises SD but is unable to recover effectively because of cognitive or physiological overload [9,21,23].

At night, visual information, the principal source of spatial-orientation cues, is reduced because the horizon, surface texture, optical flow and distance cues are less available, increasing reliance on vestibular and proprioceptive information that may be misleading in flight [21,23]. In such conditions, night vision goggles (NVGs) may provide an apparently usable but incomplete external image, potentially delaying recognition that visual flight references have become inadequate.

Night vision goggles are image-intensification devices widely used in military aviation, helicopter emergency medical services, search and rescue, police, border-guard and special-operations flying [1,22,25]. The broader term night-vision device (NVD) includes NVGs and other night-vision technologies. In this paper, NVG is used to refer to goggles, whereas NVD is retained when that broader terminology is used by a cited source. Braithwaite et al. [5] reported approximately 9 SD-related accidents per 100,000 helicopter flight hours with NVDs compared with 1.66 per 100,000 flight hours in daytime flight. This historical association does not establish that NVGs themselves cause SD. Consistent with a systems approach to accident causation [24], the present review treats risk as arising from interactions among human physiology, sensor and interface limitations, environmental conditions, mission demands, training, crew resource management (CRM) and organisational safety barriers.

The primary aim of this narrative review is to examine how NVG use and night vision imaging system (NVIS) characteristics may contribute to the occurrence or delayed recognition of SD during helicopter flight. The second aim is to identify practical implications of NVG use that may inform strategies to reduce the risk of SD during NVG-aided flight, with particular attention to recognising degraded visual conditions, transitioning to instruments, crew coordination, training, and operational go/no-go or mission-abort decisions.

METHODS

This paper is a purposive, non-systematic narrative review combined with a case-based analysis. The literature synthesis was developed from peer-reviewed publications in aviation medicine, visual psychophysiology, human factors and NVG ergonomics, together with military or government guidance and accident-investigation material. Sources were selected for their direct relevance to: (1) SD physiology and visual-vestibular conflict; (2) NVG/NVIS image characteristics and cockpit integration; (3) workload, attention, situational awareness and CRM; and (4) operational barriers relevant to DVE, inadvertent entry into instrument meteorological conditions (IMC) and night helicopter operations.

Peer-reviewed publications, military documents and government reports were prioritised. Secondary or popular sources were used only as supplementary material when a primary source was unavailable. Because the source collection was not conducted as a systematic review, retrospective database names, Boolean strings or a formal date window are not reported as though they had been prospectively defined. Instead, the reporting has been expanded to make the narrative-review scope and its limitations explicit, consistent with SANRA principles [2].

For the case analysis, events were eligible if: (1) NVG/NVD use or operation under NVIS conditions was documented; (2) the report described SD, loss of visual references, loss or misjudgement of depth/height, loss of situational awareness, entry into a DVE or IMC, or a closely related loss-of-orientation sequence; and (3) sufficient publicly accessible source material was available to distinguish investigation findings from interpretation. Seven helicopter accidents or serious incidents meeting these criteria were selected as illustrative cases. The author did not attempt to construct a complete epidemiological register of all NVG/SD events. Each case was re-examined using the same extraction framework: circumstances, official investigation findings, the NVG/NVD role explicitly stated by investigators, and the author's interpretation. Cross-case comparison was then used to identify recurrent mechanisms and to map them onto the conceptual pathways presented below. No statistical pooling or estimation of event frequency was attempted. Because the case sources identified for this purposive analysis were predominantly English-language reports from English-speaking jurisdictions, the sample may underrepresent events documented in other languages or reporting systems. In the case descriptions below, the first paragraph

summarises circumstances, official findings and any investigator-attributed NVG/NVD role; the second paragraph provides the author's interpretation.

FINDINGS

NVG technology

Aviation NVGs use image-intensification technology to amplify available visible and near-infrared (IR) energy and present an intensified image to the user. They can make terrain, obstacles, landing-zone features and selected horizon cues visible when unaided night vision is insufficient, but image quality depends on illumination, contrast, atmospheric conditions and system integration [1,9,22,25]. NVGs do not see through cloud, fog or precipitation, and a bright image does not necessarily contain the spatial cues needed to judge attitude, height or motion reliably. Their value is greatest when the scene contains usable contrast and texture and when cockpit and external lighting are compatible with the NVG.

Typical aviation NVGs provide a field of view (FOV) of approximately 40 degrees, much narrower than unaided peripheral vision [9,22]. The intensified image is monochrome or near-monochrome, has limited spatial and contrast resolution compared with daylight vision, and may be affected by scintillation, halo, blooming, reflections or automatic-gain effects.

During NVG operation, primary instruments are usually viewed below or beside the goggles, so the pilot must switch repeatedly between an intensified external image and cockpit displays. Suboptimal lighting, high workload, fixation on an external cue or an unexpected image anomaly can delay the instrument cross-check [9,22]. Accordingly, spatial orientation in NVG flight depends on the entire NVIS, cockpit lighting, external light sources, procedures, crew roles and instrument monitoring, rather than on the goggles alone.

How NVGs modify the conditions for spatial orientation

The central concern is not that NVGs create a unique form of SD. Rather, they may provide a partially reliable image: enough information to sustain visual confidence while one or more orientation-critical cues are absent or degraded. A pilot may see roads, lights, terrain or a coastline yet lack a stable horizon, usable surface texture, peripheral optical flow or reliable depth information. Under these conditions, continued visual control may become progressively less reliable even though the scene does not appear completely "lost" [1,5,17,22]. This distinction is important when applying the

classical Type I-III SD framework. NVGs do not cause the vestibular mechanisms underlying the leans, somatogyral or somatogavic illusions. Their possible contribution is indirect. If the external image provides weak or misleading corrective visual information, an erroneous vestibular or cognitive interpretation may persist longer or be recognised later. The evidence therefore supports describing NVG-related modifiers of SD conditions rather than NVG-induced textbook illusions.

The approximately five-fold NVD/daytime difference reported by Braithwaite et al. [5] is best interpreted as an exposure-level association in helicopter operations, not as a device-specific causal effect. NVDs permit demanding night tasks to be undertaken at low altitude and in environments with sparse visual cues. The resulting risk is therefore inseparable from mission type, illumination, terrain, weather, instrument monitoring, crew decisions and organisational criteria for continuing or aborting the flight.

Perceptual, operational and system factors potentially contributing to SD

The intuitive expectation is that, because NVGs allow pilots to see more at night, they should reduce the risk of disorientation. This is only partly true. NVGs increase the number of visible objects and may help preserve horizon, terrain and obstacle cues, but the intensified image differs from both daytime vision and unaided night vision. The pilot may therefore perceive the scene as usable even when information about depth, the horizon, peripheral motion or the ground or water surface is incomplete. The operational concern is not image brightness alone, but whether the image contains orientation-relevant cues of sufficient quality [1,5,17,25].

A first operational factor is the limited FOV of NVGs. The relevant orientation mechanism is the resulting reduction in peripheral optical-flow information. Peripheral motion normally contributes to the perception of self-motion, drift, bank and closure. A narrow central field therefore requires active scanning and can make subtle changes in attitude or descent harder to detect, especially over water, snow, desert or other low-texture surfaces [1,9,22].

A second operational factor is the interaction between image quality and environmental contrast. Even when acuity is acceptable under favourable night conditions, the intensified image can lose surface gradients, shadows and texture in low illumination or low contrast. Over calm water, snow, desert or uniform terrain, selected objects may remain visible while height, rate of descent

or distance may be misjudged [1,22,27]. This is a limitation of cue quality rather than simply a limitation of brightness.

Another operational factor is the transition between the external NVG scene and cockpit instruments. Aviation NVGs are normally focused for distant viewing, while primary instruments are viewed below or beside the goggles; the pilot therefore has to shift gaze between the intensified outside scene and cockpit displays. Suboptimal or incompatible cockpit lighting and high workload can further disrupt this cross-check [9,22]. These interface demands do not inherently prevent instrument scanning, but they can increase the attentional cost of switching to instruments precisely when external visual references are becoming unreliable. The NVG image may also degrade dynamically. Thin fog or cloud, moisture, dust, snow, windscreen reflections, vehicle lights or IR sources can reduce contrast or produce halo and blooming. Automatic gain can preserve apparent image brightness while useful texture or horizon information deteriorates. Sudden or unexplained degradation may additionally capture attention as the pilot tries to diagnose the image problem [1,9,15,22].

A further operational consideration is the expansion of night visual capability itself. NVGs

enable tasks that would otherwise be difficult or impracticable with unaided night vision, including low-level operations in cue-poor environments. The present evidence does not establish that NVGs induce risk-taking; rather, their operational value makes predefined criteria for judging when the external image is no longer adequate especially important.

Taken together, the relevant conditions operate across four interacting levels. Sensory-environmental factors include loss of horizon, texture, contrast and optical flow, particularly over water or other uniform surfaces [1,22,27]. Technological and interface factors include limited FOV, image-gain behaviour, halo/blooming, reflections and cockpit-lighting compatibility [9,15,22,26]. Cognitive-operational factors include workload, fatigue, mission pressure, limited NVG experience and disruption of the instrument cross-check. Organisational factors include training standards, visual-reference minima, abort criteria and crew-monitoring procedures. These levels are not additional mechanisms of SD. They are conditions that can make perceptual and cognitive mechanisms more likely or weaken safety barriers. Table 1 separates intrinsic NVG image characteristics from crew-system interface and operator-system interaction conditions relevant to spatial orientation.

Tab. 1. NVG/NVIS characteristics and interface conditions relevant to spatial orientation.

NVG feature or interface condition	Why it matters for spatial orientation	Possible operational consequence
Limited field of view	Reduces peripheral optical flow and concentrates scanning within a narrow central field	Delayed detection of bank, drift or descent; increased need for active scanning
Monochrome / reduced colour information	Reduces colour contrasts and visual differentiation compared with normal daytime vision	Harder identification of some lights, surfaces, obstacles or warning cues
Contrast and texture dependence	Low-reflectance or uniform surfaces provide little texture gradient or optical flow even when some objects remain visible	Misjudgement of height, closure or motion over water, snow, desert or uniform terrain
Automatic gain control	Apparent brightness may be maintained while useful contrast, texture or horizon information deteriorates	Late recognition of DVE, thin fog/cloud or loss of usable external references
Halo and blooming	A bright visible or IR source can saturate the intensified image and obscure scene detail	Sudden loss of a primary (visual) reference, attention capture and interrupted scan
Instrument viewing below/beside goggles (interface condition)	Requires switching between the intensified external scene and cockpit instruments, sometimes across different luminance levels	Slower instrument cross-check under high workload or image degradation
Perceived image reliability (operator-system interaction)	A partly interpretable scene may sustain visual confidence despite missing horizon, texture, optical flow or depth cues	Continued visual flight in DVE/IMC or delayed transition to instruments (IFR) after external cues have become inadequate

SD events in flights with NVG

Accidents and serious incidents involving NVG/NVD operations and SD are difficult to catalogue comprehensively because military

reports may be classified or abbreviated and civil events may be coded as loss of control in flight (LOC-I), controlled flight into terrain/water (CFIT), inadvertent entry into IMC, loss of situational

awareness or DVE rather than as NVG-related SD. The seven cases below are therefore a purposive analytical sample and should not be interpreted as an exhaustive set of publicly documented NVG/SD events. Within each case, circumstances and official or investigator-attributed findings are separated from the author's interpretation.

Pilar, New Mexico, 2005. The pilot was conducting a night positioning flight in VMC using NVGs and following a road. After approx. 15 min, he reported that something was wrong. The instruments showed a 60-70-degree descending left turn, and the helicopter subsequently collided with terrain. The National Transportation Safety Board (NTSB) identified failure to maintain helicopter control and improper use of NVGs as the probable causes and listed SD, self-induced pressure to return to base, limited NVG experience, a dark night, overcast conditions and snow-covered terrain as contributing factors [19]. Improper NVG use and limited NVG experience were explicitly identified in this accident. This case provides relatively strong evidence for an NVG-related contribution and is consistent with continued reliance on apparently useful external cues followed by late recognition of a major attitude deviation. It does not imply that NVG use alone explains the SD.

McGregor Range, 2010. An EMS training mission was conducted as an NVG operation in a moonless desert environment. The available scene consisted mainly of starlight, distant city lights, chemical light sticks and IR strobes. During an orbit, the helicopter entered a steep bank and nose-down attitude before impact; the pilot had 7.5 h of NVG flight time, and this was his first non-training NVG flight [20]. The NTSB factual record documented the very low-illumination, low-contrast environment, the pilot's recent NVG training and loss of control during the landing-zone search [20]. The official material establishes that the crew was operating with NVGs and that the pilot had very limited operational NVG experience; it does not demonstrate a technical failure of the goggles. This case is consistent with a loss of reliable attitude and closure cues in a moonless, low-contrast scene despite the presence of point-light references. This is an interpretation of the operational conditions, not a claim that NVGs directly caused a specific vestibular illusion.

MOJO 69, Santa Rosa Sound, 2015. The UH-60M crew conducted the night mission with NVGs over water in deteriorating weather and subsequently lost visual references. The Joint SOCOM and LAARNG investigation identified SD in both pilots as the direct cause of loss of control and linked the event to operating below authorised

NVG weather minima and an ineffective transition from VMC to IMC [14]. The investigation established that NVG operation formed part of the mission conditions and authorised minima, but the causal sequence emphasised degraded visual references in deteriorating weather and failure to execute an effective instrument transition rather than a technical NVG malfunction. This event strongly supports delayed transition to instruments and a failure of crew-level barriers after loss of external references. It also shows why NVGs must not be treated as a means of maintaining visual flight in IMC.

Auckland Islands, 2019. A BK117-C1 crew continued a VFR medevac positioning flight after dark using NVGs. Near Enderby Island, the pilot interpreted part of the scene as cloud and descended towards an area believed to be clear. The helicopter was lower than expected and impacted the sea [27]. The Transport Accident Investigation Commission concluded that the pilot very likely misinterpreted the NVG image. The apparent cloud was likely sea fog near the surface, while the adjacent dark area was likely an absence of reflected light from calm water. The descent also involved reliance on visual depth perception and loss of reliable vertical reference [27]. The official investigation explicitly discussed misinterpretation of the image seen through NVGs and deficiencies in the broader NVIS/CRM context. This case supports the concept of a partially reliable image, in which land features could remain visible while the water surface provided insufficient texture (featureless-terrain), optical flow and height information.

New Zealand, 2020 - serious incident. During a night NVIS helicopter emergency medical services flight, a persistent band of reflected light, attempts to improve the visual picture, navigation towards a narrowing valley and oncoming vehicle headlights progressively increased workload. The crewman observed deteriorating pilot performance and issued positive commands until control was restored [6]. The Civil Aviation Authority of New Zealand account describes loss of situational awareness followed by SD in the setting of degraded visual cues, distraction and increasing task load [6]. The event occurred in an NVIS configuration, and the Civil Aviation Authority account treated the visual disturbances as relevant to the degraded visual picture; this does not establish that NVGs alone caused SD. This case supports dynamic image degradation, attention capture and loss of effective flight-parameter monitoring, while also providing a clear example of assertive crew intervention interrupting the sequence. In this incident, the relevant sequence involved degraded

visual cues, attempts to resolve the visual problem, increasing workload, loss of situational awareness and SD. However, it should not be generalised as an “NVG-induced SD” pathway applicable to all NVG events.

HMAS Brisbane, Philippine Sea, 2021. During a night NVD recovery of an MH-60R to HMAS Brisbane, an IR source from a shipboard CCTV system produced NVD blooming at low altitude, distracted the crew and removed the primary visual reference to the ship. The crew continued the approach, an increasing rate of descent went unrecognised, and the helicopter impacted the water [7]. The Defence Flight Safety Bureau account identifies the IR illumination, NVD blooming, loss of the primary visual reference and the crew’s expectation that the source could be switched off as central elements of the event [7]. According to the investigators, the NVD-lighting interface was directly implicated. They stated that an IR source that was not hazardous to unaided vision saturated the NVD image. This case is best interpreted as a system-interface accident involving the aircraft, ship lighting, procedures, expectations and attention, rather than as a generic claim that “glare causes SD”.

Exercise Talisman Sabre 23, 2023. The MRH-90 accident occurred during a low-level night formation flight over water, with NVDs in use and degraded visual cues. The Defence Aviation Safety Authority investigation, completed in 2025 [8], identified unrecognised loss of spatial orientation as the primary cause leading to CFIT and did not identify a major airframe or system defect as an explanatory factor [8]. NVD use and degraded night visual conditions formed part of the operational context, while the investigation’s primary causal finding was unrecognised SD. This event is consistent with a combination of low-contrast over-water cues, the attentional demands of formation flying and loss of a stable reference. If the NVD image does not provide a stable horizon or surface texture, unrecognised SD may lead to a rapid, uncontrolled descent before the crew regains full SA.

Across the seven cases presented above, the strength of the evidence for an NVG/NVD contribution is not uniform. In some events, the investigation explicitly identified improper NVG use, NVG-image misinterpretation, low-contrast NVG conditions or NVD blooming. In others, NVG/NVD use formed part of the operational context, while the investigation emphasised loss of visual references, SD, workload, CRM or transition to instruments.

NVG-related mechanisms potentially contributing to SD

Braithwaite et al. [5] reported an SD-related accident rate in helicopter NVD operations more than five times that of daytime operations. As noted above, this exposure-level association should not be read as proof that goggles are inherently hazardous. The reviewed cases of SD events in NVG-aided flights instead support a systems interpretation in which NVG/NVIS characteristics interact with cue-poor environments, task demands, instrument cross-check, crew decisions and organisational barriers.

For clarity, the mechanisms below are distinguished from the factors summarised earlier. A mechanism is the immediate perceptual or cognitive process by which accurate spatial orientation is lost or recognised late. A factor is an environmental, technological, operational or organisational condition that makes a mechanism more likely or weakens a safety barrier. Thus, limited FOV is a technical condition (factor), whereas reduced peripheral optical-flow information is the associated perceptual mechanism.

The first mechanism is delayed recognition that external visual references have become inadequate. A partially usable NVG scene can sustain a mental model of visual control after orientation-critical cues have degraded. The operational consequence may be a delayed transition from external visual control to instrument flight, so that recognition and recovery occur only after a substantial attitude or flight-path deviation. The MOJO 69 investigation [14] directly documented an ineffective VMC-to-IMC transition, while the Pilar event [19] is consistent with late recognition of a descending turn during NVG use.

The second mechanism is reduced peripheral optical flow and surface-motion cues. The limited field of view of NVGs and low-texture terrain can reduce information about drift, descent, speed and bank. Operational support is strongest in the Auckland Islands case [27], where the over-water scene and depth judgement were central, and the mechanism is also consistent with the events at McGregor Range [20], involving moonless, low-contrast conditions, and Talisman Sabre 23 [8], involving over-water flight. The mechanism is loss of usable motion cues; limited FOV is one condition that can intensify it.

The third mechanism is over-reliance on a partially reliable image. Some scene elements may remain visible while the horizon, depth or surface cues are inadequate. The Pilar [19] and Auckland Islands [27] cases support this pattern: visual information was available, yet the aircraft’s attitude

or height relative to the surface was not reliably perceived. This mechanism should be understood as a cognitive-perceptual interaction between image content, expectations and continued visual control, not as evidence that any bright NVG image is misleading.

The fourth mechanism is attentional capture during dynamic degradation of the NVG/NVD image. Fog, moisture, reflections and visible or IR light are conditions that can degrade the visual scene gradually or abruptly. The 2020 New Zealand incident [6] provides operational evidence of attention capture during changing reflections and exposure to headlights, while the HMAS Brisbane event [7] provides direct evidence of IR-induced NVD blooming and loss of a primary visual reference. Here, image degradation is the precipitating condition; the mechanism of interest is diversion of attention and delayed recognition of cue failure. The fifth mechanism is sustained channelised attention and a breakdown in instrument cross-checking under workload. NVG flight requires attention to the external scene, instruments viewed around the goggles, navigation, communication, obstacles and

the operational task. After attention is captured by an image anomaly or mission problem, instrument monitoring can remain degraded. The 2020 New Zealand event [6] most clearly supports this sequence. HMAS Brisbane [7] and Pilar [19] are also consistent with delayed recognition of critical flight parameters. Where direct eye-tracking or scan data are unavailable, this link is treated as an interpretation rather than an investigator-proven mechanism.

Proposed conceptual pathways from NVG-aided flight to SD

For operational safety analysis, the mechanisms potentially contributing to SD can be arranged into five proposed recurrent pathways (Fig. 1). These pathways are an interpretive synthesis, not a separate causal taxonomy, epidemiological model or claim that NVGs alone cause SD. Their purpose is to show how different combinations of image quality, environmental cues, attention, instrument monitoring and crew barriers can converge on the same state of SD.

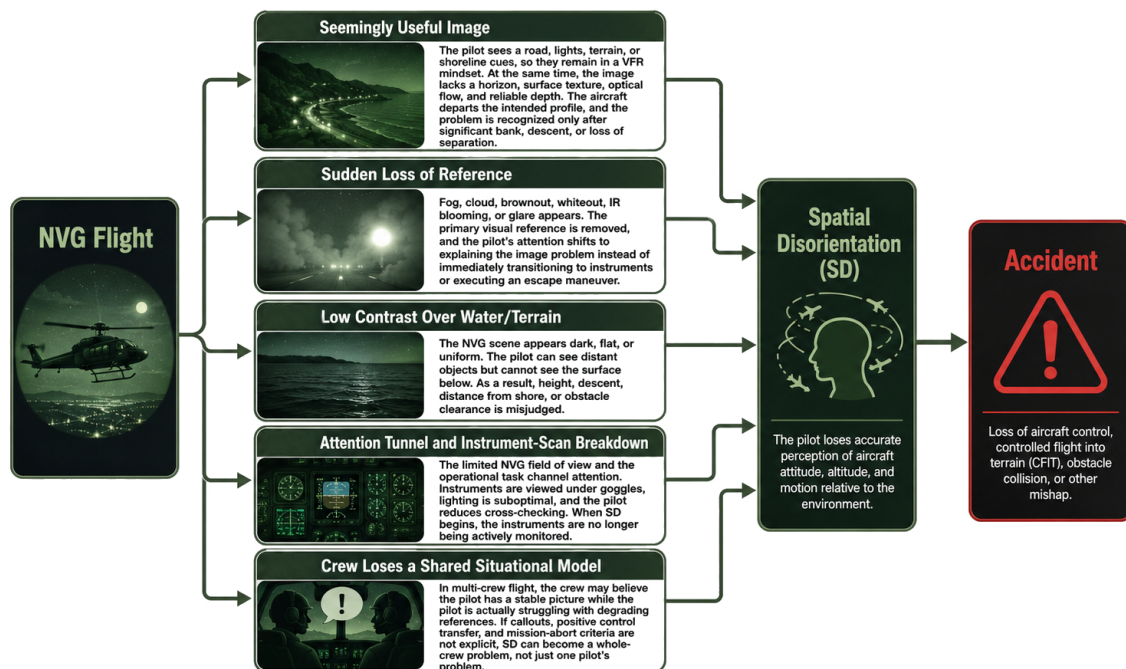


Fig. 1. Proposed conceptual pathways from NVG-supported flight to SD and an adverse event. The pathways are an interpretive synthesis and do not imply that NVG use alone causes SD.

The five proposed pathways provide an operational representation of the findings from the analysed cases. They are illustrated by the following cases: “Seemingly Useful Image” (Pilar; Auckland Islands), “Sudden Loss or Degradation of Reference” (HMAS Brisbane; 2020 New Zealand; MOJO 69), “Low Contrast Over Water/Terrain” (McGregor Range;

Auckland Islands; Talisman Sabre 23), “Attention Tunnelling and Instrument-Scan Breakdown” (2020 New Zealand; HMAS Brisbane; Pilar), and “Crew Loses a Shared Situational Model” as a system-level barrier failure (MOJO 69; 2020 New Zealand).

The first three pathways describe the quality of the external visual scene. A scene may remain

seemingly useful while lacking critical orientation cues; it may degrade suddenly because of fog, cloud, reflections or blooming; or it may remain persistently low in contrast over water or uniform terrain. In each configuration, the operational hazard arises when the crew continues to rely on external information that is insufficient for stable orientation rather than transitioning promptly to an instrument-supported flight profile or aborting the manoeuvre.

The fourth pathway concerns attention tunnelling and instrument-scan breakdown. NVG operation can increase the need to switch between the outside scene, instruments and mission tasks. The limited NVG field of view and the demands of the operational task may focus the pilot's attention on a selected part of the external scene. At the same time, instruments are viewed below the goggles, cockpit lighting may be suboptimal and the frequency of instrument cross-checks may gradually decrease.

The fifth pathway concerns a crew-level failure to develop or maintain a shared picture of deteriorating visual conditions. SD does not have to affect only one pilot. Other crew members may assume that the pilot flying has a stable and reliable picture of the situation while, in reality, the pilot is struggling with degraded visual references. If clear callouts, positive commands, effective parameter monitoring and explicit mission-abort criteria are not effectively implemented by the crew, an individual problem may become a whole-crew problem. The MOJO 69 [14] and 2020 New Zealand [6] events demonstrate

why crew monitoring and assertive intervention are important in NVG operations, while the underlying CRM principles remain applicable to non-NVG flight as well.

The final block in Fig. 1, "Accident", indicates possible consequences of unrecognised or improperly managed SD. Interrupting the pathway leading to SD requires prompt stabilisation using flight instruments when external cues are inadequate [8,10], effective crew communication and conservative operational decision-making. These five pathways should not be interpreted as mutually exclusive, because more than one may be active in a single event. The following cascade is therefore also possible: seemingly useful image → degradation of references → increased workload → loss of SA → delayed or ineffective transition to instruments → LOC-I/CFIT. Moreover, the fact that a case is consistent with a pathway does not prove that NVG use was an independent cause of the event.

Table 2 is an evidence-traceability matrix for the proposed pathways (Fig. 1). For each pathway, it identifies the reviewed cases, separates investigation-supported observations from the NVG/NVD or interface element used in the synthesis, and states the main limits of interpretation. Figure 1 provides a conceptual overview of how pathways may converge on SD, whereas Table 2 makes the evidentiary basis and uncertainty of each proposed pathway explicit.

Tab. 2. Operational support and limits of interpretation for the five proposed conceptual pathways.

Conceptual pathway	Reviewed case	Investigation-supported element	NVG/NVD or interface element	Limits of interpretation
Seemingly useful image	Pilar; Auckland Islands	External visual information remained available while judgement of attitude/height or scene interpretation failed	Partially usable image with inadequate orientation-critical cues (the image may remain apparently bright but lack horizon, depth or surface definition)	Conceptual grouping; does not establish NVG as an independent cause
Sudden loss or degradation of reference	HMAS Brisbane; 2020 New Zealand; MOJO 69	IR blooming, reflections/headlights, or weather-related reference loss	Image saturation/ degradation or ineffective transition after visual-reference loss	Direct evidence for some elements; the exact perceptual sequence has been partly reconstructed
Low contrast over water/terrain	McGregor Range; Auckland Islands; Talisman Sabre 23	Moonless/low-contrast terrain, over-water flight or degraded visual cues	Dependence on contrast/texture combined with limited peripheral cue availability	The environment is a major causal context in which the contribution of NVGs varies
Attention tunnelling / instrument-scan breakdown	2020 New Zealand; HMAS Brisbane; Pilar	Distraction, workload, late recognition or missed flight parameters	Image anomalies and switching between external visual references and instruments can add to the attentional load	Direct scan data are unavailable in most accident reports
Shared situational model / barrier failure	MOJO 69; 2020 New Zealand	Crew transition, monitoring or intervention affected the event sequence	The quality of the pilot flying's NVG image may not be obvious to other crew members unless explicitly communicated	Not an NVG-specific perceptual mechanism; retained as a system-level safety-barrier pathway

DISCUSSION

The reviewed evidence indicates that NVG/NVIS characteristics can alter the quality, availability and clarity of external visual cues, but their operational significance depends on environmental conditions, instrument monitoring, crew coordination and organisational barriers. The proposed pathways (Fig. 1) should therefore be understood as hypothesis-generating representations of recurrent configurations in the reviewed cases, not as independent causal mechanisms or estimates of pathway frequency.

Prevention of SD in NVG operations

Prevention of SD in NVG operations requires recognition that NVGs are one component of the NVIS and a visual aid for appropriately conducted visual operations, not a substitute for instrument references when external cues become inadequate [1,9,11,22]. Practical barriers should be defined before flight: acceptable illumination, contrast and other usable external references; criteria for aborting an approach or mission; a procedure for inadvertent entry into IMC; compatible cockpit and external lighting; radar-altimeter and flight-parameter monitoring; and clear pilot-flying/pilot-monitoring or pilot/crewman roles. Training should include genuinely low-illumination and low-contrast scenes, flight over water or featureless terrain, entry into fog or cloud, reflections and visible/IR blooming rather than only favourable NVG conditions. The McGregor Range accident [20] illustrates that recent NVG training does not by itself ensure readiness for operational conditions with very low illumination.

Active crew cross-checking is particularly important when the external scene can deteriorate gradually. A second pilot or crew member should have both the information and the authority to report deteriorating image quality, abnormal attitude, descent, loss of SA or the need to transition to instruments or abort the manoeuvre. The 2020 New Zealand incident [6] illustrates the potential value of assertive crew intervention, whereas MOJO 69 [14] underscores the importance of a prompt, rehearsed transition from VMC to instrument flight after visual references are lost.

The most effective preventive actions in NVG operations are procedural and team-based rather than equipment-based. Crews should define when the external image is no longer sufficient for reliable orientation and act before SD develops. NVG capability can extend night operations, but safe use depends on conservative operational limits, instrument discipline, lighting control, realistic DVE

training and CRM barriers that are effective in the event of partial or sudden loss of visual information.

Knowledge gaps and research directions

Although the effects of NVG use on pilot performance have been studied [16], several important questions remain. One concerns the measurement of visual scanning and workload in real NVG operations. Simulator studies using eye-tracking indicate that SD changes the distribution of attention, delays the return of gaze to the attitude indicator, impairs change detection and increases mental workload [3,10,12,16]. However, studies specific to goggles, different phosphor types, thermal fusion and helmet-mounted displays are needed.

Image fusion, augmented reality, helmet-mounted symbology and artificial-intelligence (AI) warnings may improve orientation, but they may also introduce clutter, delay, overtrust or new conflicts between the image and instrument readings. Experimental work on AI assistance for a degraded-spatial-information self-stabilisation task [18] provides proof-of-concept evidence, but it is not operational validation in helicopter NVG flight. Each new layer of information should therefore be evaluated not only in terms of obstacle detection, but also in terms of its effect on SD, instrument scanning, reaction time, user trust and the decision to abort the task.

Classical training in visual and vestibular illusions is often separated from NVG equipment training, while NVG syllabi may emphasise device use and procedures. Future training research should combine realistic low-cue NVG scenarios with SD recognition, prompt transition to instruments and CRM, and should evaluate whether these interventions improve recognition and recovery rather than merely proficiency in using the equipment.

Limitations

This review is a non-systematic narrative review rather than a systematic review, and the seven cases form a non-exhaustive analytical sample selected on the basis of the availability and interpretability of publicly accessible sources. Most case material comes from English-language reports, so relevant events documented elsewhere may be underrepresented. Investigation reports differ in scope, terminology and evidentiary detail, and some mechanisms, particularly attentional and instrument-scan processes, had to be inferred from operational sequences because direct eye-tracking or physiological data were unavailable. The proposed pathways are therefore hypothesis-generating

conceptual syntheses. They indicate recurring configurations observed across the reviewed material but do not establish incidence, independent NVG causation or the relative risk associated with individual pathways. These limitations should be considered when generalising the operational implications.

CONCLUSIONS

NVGs do not appear to create a distinct form of SD; rather, they can modify the visual and operational conditions in which established SD mechanisms become more likely to occur or are recognised too late. Across the seven reviewed helicopter events, the most consistent pattern was continued reliance on an external scene that remained at least partly interpretable while one or more orientation-critical cues were absent, degraded or suddenly lost. The following conclusions are supported by the reviewed literature and case material:

- NVGs improve the detection of terrain, objects and obstacles at night but do not reproduce daytime vision or guarantee a reliable horizon, surface texture, optical flow or depth information;
- the NVG/NVIS-related pathways supported by the reviewed cases include low-contrast or

featureless scenes, dynamic image degradation or blooming, delayed transition from external visual cues to flight instruments, and channelised attention with reduced instrument monitoring;

- the historically higher SD-related accident rate reported for NVD operations is exposure-level evidence and should not be interpreted as proof of direct NVG causation;
- NVG/NVIS characteristics may weaken corrective visual cues, but direct case evidence linking the goggles to a named vestibular illusion is limited. Classical vestibular illusions such as the leans, Coriolis, somatogravic and somatogyral illusions are not specific to NVG flight in helicopter operations;
- crew communication, shared situational awareness and organisational minima are best understood as safety barriers and contributing factors rather than NVG-specific perceptual mechanisms; and
- the most defensible safety measures are predefined visual-reference and abort criteria, early transition to flight instruments when those criteria are no longer met, compatible lighting, radio-altimeter and flight-parameter monitoring, realistic DVE/NVG training, and assertive crew callouts and intervention.

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