



# VISUAL TARGET DETECTION AND RECOGNITION PERFORMANCE UNDER NVG-AIDED AND PHOTOPIC CONDITIONS

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**Introduction:** Night vision goggles (NVGs) introduce several limitations to human vision, including a reduced field of view, monochromatic imagery, lower visual acuity, and impaired depth perception. These factors make object detection and recognition during NVG-supported night flights, particularly at low altitudes, especially demanding. The aim of this study was to assess the effectiveness of flight crew members in detecting and recognizing visual targets representing potential terrain threats under NVG-aided versus NVG-free photopic conditions.

**Methods:** Seventy NVG-inexperienced flight personnel were randomly assigned to a control group (n = 33) or an experimental group (n = 37). Participants performed a target discrimination task using a 3D terrain model under two lighting conditions: natural daylight (photopic vision) for the control group and NVG display screen illumination for the experimental group. The task involved detecting and recognizing six high-contrast geometric targets (triangles and squares) simulating terrain obstacles. Responses were recorded using a structured questionnaire.

**Results:** Detection and recognition performance was significantly lower under NVG-aided conditions. Age and flight experience did not influence outcomes, and target shape had no significant effect on recognition accuracy in either condition.

**Conclusions:** NVG use was associated with impaired target detection and recognition, independent of participant demographics. The results point to both optical and system-level limitations, underscoring the need for improved NVG calibration procedures and performance assessments under realistic, lower-contrast conditions, as well as targeted user training to ensure reliable operational performance and flight safety.

**Keywords:** visual perception, night vision, NVG, aviation medicine, flight safety

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## INTRODUCTION

The proper predispositions, and above all the training, of flight crews are critical to ensuring the effective and safe execution of flight operations under varying lighting conditions. This is especially true for flight crews maintaining 24-hour readiness, where nearly half of operational hours may involve night flying. The requirement of using night vision goggles (NVGs) for all after-dark flights has increasingly become the standard for enhancing flight safety, not only in Europe. This requirement applies not only to military aviation, but also to police units, emergency medical services, border guards, fire departments, and forest protection services.

Night flights are often conducted at the limits of human capability, primarily due to the physiological limitations of the human visual system, such as the decline in visual performance as ambient light levels decrease. These limitations are the main reason for adopting night vision enhancement technologies [38].

Although NVGs significantly improve visual perception, situational awareness, and overall operational safety, insufficient understanding of their limitations, combined with overestimation of one's capabilities when using NVGs, remains one of the most common causes of accidents during night flight missions [27]. The limited field of view (FOV) of NVGs – approximately 40° – requires the user to perform continuous head movements to cover the same visual area that would normally be scanned using only simple eye movements [56]. Under normal photopic conditions, a much larger visual area (up to 70–80° horizontally and 50–60° vertically) can be monitored primarily through eye movements.

This restriction in FOV under NVG conditions not only increases the physical demand of scanning but also impairs perceptual functions such as motion detection [37]. This is particularly relevant because the peripheral retina, outside the high-acuity central zone, is densely populated with rod photoreceptors, which are highly sensitive to changes in luminance and motion. Restricting this peripheral input through a narrow FOV may therefore compromise the detection of dynamic or peripheral stimuli. It is worth noting that the image produced by NVGs has an output brightness calibrated to the mesopic range of human vision [38], in which visual acuity and some degree of color perception are still maintained [40]. However, NVG-aided vision is generally comparable to low-light vision rather than vision under normal daytime illumination.

The common limitations associated with NVG use include reduced depth perception [27,47,56], increased visual fatigue due to eye strain and tension [51], and physical fatigue related to the increased helmet weight, since the NVGs are mounted directly onto the helmet [22,39]. Neck muscle fatigue has been associated with the increased head movement required to compensate for the narrow FOV, as well as to the location of the center of gravity of the helmet-NVG system [17].

The use of NVGs for detection (determining that an object is present), recognition (determining the object's class, e.g., rotary-wing or fixed-wing aircraft), and identification (discerning the specific type, e.g., AH-64E, Mi-24) of targets under varying conditions – such as different image intensifier technologies and ambient light levels – has been the subject of extensive research [11,19]. Several studies [2,3] suggest that the effectiveness of visual discrimination (including detection and recognition) while using NVGs depends mainly on the scanning technique employed. This is explained by the fact that improper or absent scanning strategies may prevent users from fully benefiting from the capabilities offered by NVG technology.

NVG users demonstrate head-scan patterns similar to those in traditional visual search studies; however, their head movements are generally faster and of greater amplitude. This may be attributed to the reduced image quality provided by NVGs, which could lead aircrew to scan more frequently, either subconsciously, in an effort to acquire more visual information, or deliberately, to avoid missing transient visual cues.

Notably, target visibility directly influences the speed of head movements during search tasks [19]. In contrast, fixation duration remains relatively stable, regardless of NVG use or target conspicuity. This suggests that the time spent focusing on a detected target is not significantly influenced by these factors [19]. These findings indicate that NVGs do not fundamentally alter the mechanics of head and eye coordination, but they do affect the efficiency of visual search, particularly as a function of target detectability. This is consistent with broader research [53,59] demonstrating that head and eye movements operate in a coordinated manner during complex visual tasks, with peripheral vision contributing to the detection of salient stimuli.

Although some studies [23,31] suggest that training in scanning techniques can improve target detection response times, formalized scanning patterns may not always prove beneficial.

This is primarily due to an observed increase in false-positive detections, where participants erroneously 'detected' targets that were not present in the scene [10,15]. Other research findings [36] indicate that search failures may not necessarily result from the absence or incorrect application of scanning techniques, but rather from the inability to discriminate the target from its surrounding background. This suggests that while eye movements play a substantial role in object detection, merely fixating on a target does not guarantee its detection [33,36].

Given the above considerations, some scanning methods recommend the use of free or natural search patterns rather than formalized scanning routines [10,15]. Successful visual search appears to depend not only on motor behavior but also on knowing which aspects of a target become salient in a specific environment. Kotulak [31] proposed scanning techniques that focus less on physical behaviors, such as eye and head movements, and more on cognitive strategies. He emphasized the superiority of 'scanning with understanding' over memorized or routine-based scanning patterns. According to Kotulak [31], to reduce the likelihood of visual search failures, operators should direct their attention toward specific objects of interest, rather than scanning general areas. Furthermore, direct fixation on objects is recommended. In unaided scotopic vision, a central black spot is present, whereas this does not occur in NVG-aided vision. Therefore, central vision remains effective even in low-light conditions. This black spot arises because the fovea is devoid of rods and therefore nonfunctional under scotopic conditions, whereas NVGs amplify light to maintain cone-mediated central vision. During scanning, viewers are advised not to fixate on any single object for more than one or two seconds, and to make frequent return fixations during recognition tasks if needed [31].

### The aim of the study

In light of the aforementioned considerations related to NVG-aided flight, particularly when operating at low altitudes over varied terrain, this study aimed to assess the effectiveness of aviators in a task involving the detection and recognition of targets under photopic and NVG-aided vision. The targets represented potential terrain hazards, which, according to procedures commonly employed by aviators, are considered priority objects during visual search in low-altitude night flights using NVGs [31].

Understanding the factors that influence effective visual observation using NVGs may be valuable

not only from the perspective of flight safety (e.g., avoiding terrain obstacles, a critical element in determining operational parameters such as flight altitude), but also in defining the minimum observable size of a target required for successful detection and recognition in operational conditions.

## METHODS

### Experimental design

The study employed a between-subjects design with one independent variable: vision condition (photopic vs. NVG-aided scotopic). Participants were randomly assigned to one of two groups, with each group performing the tasks under a single, distinct lighting condition. The primary analyses focused on between-group comparisons to assess the effect of lighting condition on task performance (detection, recognition, and identification of targets). Due to the constrained nature of the recognition task, limited to two geometrically simple stimuli (targets: square vs. equilateral triangle), recognition and identification were treated as equivalent. Given the low ambiguity and high discriminability of stimuli, correct recognition was assumed to indicate correct identification, rendering further separation of these stages methodologically unnecessary.

### Participants

A total of 70 volunteer participants (two females), all active helicopter flight crew members, took part in the study. Their ages ranged from 26 to 52 years ( $M = 34.1$ ,  $SD = 5.59$ ), and total flight experience ranged from 230 to 2,100 hours ( $M = 707.2$ ,  $SD = 383.48$ ). None of the participants had prior experience with NVGs or had undergone formal training in visual scanning techniques for flight with NVGs.

Participants were recruited based on predefined inclusion criteria, including a medically documented:

- best corrected monocular visual acuity of at least 20/20 at 6 meters,
- stereoacuity of at least 40 arc seconds, tested using the Stereotest – Circles (Stereo Optical Company Inc., Chicago, IL, USA),
- age-appropriate monocular amplitudes of accommodation,
- no more than three errors on the 14 plates of the 38-plate edition of the Ishihara colour test (Kanehara & Co., Ltd., Tokyo, Japan), conducted under daylight or artificial light closely resembling natural daylight (D65 light source, 6500K white LED, 98 CRI),

- contrast sensitivity, assessed using the Functional Vision Analyzer (Stereo Optical Company Inc., Chicago, IL, USA).

Participants were randomly assigned to one of two groups:

- the experimental group included 37 participants (age  $M = 34.6$  years,  $SD = 5.85$ ; flight  $M = 743.4$  hours,  $SD = 434.33$ ), who performed tasks under scotopic vision conditions using NVGs,
- control group consisted of 33 participants (age  $M = 33.7$  years,  $SD = 5.34$ ; flight  $M = 666.7$  hours,  $SD = 318.86$ ), who completed the same tasks as individuals from experimental group but under photopic (daylight) vision conditions.

Participation in the study was entirely voluntary. Volunteers were recruited from a training course on the aeromedical aspects of night vision device use, conducted at the Military Institute of Aviation Medicine (WIML) in accordance with STANAG No. 7147 – AAMedP-1.21, Edition A [60].

All experimental procedures were approved by the Ethics Committee of the WIML (Poland) and conducted in full compliance with the Declaration of Helsinki and applicable regulations on the protection of human subjects. All participants provided written informed consent and were informed of their right to withdraw from the study at any time without consequence.

## Apparatus

### NVG

The study utilized a set of binocular PNL-3 NVGs with a  $40^\circ$  field of view, manufactured by PCO S.A. (Poland) (serial numbers: 006, 020, 028, and 037). These NVGs were equipped with P-43 phosphor (green) image intensifier tubes (IITs), specifically the XD-4 model (Photonis, France), which lack automatic gain control and automatic brightness control, limiting the system's output luminance regulation. Under optimal viewing conditions, the spatial resolution of the PNL-3 goggles is at least 1.15 cycles/mrad. The characteristics of the display screen in the PNL-3 NVGs (without optics, measured data provided by the manufacturer Photonis, France) are as follows: limiting resolution (at center): 64 lp/mm, luminance (max. output brightness): 17 cd/m<sup>2</sup>, equivalent background illuminance: 0.15  $\mu$ lx – determining the lowest light level (the background illuminance and the background noise of image intensifier) at which objects can be detected, signal-to-noise ratio: 22.

The luminance imbalance between the right and left eyepieces of each the NVG did not exceed the recommended 10% threshold for luminance

variation [35]. As a result, binaural luminance balance was maintained, and the occurrence of perceptual conflicts, such as the Pulfrich effect, between the binocular views provided by the NVGs is unlikely [35].

The goggles were powered by two nickel-cadmium (Ni-Cd) batteries, each providing 1.2 V. When mounted on the THL-5NV helmet (FAS Mariusz Ficon, Poland), the system allowed for precise adjustment to both the pilot's head and individual visual characteristics. The total weight of the NVG system, including the power supply and helmet, was approximately 2.4 kg. A detailed description of the NVGs and their technical specifications can be found in the papers [25,32,41,42,50].

### Terrain model board

To simulate a flight environment under photopic and scotopic vision conditions, the Night Vision Training System (NVTS) (ETC-PZL Aerospace Industries, Poland) [16] was used. The central component of the NVTS is a terrain model board (Fig. 1), which represents a scaled-down landscape at a 1:160 scale. The model features diverse topography, including both flat and hilly terrain, as well as urban and rural areas and a runway, providing a realistic and varied visual environment for NVG-based tasks.

For comparison, the experimental set-up with the terrain model board, seen in photopic vision and under the NVG-aided vision, is presented in Fig. 1 and Fig. 2, respectively.

### Targets

Two-dimensional geometric shapes (squares and equilateral triangles) of 25 mm size were used as targets, placed at a distance of 3.5-4 meters from the observer, simulating a real-world size of 4×4 meters viewed from 600 meters. Each target was made of opaque, white, semi-matte cardboard, with a thickness of 0.5 mm. For the given viewing distance, the targets subtended approximately 6.25 mrad of visual angle, which corresponds to an angular spatial frequency of about 0.16 cycles/mrad, assuming one full spatial cycle (bar + space) spans the target width.

Thresholds for visual discrimination (detection and recognition) of the targets were defined in accordance with the current standard for two-dimensional target evaluation [44], based on the Johnson criterion [26]. According to this criterion, the number of cycles required across the target width to achieve a 50% probability of detection and recognition is 1 and 4, respectively. This corresponds to minimum angular spatial frequencies of 0.16



Fig. 1. A view of the terrain model board through unaided eye in photopic vision (photo may not reflect the true luminance level).

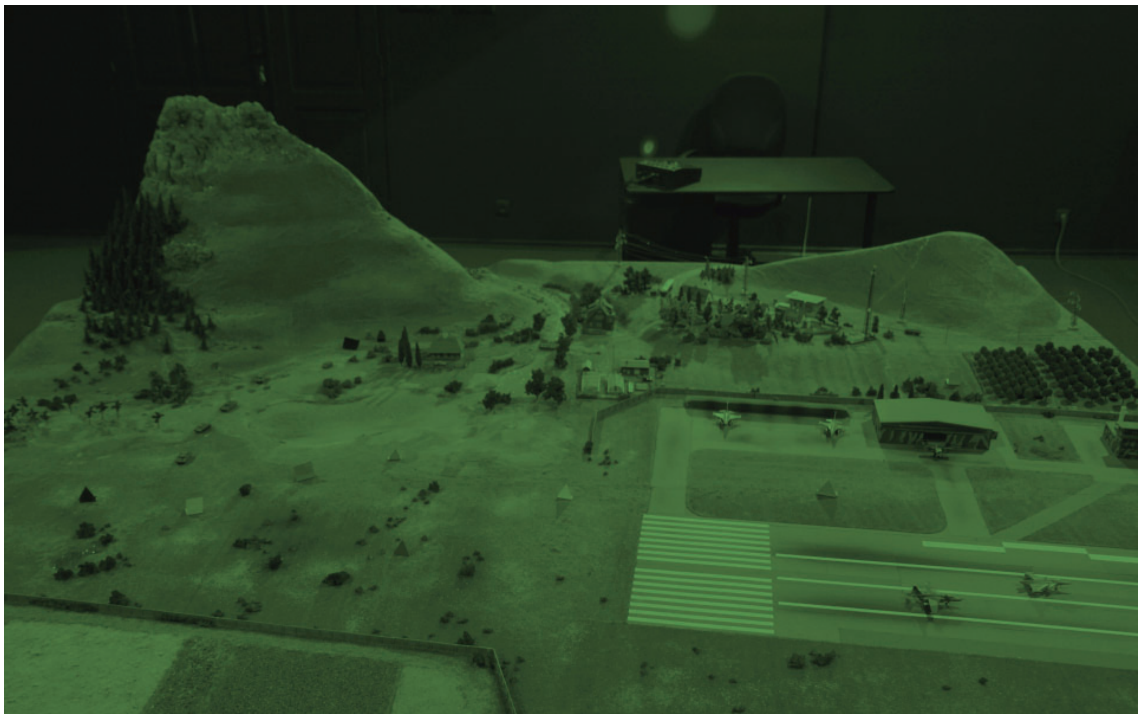


Fig. 2. A view of the terrain model board produced by NVG (photo may not reflect the true luminance level).

cycles/mrad for detection and 0.64 cycles/mrad for recognition. While the Johnson criterion specifies a requirement of approximately four cycles across the target (0.64 cycles/mrad) for recognition at a 50% probability level, this threshold was originally developed for complex military targets. In our study, however, the recognition task involved only two simple geometric shapes

(a square and an equilateral triangle), each with clearly distinctive contour characteristics. Given the high perceptual salience of these shapes and the limited number of possible target classes, the actual spatial frequency required for successful recognition is expected to be substantially lower than the classical threshold.

Therefore, we assumed that the target is likely to be recognized when the minimum angular spatial frequency reaches at least 0.35 cycles/mrad. It is important to note that the values used for detection and recognition thresholds (0.16 and 0.35 cycles/mrad, respectively) refer to the resolving power required by the visual system, rather than properties inherent to the target itself. Given that the unaided human eye has a resolving power of approximately 1 arcminute (approx. 0.3 mrad), corresponding to about 3.33 cycles/mrad [49], a high-contrast target with a physical size of 25 mm can be both detected and reliably recognized.

### Light stimuli

An LED lamp with a 2856 K color temperature (in accordance with MIL-L-8576A, 1986) was used to simulate daylight illumination. An additional light source, equipped with an aperture system to control illumination intensity without affecting color temperature, was used to simulate one-half moonlight illumination at a level of 0.07 lux [45]. Both light sources were positioned 4 meters above the terrain model board to simulate two distinct ambient illumination conditions. Under simulated daylight conditions, the surface luminance of the terrain model was measured at 16 cd/m<sup>2</sup>, while under simulated one-half moonlight conditions it was reduced to  $3.4 \times 10^{-2}$  cd/m<sup>2</sup>. When viewed through the NVGs, the resulting output luminance observed through each eyepiece under moonlight-level illumination was approximately 8.3 cd/m<sup>2</sup>. Therefore, the effective luminance experienced through the NVG system was comparable to the direct luminance of the terrain model under daylight conditions.

Luminance measurements were used to calculate target-background contrast under both viewing conditions. In the daylight condition, with a background luminance of 16 cd/m<sup>2</sup> and target luminance of 74 cd/m<sup>2</sup>, the resulting Michelson contrast was 0.64. In the moonlight condition, the background luminance was  $3.4 \times 10^{-2}$  cd/m<sup>2</sup>, and the target luminance was 0.193 cd/m<sup>2</sup>, yielding a Michelson contrast of 0.70.

All illuminance and luminance measurements were conducted using an ILT1700 photometer with an SED033 detector equipped with a Y-photopic filter (International Light Technologies, USA). To measure illuminance, the detector was fitted with a W wide-eye diffuser. For luminance measurements, an R barrel hood with a narrow 1.5° field of view was used. The photometer and detector were supplied with a certificate of calibration in accordance with ISO/IEC 17025:2018-02, and were fully compliant with the required accuracy and reliability standards for photometric measurements.

### Resolution test chart

To rapidly assess the operational status of the NVGs and verify their ability to resolve detail at a specified level in the main study phase, a resolution test chart was used as a functional screening tool for participants. Fitting and focusing of the goggles is a standard procedure and a prerequisite for effectively compensating for the limitations of these devices, such as low visual acuity, narrow field of view, and substantial weight [5,31,38]. The chart was developed at the WIML (Poland) and is based on the optical resolution test defined in the U.S. Air Force MIL-STD-150A (1951) [13]. This high-contrast (>95%) square-wave grating chart was positioned at eye level, at a distance of 4 meters from the participant, and illuminated using a 2856K color temperature light source, calibrated to simulate one-half moonlight conditions (0.07 lux). The resolution pattern was designed to match a Snellen visual acuity level of 20/35, allowing for consistent and objective evaluation of the goggles' performance. This test chart is routinely used for pre-flight PNL-3 NVG adjustments, and in this study it was applied to ensure that the NVGs were functioning optimally before task performance.

### Data collection

A custom-designed questionnaire featuring a photographic image of the terrain model board (Fig. 3) was used to collect research data. In addition to standard demographic questions (age, aircraft type, total flight hours), participants were asked to mark the locations of the detected and recognized targets (triangles and squares) directly on the photo. To assist with this task, the photo of the terrain model was overlaid with white circles indicating the possible locations of the objects placed on the board surface (Fig. 3). A misidentified or incorrectly marked location was counted as a recognition error. Participants were explicitly instructed to mark only those targets they had actually detected and recognized, and to avoid guessing.

Given that the participants were a homogeneous group (each individual was certified flight personnel with current medical clearance), it was assumed that the working memory (including spatial memory) component involved in the task was comparable across both the control and experimental groups. Therefore, the study results (i.e., the number of detected and recognized targets) were influenced primarily by factors related to visual perception rather than cognitive variability, such as memory capacity.

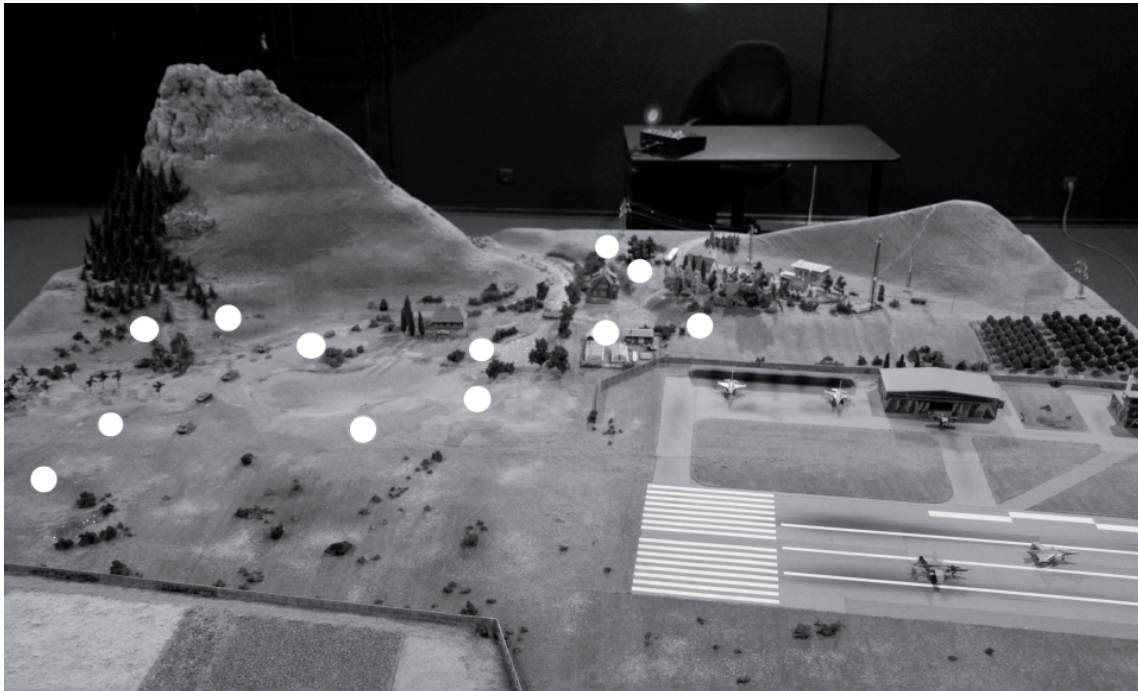


Fig. 3. Photo of terrain model board with possible target locations.

## Procedure

All participants were familiarized with the experimental procedure, including the task instructions and response format. Prior to the experimental task, participants were shown visual examples of the two target types used in the study: squares and triangles. In addition, participants in the experimental group underwent a mandatory NVG fit and focus calibration procedure, conducted in the test environment with ambient light adjusted to simulate one-half moonlight conditions. The calibration involved interpupillary distance adjustment and focusing of objective and eyepiece lenses using a resolution test chart placed 4 meters away (matching the target observation distance in the main task). This procedure ensured that participants achieved a minimum visual acuity of 20/35, which was a prerequisite for inclusion in the experimental phase.

The experiment comprised two sequential tasks:

**Task 1—object detection and recognition**—participants viewed a terrain model board (Fig. 2) and were instructed to detect, recognize, and memorize the locations of six objects (three triangles, three squares). Participants were instructed to scan the illuminated scene freely and naturally, without using any formalized visual scanning patterns. The observation was conducted from a fixed distance of 4 meters, simulating an aerial viewing height of approximately 300 meters above ground level. The viewing time was fixed at 60 seconds, corresponding to the average duration of a helicopter overflight of a similarly sized area.

Throughout the testing, only one participant and the researcher were present in the room at any time to maintain experimental control.

**Task 2 – spatial recall** – after a five-minute delay, participants were asked to mark the locations of the previously recognized targets on a photographic image of the terrain model board (Fig. 3).

Each participant completed task 1 under one of the two vision conditions (photopic or NVG-aided scotopic), depending on group assignment, and task 2 under photopic vision.

After completing both tasks, participants filled out a questionnaire collecting demographic and flight-related data (e.g., age, total flight hours, aircraft type). All study procedures were conducted in the morning hours.

## Statistical analysis

To assess the effects of vision condition on performance in a target observation task, two separate Wilcoxon rank-sum tests were used to compare the number of detected and recognized targets between the control group (photopic vision) and the experimental group (NVG-aided scotopic vision). Another Wilcoxon signed-rank test was used to assess whether recognition accuracy differed between triangle and square targets, with target shape treated as a within-subject factor.

In addition to the group comparisons, rank-based linear regression models were conducted for each dependent variable to examine the influence of age

and flight experience (total flight hours) as potential covariates. This approach allowed for assessing the unique contribution of each predictor on the rank-transformed performance scores, while accounting for non-normality.

Vision condition was included as a categorical predictor, and age and flight experience were entered as continuous covariates. Effect sizes for group differences were reported using rank-biserial correlation ( $r$ ) to quantify the magnitude of the observed effects in the Wilcoxon tests.

All analyses were conducted using R (ver. 4.4.2) [43], with the rstatix package version 0.7.2 [28], dplyr package version 1.1.4 [57], effectsize package version 1.0.1 [4], ggplot2 [58], and ggpubr package version 0.6.1 [29]. Statistical significance was set at  $p = 0.05$ .

## RESULTS

All 70 volunteers completed the study, and there were no data dropouts. The median number of detected and recognized targets under photopic and NVG-aided scotopic vision conditions is shown in Fig. 4.

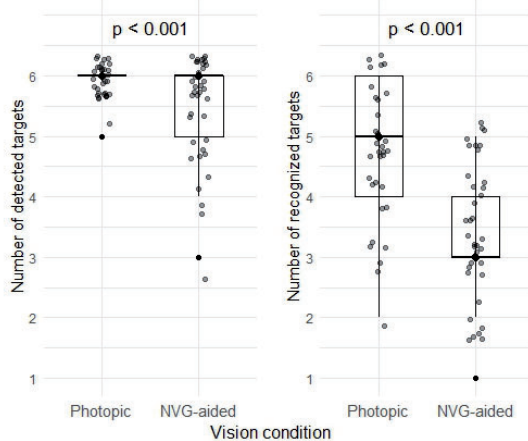


Fig. 4. Median number of detected and recognized targets across vision conditions. Boxplots display the median (center line) and the interquartile range (IQR), defined as the 25th to 75th percentile. Whiskers extend to values within  $1.5 \times \text{IQR}$  from the quartiles. Individual data points are shown as jittered dots to reduce overlap.

A Wilcoxon rank-sum test revealed a significant effect of vision condition on the number of detected targets ( $W = 825.5$ ,  $p < 0.001$ ,  $r = 0.42$ ) (Fig. 4). Participants in the experimental group (NVG-aided scotopic vision) detected significantly fewer targets than those in the control group (photopic vision). The median (IQR, 25th–75th percentile) number of detected targets was 6 (6–6) in the photopic group and 6 (5–6) in the NVG group.

To account for potential covariate effects, a rank-based linear regression was performed on the ranked detection scores. This model was statistically significant overall,  $F(3, 66) = 5.31$ ,  $p = 0.002$ . The vision condition remained a significant predictor ( $p < 0.001$ ), while neither age ( $p = 0.983$ ) nor total flight hours ( $p = 0.541$ ) significantly predicted detection performance.

A second Wilcoxon rank-sum test showed a significant difference in the number of recognized targets between groups ( $W = 950.5$ ,  $p < 0.001$ ,  $r = 0.49$ ) (Fig. 4). Again, participants in the NVG group recognized significantly fewer targets than those in the photopic group. The median (IQR, 25th–75th percentile) number of recognized targets was 5 (4–6) in the photopic group and 3 (3–4) in the NVG group.

A rank-based regression model for recognition was also statistically significant,  $F(3, 66) = 7.62$ ,  $p < 0.001$ . The effect of vision condition remained significant ( $p < 0.001$ ), while neither age ( $p = 0.306$ ) nor flight hours ( $p = 0.500$ ) significantly predicted recognition performance.

The Wilcoxon signed-rank test for dependent samples showed no statistically significant differences between the target types (triangles and squares) in their recognition under two different viewing conditions: photopic vision (control)  $V = 101.5$ ,  $p = 0.63$  and NVG-aided scotopic vision (experimental)  $V = 154$ ,  $p = 0.58$ . In photopic condition, participants recognized slightly more squares than triangles (Fig. 5).

Differences in recognition performance between target types (shape) did not emerge under the experimental vision condition either. Thus, target shape was not a significant determinant of recognition accuracy.

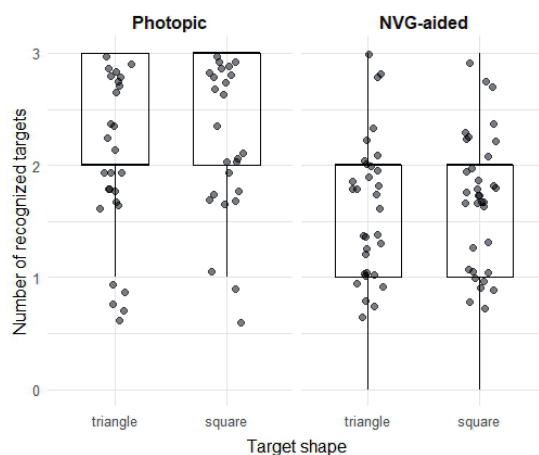


Fig. 5. Number of correctly recognized target shapes (triangles and squares) under photopic and NVG-aided vision conditions. Boxplots display the median (bold horizontal line) and the interquartile range (IQR), defined as the 25th to 75th percentile (box edges). Whiskers extend to the most extreme data points within  $1.5 \times \text{IQR}$  from the box. Individual data points are shown as jittered dots to reduce overlap.

## DISCUSSION

The primary objective of this study was to assess whether target detection and recognition performance, in the absence of standardized scanning strategies, differs as a function of visual conditions – specifically, photopic vision versus NVG-aided vision. Despite the similar luminance levels of the terrain model under photopic viewing and the NVG display screens (16 cd/m<sup>2</sup> vs. 8.3 cd/m<sup>2</sup>), the reduced performance observed under NVG conditions (Fig. 4) likely reflects physiological and optical limitations of the visual system when aided by night vision devices. The discussion below is structured around four key areas: (1) limitations associated with field of view, (2) depth perception and distance estimation, (3) spatial resolution and contrast transmission, and (4) individual visual differences.

### Field of view

A critical factor contributing to reduced performance under NVG-aided conditions is the limited field of view (FOV), typically restricted to approximately 40° in both horizontal and vertical dimensions. This narrowing limits peripheral awareness and demands greater head movement, thereby increasing cognitive and physical workload. Previous studies have consistently demonstrated that a reduced FOV impairs visual search effectiveness, particularly in tasks that require wide-area scanning or the simultaneous monitoring of multiple spatial targets [24,55]. In our task, participants were required to detect and recognize six spatially distributed targets, likely exceeding the spatial scanning capabilities afforded by the NVG FOV. In contrast, participants under photopic conditions, with unrestricted FOV, demonstrated significantly higher performance. While compensatory scanning strategies may develop over time with experience [18,20], none of our participants had prior NVG training, which likely contributed to the observed performance gap.

### Depth perception and distance estimation

Although the task did not explicitly require distance judgments, depth perception remains a relevant factor under NVG use. Binocular depth cues, such as convergence and disparity, can be affected by technical inconsistencies between the image intensifier tubes. Even in binocular NVG systems, mismatches in resolution, contrast, focus, or luminance between left and right channels may disrupt stereopsis [9,54] and degrade distance estimation [21,30]. Moreover, stereoscopic

benefits diminish with increasing distance and declining image quality [21]. In our study, the viewing distance (3.5–4 meters) was designed to simulate operational distances (~600 m), where subtle visual disparities could reduce perceptual reliability. To mitigate the risk of mislocalization, predefined target zones were marked on the terrain model photograph (Fig. 3), and spatial errors were conservatively classified as recognition failures rather than localization deficits.

### Spatial resolution and contrast

Understanding how well targets can be detected and recognized through NVGs depends not only on the imaging technology itself but also on the capabilities of the human visual system to perceive detail and contrast under low-light conditions. To evaluate these limits, we used the Modulation Transfer Function Area (MTFA) framework – a validated model that links image quality with visual performance [12]. The MTFA, depicted as the shaded gray region in Fig. 6, is bounded by three key components.

The first curve (yellow) represents the NVG Modulation Transfer Function (MTF) [52], describing how well the PNL-3 system with XD-4 tubes (data provided by the manufacturer of the image intensifier tube [61]) preserves image contrast across different spatial frequencies. A greater area under this curve generally corresponds to better image fidelity. The second curve (green) shows the Stereo Human Contrast Threshold Function (Stereo HCTF), representing the minimum contrast required by the binocular human visual system to perceive depth at various spatial frequencies [14]. The third boundary, indicated by a vertical dashed black line, marks the lowest usable spatial frequency defined by the angular size of the target at a viewing distance of 4 meters.

Additionally, the red dashed curve labeled “NVG & Target MTF” represents the effective MTF after accounting for the actual contrast of the targets used in the experiment (Michelson contrast ≈ 0.7). This curve was calculated by multiplying the NVG MTF values by the target contrast level, providing a more realistic representation of NVG performance under operational conditions. Two critical points are marked on the NVG & Target MTF curve (Fig. 6): point D (0.64 lp/mm) corresponds to the minimum spatial frequency at which target detection is possible, and point R (2.56 lp/mm) indicates the minimum frequency for successful target recognition. Importantly, both points fall well within the MTFA, confirming that the NVG system, under the given conditions (viewing

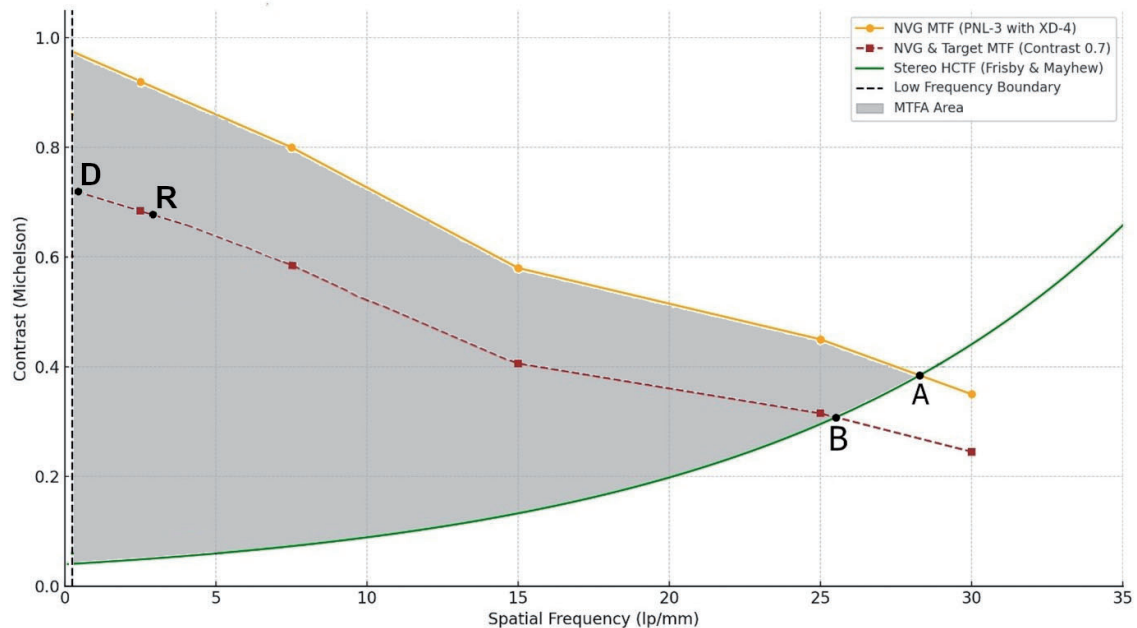


Fig. 6. The modulation transfer function area (MTFA) for contrast target viewed with NVGs. Point D indicates the minimum spatial frequency (0.64 lp/mm) at which it is possible to detect targets; Point R represents the minimum spatial frequency (2.56 lp/mm) at which it is possible to recognize targets. Point A indicates the maximum spatial frequency at which stereoscopic depth perception is possible under optimal NVG imaging conditions; Point B shows the limiting spatial frequency for stereoscopic depth perception under realistic target contrast.

distance = 4 m, contrast = 0.7), provides sufficient spatial resolution and contrast to support both detection and recognition tasks.

Although the applied NVG system theoretically provides sufficient spatial resolution and contrast to support both detection and recognition tasks, as indicated by the MTFA range (Fig. 6), this assumes ideal or near-nominal performance of the image intensifier tubes. In practice, however, partially worn image intensifiers, which may have degraded over time, may exhibit reduced contrast transfer capabilities, effectively lowering the NVG MTF curve. As a result, some NVGs may have failed to deliver sufficient image quality for reliable target recognition, even if they had previously passed calibration using high-contrast resolution test charts. This highlights the need to account for in-service degradation when evaluating NVG performance in operational or research settings, particularly by assessing system performance not only using high-contrast test charts, but also under reduced-contrast conditions that more closely reflect real-world operational environments.

Taken together, these findings underscore that the effective detection and recognition of targets using NVGs is influenced by both system-level image quality and the visual system's ability to extract information under constrained viewing conditions. Even when NVG-generated

image specifications appear to meet theoretical thresholds for performance, real-world limitations, such as contrast loss due to image intensifier wear and individual variability in visual processing [7], can compromise the observer's ability to detect or correctly identify targets. Therefore, comprehensive NVG performance evaluation should integrate both technical assessments (e.g., MTF-based analysis) and user-centered factors, particularly under contrast conditions that realistically simulate operational environments. Only by combining these perspectives can we ensure that the visual information presented through NVGs is not only technically sufficient, but also perceptually accessible to the end user.

### Individual differences

Our analysis showed that NVG-aided vision significantly impaired both target detection and recognition ( $p < 0.001$ ), and this effect was not moderated by participants' age or flight experience. Neither age nor total flight hours significantly predicted performance in either task, indicating that the performance decrement under NVG conditions reflects inherent limitations of the visual environment (photopic vs. NVG-aided), rather than differences in individual ability.

Although the participant sample was medically screened and relatively homogeneous, individual

visual traits may have influenced NVG-based task performance. One relevant factor is accommodative response in low-light environments. Research suggests a natural tendency for the eye to accommodate to a near focal distance (known as “dark focus”) under scotopic or visually sparse conditions [48]. This could impair image clarity when viewing NVG displays focused at optical infinity, particularly in users with a strong tendency toward near accommodation [46]. Additionally, binocular suppression, especially of the non-dominant eye, may reduce effective binocular integration, thus narrowing perceived FOV and decreasing contrast sensitivity [1,8]. Such effects may be exacerbated by interocular luminance imbalances, further degrading visual performance. Nonetheless, no participants in the current study reported discomfort or visual strain, suggesting these individual differences, while theoretically impactful, did not manifest overtly in our sample.

### Study limitation

While the findings of this study provide insight into NVG performance in controlled conditions, several limitations should be considered when interpreting the results.

First, the conditions under which the experiment was conducted may not have been sufficiently demanding to replicate the operational stressors associated with real-life NVG missions. Specifically, the study took place during daytime hours, which likely minimized the physiological and cognitive fatigue typically induced by prolonged nighttime operations. In actual scenarios, extended missions, especially those that disrupt natural circadian rhythms, are associated with a range of performance hazards, such as complacency, computational errors, communication breakdowns, poor decision-making, and irritability [6]. Circadian disruption is almost inevitable during night flights, and these factors must be considered when evaluating the external validity of our findings.

In addition to environmental limitations, methodological challenges related to visual behavior should be considered. While the target detection and recognition task relied on NVG use, participants were not instructed in standardized scanning strategies. As a result, each subject may have adopted a personal approach to visual search, which varied in effectiveness. Rapid or erratic scanning patterns may have caused image instability or blurring, potentially contributing to missed targets or misidentifications [34]. This variability constitutes a confounding factor that may have influenced the observed outcomes.

Finally, there are conceptual limitations related to the use of Johnson’s Criteria [26] as a predictive model originally developed for thermal imaging performance. Although this model remains a widely used and accessible standard for estimating detection range, it is fundamentally empirical and idealized. It does not account for important human performance variables such as observer experience, fatigue, and attentional capacity. Moreover, it is based on a 50% probability threshold and does not describe how detection probability increases beyond that point with improved resolution or image quality. Thus, while Johnson’s Criteria provide a useful benchmark, they may not fully reflect real-world operational effectiveness.

### CONCLUSIONS

We found that visual target detection and recognition performance was significantly impaired under NVG conditions, regardless of participants’ age or flight experience. The NVG condition resulted in both statistically and practically meaningful declines in recognition accuracy, underscoring the perceptual limitations associated with night vision technology.

The observed performance differences between NVG-aided and photopic conditions likely result from a combination of system-level constraints (e.g., restricted field of view, reduced contrast sensitivity), optical factors (image intensifier variability), and possible individual visual characteristics. Although the NVG system met theoretical thresholds for resolution and contrast, worn intensifiers may have reduced image quality below operational requirements, particularly under realistic, lower-contrast conditions.

These findings highlight the need to assess NVG performance not only with high-contrast charts, but also under degraded contrast to reflect real-world use. Incorporating both system diagnostics and user-centered factors is essential for ensuring reliable detection and recognition in operational settings.

In addition, to improve user performance, reduce visual fatigue, or identify individuals most likely to succeed in NVG-supported flight operations, further investigation is necessary. This includes the development of screening tools sensitive to these factors, as well as the design of enhanced training protocols targeting visual skills. Such efforts may help ensure safer and more effective use of NVG systems across a broader range of operational scenarios.

## AUTHORS' DECLARATION

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## REFERENCES

1. Arditi A. Binocular vision. In: Boff KR, Kaufman L, Thomas JP, editors. *Handbook of Perception and Human Performance Vol 1*. 1st ed. New York (NY), US: John Wiley and Sons Inc; 1986.
2. Banks JH, Sternberg JJ, Cohen BJ, DeBow H. Improved Search Techniques with Passive Night Vision Devices. (Technical Research Report 1169, NTIS No. AD 722 236). Arlington, VA; 1971.
3. Banks JH, Sternberg JJ, Farrell JP, Dalhamer WA, Vreuls D. Effects of search area size on target acquisition with passive night vision devices (Technical Research Report 1168, NTIS No. AD 722 235). Arlington, VA; 1971.
4. Ben-Shachar MS, Lüdecke D, Makowski D. effectsize: Estimation of Effect Size Indices and Standardized Parameters. *J Open Source Softw.* 2020; 5(56):2815.
5. Berkley WE. Issues and developments in aircrew NVG training. In: 6th Annual Joint Service Night Vision Conference, Phoenix, AZ; United States; 1991.
6. Biernacki MP, Lewkowicz R. The role of visual conditions and aircraft type on different aspects of pilot workload. *Appl Ergon.* 2024; 118:104268 Contents.
7. Borissova D. Methods for NVG Visual Acuity Determination. 2003; 3(2):25–33.
8. Brickner MS. Helicopter flights with night-vision goggles: Human factors aspects. NASA Technical Memorandum 101039. Moffett Field, CA; 1989.
9. Chang Y-H, Lee JB, Kim NS, Lee DW, Chang JH, Han S-H. The effects of interocular differences in retinal illuminance on vision and binocularity. *Graefes Arch Clin Exp Ophthalmol.* 2006; 244(9):1083–8.
10. Clare JN. Recognition as an extension to the detection process. In: Clare JN, Sinclair MA, editors. *Search and the Human Observer*. London, UK: Taylor and Francis; 1979.
11. CuQlock-Knopp VG, Merritt JO, Bender EJ, Wright-Hector L. Object recognition and contrast sensitivity with image intensifiers employing white phosphor versus green phosphor displays. In: *Proceedings of the SPIE - the International Society for Optical Engineering*. San Diego, USA: Bellingham, Wash., USA: SPIE-The International Society for Optical Engineering; 2000. p. 29–37.
12. Decker JJ, Pigion RD, Snyder HL. A literature review and experimental plan for research on the display of information on matrix-addressable displays. (Technical Memorandum 4-87). Aberdeen Proving Ground, MD; 1987.
13. Department of Defense. *Photographic Lenses (Military Standard MIL-STD-150A) (including changes through 28 January 1963)*. Washington, DC: U.S. Government Printing Office; 1959.
14. Frisby JP, Mayhew JE. Contrast sensitivity function for stereopsis. *Perception.* 1978; 7(4):423–9.
15. Gale AG, Worthington BS. The Utility of Scanning Strategies in Radiology. In: Groner R, Menz C, Fischer DE, Monty RA, editors. *Eye Movements and Psychological Functions*. New York, NY, US: Lawrence Erlbaum; 1983. p. 169–91.
16. Gąsik M, Stasiak K, Kowalczyk K. Night vision training and education system at WIML. [System szkolenia i treningu widzenia nocnego w WIML]. *Pol Przegląd Med Lotniczej.* 2006; 12(3):279-289 (in Polish).
17. Genco L V. Night vision support devices: Human engineering integration. AGARD CP-379. In: *Visual Protection and Enhancement*. Neuilly-Sur-Seine, France; 1985. p. 6.1-6.8.
18. Geri GA, Wetzel PA, Martin EL. Head and Eye Movements in Free Visual Search: Effects of Restricted Field of View and Night Vision Goggle Imagery (Report No. AFRL-HE-AZ-TR-1999-0249). Mesa, AZ; 2000.
19. Geri GA, Martin EL, Wetzel PA. Head and eye movements in visual search using night vision goggles. *Aviat Space Environ Med.* 2002; 73(8):779–86.
20. Glaholt MG. Field of view requirements for night vision devices. A review of empirical research. (DRDC-RDDC-2016-R032). Toronto, Canada; 2016.
21. Harrington LK, McIntire JP, Hopper DG. Assessing the binocular advantage in aided vision. *Aviat Space Environ Med.* 2014; 85(9):930–9.
22. Harrison MF, Coffey B, Albert WJ, Fischer SL. Night vision goggle-induced neck pain in military helicopter aircrew: a literature review. *Aerosp Med Hum Perform.* 2015 Jan; 86(1):46–55.

23. Hoffman JE, Nelson B, Houck MR. The role of attentional resources in automatic detection. *Cogn Psychol*. 1983; 15(3):379–410.
24. Jansen SEM, Toet A, Delleman NJ. Restricting the Vertical and Horizontal Extent of the Field-of-View: Effects on Manoeuvring Performance. *Ergon Open J*. 2010; 3(1):19–24.
25. Jezierski M, Prost M, Stasiak K, Kuliński J, Gąsik M, Skibniewski F. An assessment of visual acuity during the use of night vision goggles PNL-3. [Ocena ostrości wzroku w trakcie posługiwania się goglami noktowizyjnymi PNL-3]. *Pol Przegląd Med Lotniczej*. 2005; 11(3):237-241 (in Polish).
26. Johnson J. Analysis of Imaging Forming Systems. In: Johnson RB, Wolfe WL, editors. Selected papers on infrared design. SPIE-the International Society for Optical Engineering; 1985. p. 1028.
27. Kaiser MK, Foyle DC. Human Factors Issues in the Use of Night Vision Devices. *Proc Hum Factors Soc Annu Meet*. SAGE Publications; 1991; 35(20):1502–6.
28. Kassambara A. rstatix: Pipe-Friendly Framework for Basic Statistical Tests. 2023.
29. Kassambara A. ggpubr: “ggplot2” Based Publication Ready Plots. 2025.
30. Knight KK, Apsey DA, Jackson WG, Dennis RJ. A comparison of stereopsis with ANVIS and F4949 night vision goggles. *Aviat Space Environ Med*. 1998; 69(2):99–103.
31. Kotulak JC. Methods of Visual Scanning with Night Vision Goggles (Report No. USAARL 92-10). Fort Rucker, AL, U.S.; 1992.
32. Kuliński J, Prost M, Stasiak K, Jezierski M, Latek-Najder M. Visual performance in night vision goggles PNL-3 assessed with contrast sensitivity tests. [Sprawność widzenia w goglach noktowizyjnych PNL-3 na podstawie testów]. *Pol Przegląd Med Lotniczej*. 2005; 12(2):137-143 (in Polish).
33. Kundel HL, Nodine CF, Carmody D. Visual scanning, pattern recognition and decision-making in pulmonary nodule detection. *Invest Radiol*. 1978; 13(3):175–81.
34. Lounis C, Peysakhovich V, Causse M. Visual scanning strategies in the cockpit are modulated by pilots’ expertise: A flight simulator study. *PLoS One*. 2021; 16(2 February).
35. McLean WE. An Assessment of Luminance Imbalance with ANVIS at an Army Helicopter Training Airfield. USAARL Report No. 97-21. Fort Rucker, AL; 1997.
36. Nodine CF, Carmody DP, Kundel HL. Searching for NINA. In: Monty RA, Fisher DF, Senders JW, editors. Eye movements and the higher psychological functions. Hillsdale, NJ, US: Laurence Erlbaum; 1978. p. 241–58.
37. Oldham TW. Night vision and night vision goggles. (DTIC No. AD-A241 057). Maxwell Air Force Base, AL; 1990.
38. Parush A, Gauthier MS, Arseneau L, Tang D. The Human Factors of Night Vision Goggles: Perceptual, Cognitive, and Physical Factors. *Rev Hum Factors Ergon*. SAGE PublicationsSage CA: Los Angeles, CA; 2011; 7(1):238–79.
39. Pousette MW, Lo Martire R, Linder J, Kristoffersson M, Ång BO. Neck Muscle Strain in Air Force Pilots Wearing Night Vision Goggles. *Aerosp Med Hum Perform*. 2016; 87(11):928–32.
40. Price DR, Mclean WE. Aeromedical Lessons Learned With Night Vision Devices. In: Visual Protection and Enhancement, AGARD CP-379. Neuilly-Sur-Seine, France: AGARD; 1985. p. 8.1-8.10.
41. Prost M, Jezierski M, Stasiak K, Kuliński J, Gąsik M. Study on stereopsis with night vision goggles PNL-3. [Badania widzenia stereoskopowego w trakcie posługiwania się goglami noktowizyjnymi PNL-3]. *Pol Przegląd Med Lotniczej*. 2005; 11(4):359-363 (in Polish).
42. Prost M, Stasiak K, Jezierski M, Kowalski W, Kuliński J. Influence of heat load on visual acuity in night vision goggles PNL-3. [Wpływ obciążenia termicznego na ostrość wzroku w goglach noktowizyjnych PNL-3]. *Pol Przegląd Med Lotniczej*. 2005; 11(1):51-56 (in Polish).
43. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria; 2016.
44. Ratches JA. Static Performance Model for Thermal Imaging Systems. *Opt Eng*. SPIE; 1976; 15(6):525–30.
45. RCA. Electro-optics handbook technical series EOH-11. Lancaster: RCA Corporation; 1974. 255 p.
46. Roscoe SN. Bigness is in the eye of the beholder. *Hum Factors*. 1985; 27(6):615–36.
47. Sheehy JB, Wilkinson M. Depth perception after prolonged usage of night vision goggles. *Aviat Space Environ Med*. 1989; 60(6):573–9.
48. Simonelli NM. The Dark Focus of Visual Accommodation: Its Existence, Its Effects, Its Measurement. University of Illinois at Urbana-Champaign; 1980.
49. Snyder AW, Laughlin SB, Stavenga DG. Information capacity of eyes. *Vision Res*. Pergamon; 1977; 17(10):1163–75.
50. Stasiak K, Prost M, Jezierski M, Kuliński J, Gąsik M. Changes in the vision field with the use of night vision goggles PNL-3. [Zmiany w polu widzenia w trakcie stosowania noktowizora PNL-3]. *Pol Przegląd Med Lotniczej*. 2005; 11(3):231-236 (in Polish).

51. Stasiak K, Zyskowska M, Głowinkowska I, Kowalczyk K, Lewkowicz R. Influence of night vision goggles with white and green phosphor screens on selected parameters of the eye and fatigue. *Ergonomics*. 2022; 65(7):999–1014.
52. Stefanik R. Image intensifier system resolution based on laboratory measured parameters. Technical Report No. 0112. Fort Belvoir, VA; 1994.
53. Stein N, Watson T, Lappe M, Westendorf M, Durant S. Eye and head movements in visual search in the extended field of view. *Sci Rep*. 2024; 14(1):8907.
54. Stevenson SB, Cormack LK. A contrast paradox in stereopsis, motion detection, and vernier acuity. *Vision Res*. 2000; 40(21):2881–4.
55. Toet A, Jansen SEM, Delleman NJ. Effects of field-of-view restriction on manoeuvring in a 3-D environment. *Ergonomics*. 2008; 51(3):385–94.
56. Verona RW, Rash CE. Human Factors And Safety Considerations Of Night Vision Systems Flight. In: *Proceedings of the SPIE Technical Symposium on Aerospace Sensing*. Orlando, FL, United States: SPIE; 1989. p. 2–12.
57. Wickham H, François R, Henry L, Müller K, Vaughan D. *dplyr: A Grammar of Data Manipulation*. 2025.
58. Wickham H. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York; 2016.
59. Zelinsky GJ. Eye movements during change detection: Implications for search constraints, memory limitations, and scanning strategies. *Percept Psychophys*. 2001; 63(2):209–25.
60. Standard NATO Agreement (STANAG) Aeromedical aspect of night vision device (NVD) training. No. 7147.
61. XD-4TM Image Intensifier [Internet]. Available from: <https://pdf.directindustry.com/pdf/photonis/xd-4/82199-327297.html>