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Analysis of Pilot Distance Estimation in Different Lighting and Visibility Conditions

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ABSTRACT

Several studies on distance and size estimation have focused on normal and night vision goggles (NVGs), but none of them have been performed during the twilight period. Hence, in this study, distance was estimated for the first time during nautical twilight. According to the findings, the accuracy of distance estimation reduces as visibility decreases and is restricted. When compared with Day Limited Helmet Mounted Display Vision (M = 5.27, SD = .59), Twilight Normal Vision (M = 5.33, SD = .69) and Twilight Helmet Mounted Display Vision (M = 5.20, SD = .61), NVG (M = 4.79, SD = .57) appears to have a lower error rate. In this study, distance was estimated considering objects determined during the helicopter flight by the pilots in different visibility conditions, which are significant in the field of aviation. This work is unique owing to its coverage of helicopter pilots and the estimation during the twilight period. In view of our findings, it may be reasonable to postpone the planned helicopter flights during poor visibility conditions.

Keywords: Aviation; Distance estimation; Twilight condition; Restricted vision; Night vision goggles; Helicopter pilots

NOMENCLATURE

DN	: Day Normal Vision
DH	: Day Limited Helmet Mounted Display Vision
TN	: Twilight Normal Vision
TH	: Twilight Helmet Mounted Display Vision
NVGs	: Night Vision Goggles

1. INTRODUCTION

1.1 Background

Approaching a designated point without a runway is the crucial difference between helicopters and fixed-wing aircrafts[1]. Helicopter pilots often face risky situations, such as low visibility, bad weather and night-time operations [2]. Maintaining the orientation is vital, and pilots rely heavily on their vision to hover steadily and choose visual reference points[3]. Loss of orientation in compromised visibility conditions can lead to loss of control, and hence, fatal accidents[4].

Daytime vision relies on cone cells, whereas rod cells enable low-light perception and peripheral vision[5]. Photopic vision refers to high-intensity vision enabled by cone cells, while scotopic vision occurs in very low light conditions with limited colour sensitivity[6]. On the contrary, mesopic vision experienced during twilight involves reduced efficiency of both cone and rod cells and may affect object perception [7].

Twilight, the transition between daylight and darkness, poses challenges in detecting obstacles owing to decreasing brightness[8].Visual recognition functions deteriorate rapidly during twilight, which affects sharpness and contrast sensitivity[9].

1.2 Night Vision Devices

Image intensifier systems, which were originally used in military, astronomy and research, found applications in aviation with the development of night vision goggles (NVGs). These systems, attached to helmets, gained popularity in the American Army during the 1970s[10].

Figure 1 depicts the operating principles of NVGs. NVG works on the principle of light emanating from the object being focused on the photocathode by objective lens. Light photons striking the photocathode cause electrons to be released in direct proportion to the amount of light reflected by the lens. The freed electrons are accelerated from the photocathode surface by an electric field generated via the power source of NVGs. The number of electrons striking the phosphor screen is increased using a microchannel plate, which is a thin honeycomb composed of thin glass tubes[12].

All night vision tasks involve numerous phases, such as identifying, detecting and recognizing objects in the environment as well as estimating their size and distance from the operator. The improved image quality makes wearing NVGs comfortable. In this context, visual acuity, viewing angle and depth perception are crucial[13].

In Fig. 2, the points of view of a pilot seated in the cockpit with/without NVG are depicted. The angle of view is the angular expression of the vision falling on the retina through the tube when looking at a fixed object or place with NVGs. Typically, visual angles of 30°–40° are common in NVGs but

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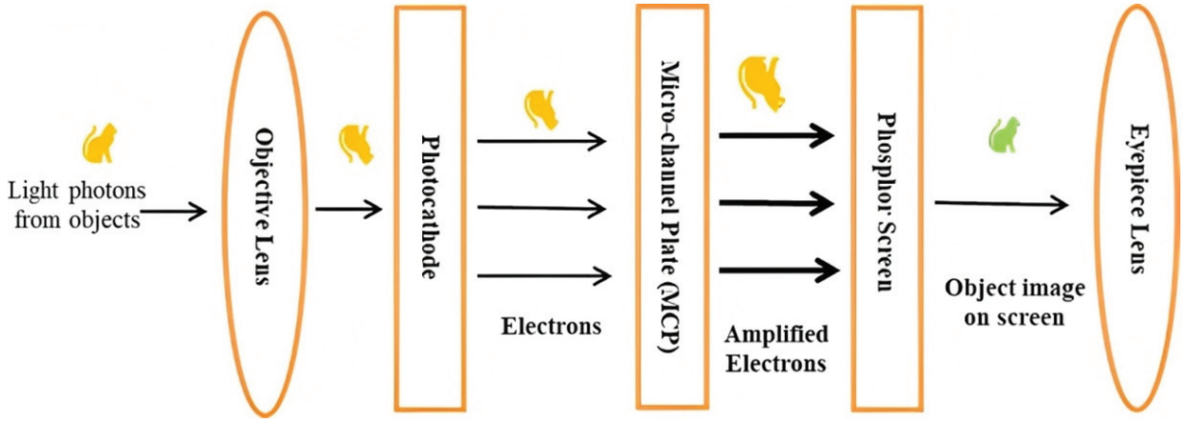
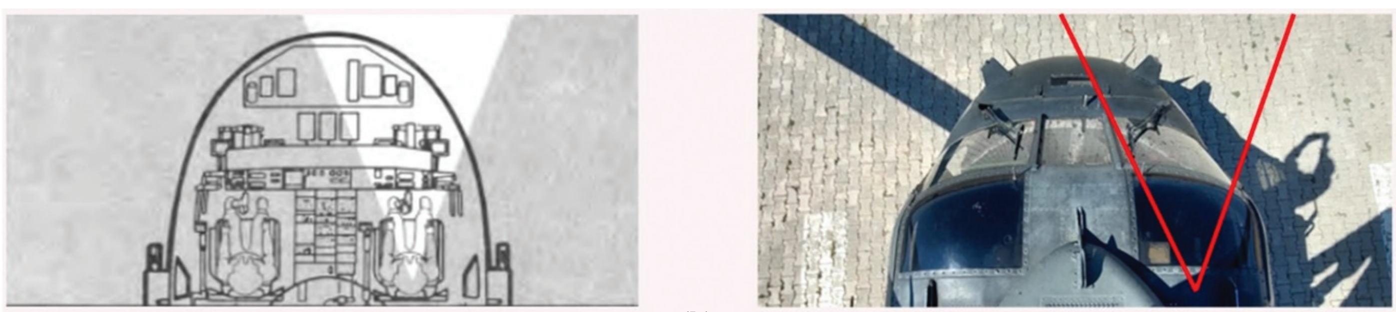


Figure 1. A schematic diagram of NVG components[11].

(a)



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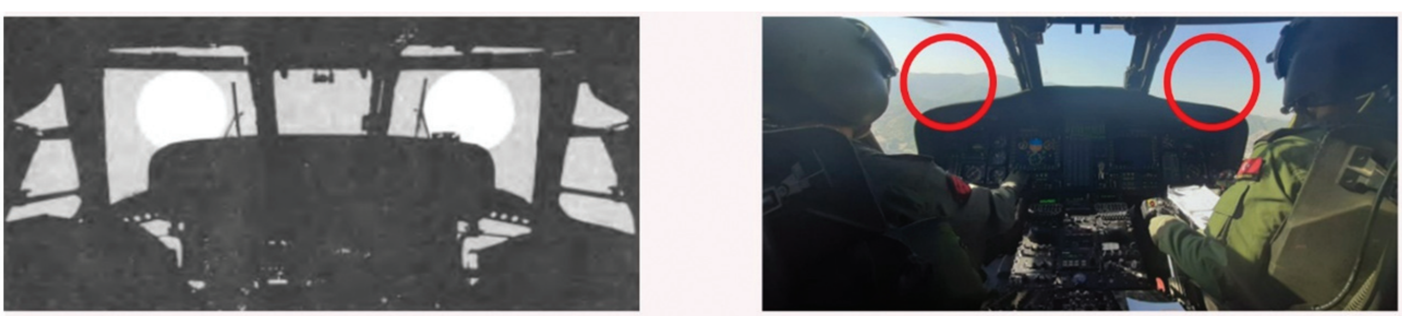

(c)

Figure 2. Normal (day) and NVG views from the UH-60 cockpit (images on the left are from the literature, and those on the right were captured by our pilots)[14]: (a) Shaded areas are areas of the pilot's field of view from the UH-60 helicopter cockpit structures, (b) Field of view of the pilot wearing the NVG and looking straight ahead, and (c) The circle show the limited field of view of both pilots wearing the NVG.

reduced visual acuity at these angles increases the likelihood of disorientation[15-16]. Moreover, while a narrow perspective increases the disorientation because of the absence or reduction of external visual cues[17], maintaining orientation or situational awareness poses cognitive challenges when using NVGs[18].

1.3 Distance Estimation

Accurate distance estimation is an important task for most aircraft pilots, but it is all the more critical for helicopter pilots. Owing to its inherent nature, the helicopter can fly at low altitudes and hover at a set height, land in places with very little clearance, and manoeuvre between trees and other

Table 1. A literature review of distance estimations in different environments

	Environment						Vision systems			
Autor(s)	**By pilot**	**Day**	**Night**	**Twilight**	**Virtual reality**	**Augmented reality**	**Human eye (unrestricted)**	**NVG**	**Restricted (without NVG)**	**Helmet mounted display**
18	✓*	✓	✓	X	-	-	✓	✓	✓	-
13	-	-	✓	X	-	-	✓	✓	-	-
19	-	✓	✓	X	-	-	✓	✓	-	-
20	✓	✓	✓	X	-	-	✓	✓	-	-
21	-	✓	-	X	-	-	✓	-	✓	✓
22	-	✓	-	X	✓	✓	✓	-	-	✓
23	-	✓	-	X	-	-	✓	-	✓	✓
24	-	✓	-	X	✓	-	-	-	✓	✓
25	-	✓	-	X	✓	-	✓	-	✓	✓
26	-	✓	-	X	✓	-	✓	-	-	✓
27	-	✓	-	X	✓	-	✓	-	-	✓

*Military personnel

obstructions. All these piloting tasks require accurate distance estimation to execute the manoeuvre accurately and safely[19]. Distance estimation types are summarised in Table 1. Literature review revealed a lack of studies on distance estimation during twilight (X) by helicopter pilots. Hence, this study is unique.

1.4 Flight Safety In Restricted Visibility and Poor Lighting Conditions

Nascimento, *et al.* have reported that accident rates of helicopters flying to offshore oil and gas platforms are at least five times higher in night sorties than during the day[28]. In another study conducted in parallel with this subject but as a different concept, the findings showed that twilight and the first hour of darkness are usually the peak times for pedestrian fatal crashes[29].

This study aimed to investigate the perceptual function of distance estimation due to decreased visual cues and depth perception during unaided vision using NVGs compared to daytime (photopic) illumination levels. Distance estimation at twilight is the most difficult, and this period is associated with illusions and road accidents[30]. Therefore, this study was performed to reduce illusions and alleviate the risks of accidents in this time period and also propose possible solutions to the problem. Contribution of the study are as follows:

- The accuracy of distance estimation decreases when the vision is restricted or degraded. Hence, proper vision of the pilots of aircrafts and other air vehicles is essential for safety and military operations. Therefore, in this study, distance estimation by pilots of air vehicles was performed under three conditions, including twilight, which was performed for the first time in the literature
- While revealing the relationships of different aircraft types, such as utility, attack and observer on distance estimation accuracy, which distances a pilot can estimate more accurately under which conditions were investigated
- The effects of various parameters, such as flight year and NVG flights, on pilot distance estimation were also investigated
- Whether the distances estimated by the pilots with different flight times under different lighting and visibility conditions were either overestimated or underestimated and which distances were determined more accurately by the pilots were researched.

2. MATERIALS AND METHODS

In this study, distance was estimated by eight helicopter pilots in different circumstances. The pilots estimated the distance in different light (illumination) conditions (day, twilight and night) and distinct occasions w/o NVGs and limited view field Head Mounted Display (HMD). All details were placed in the dataset; additionally, the dataset contained the real and estimated distance values as well as the estimation error calculated from the difference between these two values. The dataset comprised the above-mentioned features and involved 240 records (8 pilots/5 distinct conditions/6 different distance estimations). The general characteristics of the pilots are given in Table 2.

Information regarding the eight pilots is presented in Table 2. The mean age of the pilots was 31 with a standard deviation of 3.39 and the experience of average flight duration

Table 2. Pilot information

Pilot	Age	Flight experience (Year)	Total flight (Hrs)	Total NVG (Hrs)	Helicopter type
P1	27	4	715	62	Attack
P2	29	3	610	62	Utility
P3	31	3	560	16	Utility
P4	31	4	697	70	Attack
P5	37	10	2374	308	Attack
P6	35	9	2297	345	Attack
P7	31	5	842	111	Attack
P8	28	8	280	23	Attack

of the pilots was 5.75 hrs with a standard deviation of 2.81. Moreover, average flight hours and average NVG flight hours were 1046.87 hr. and 124.62 hr., with standard deviations of 811.92 and 128.35, respectively. All pilots had utility helicopter ratings, and six of them had T-129 attack helicopter ratings; therefore, two of them were excluded and evaluated under distinct aircraft type. All pilots made estimations with the same type of NVGs (Gen 3), and the time-dependent efficiency reduction was neglected while using NVGs. HMD is a basic training tool for restricting normal vision and is used to perform instrument flight training for not scanning outside the helicopter. Pilots who flew with the T-129 helicopter had a Targeting Sight Unit (TSU) system, which measures the distance between the target and the helicopter, as a concept. Whether flying with this concept exerted an effect on accurate distance estimation was investigated. All eight pilots had undergone the aircrew medical examination, including specialist examinations and fitness assessments, not more than 1 year before the start date of the experiment. Moreover, the pilots did not have any eye disorders or defects.

3. PRELIMINARIES

The study was conducted during daytime, twilight and nighttime on the same day. The weather conditions included clear cloud cover at 4000 feet for the ceiling and broken visibility at 10000 feet (according to the METAR report). The chosen twilight fell between 18:10 hrs and 18:42 hrs, which provided a lighting condition in which object outlines could be seen on the ground while the horizon line remained blurred. During this period, although stars were visible for navigation, object details were indistinguishable.

Moon visibility was at 21 per cent on the study day, with an angle below -30°. The estimations were made using NVGs in the absence of lunar illumination. Owing to complete cloud cover at 10000 feet, starlight was not considered a significant factor, with an illumination level of 0.00022 lux. The reflection of city centre lights at a distance of 1.2 nm (2.22 km) was evaluated to contribute to NVG distance estimation.

A white cardboard measuring 210 × 297 mm was used for distance estimation and was positioned horizontally approximately 140 cm from the floor at a height of 4 feet. Time constraints were disregarded during each estimation, and the pilots were turned away in different directions to minimize any influence on their distance estimation. Actual distances were measured using a precision laser meter for comparison with the pilots' estimations.

Each pilot was asked to make six estimations for each condition. The pilots were not provided with any feedback or distance information either before or after the estimation. The distance estimation test involved eight pilots, with independent estimates performed using their own perspective (egocentric). The estimation process was monitored exclusively by the supervisory staff, which ensured confidentiality.

In summary, distance estimations were performed in the study during daytime, twilight and nighttime conditions. Specific weather conditions, moon visibility and the use of NVGs were considered, and white cardboard was used as a reference for distance estimation. The test involved eight pilots making multiple estimations, with independent assessments and no feedback.

4. RESULTS AND DISCUSSION

To investigate the relationships between pilot characteristics and factors affecting distance estimation, the normal distribution of the distance error values was examined. However, the skewness and kurtosis values of the error fell outside the range of ±1.96, which indicated that they did not follow a normal distribution. This finding was further supported by the results of the Kolmogorov–Smirnov and Shapiro–Wilk tests, which also implied non-normal distribution of the estimation error values.

All statistical analyses were performed using the SPSS 28.0 program. The Skewness–Kurtosis, Kolmogorov–Smirnov and Shapiro–Wilk values are presented in Table 3.

Table 4 shows that while daytime normal vision had a lower error than day-HMD vision, the errors under twilight normal and twilight-HMD conditions were almost the same. This observation reveals that the detrimental effect of limited vision on distance perception occurs only in daylight conditions. Furthermore, when the twilight error values (TN = 5.33 – TH = 5.20) were examined, a high error rate was observed, which might have resulted from the insufficient functioning of cone and rod cells.

The boxplots of the visibility conditions are depicted in Fig. 3. As expected, DN vision produced the lowest error of all visibility conditions. Interestingly, the TN error was slightly higher than the TH error; thus, it can be concluded that the effect of the use of a vision-restricting HMD was negligible in poor

Table 3. Descriptive and test of normality values of estimation error

		Statistic	Std. error	Sig.
Estimation error	Mean	4,9042	,26620	-
	Median	4,0000	-	-
	Variance	17,008	-	-
	Std. deviation	4,12402	-	-
	Minimum	,00	-	-
	Maximum	20,00	-	-
	Skewness	,991	,157	-
	Kurtosis	,849	,313	-
Test of normality	Kolmogorov–Smirnov	-	-	<0.001
	Shapiro–Wilk	-	-	<0.001

Table 4. Vision types and error relationship

Vision	*Mean ± SD*	Median (Min.–Max.)
DN	3.92 ± 0.50	3.00 (0–13.00)
DH	5.27 ± 0.59	5.00 (0–16.00)
TN	5.33 ± 0.69	4.00 (0–20.00)
TH	5.20 ± 0.61	4.00 (0–13.00)
NVGs	4.79 ± 0.57	4.00 (0–20.00)

DN: Day Normal, DH: Limited Day HMD, TN: Twilight Normal, TH: Twilight HMD, NVG: Night Vision Goggles

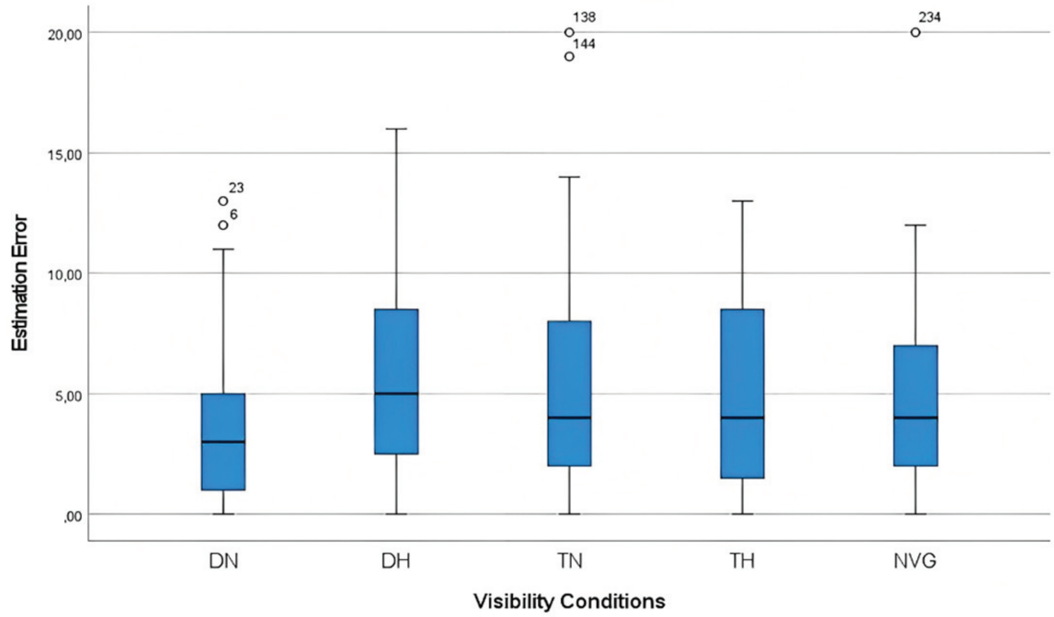

Figure 3. Visibility conditions–error rate graphic display.

visibility conditions. Although these data are important for the twilight condition in which there is an insufficient use of cone and rod cells, it is considered a subject open to interpretation owing to the higher error rate of the day-restricted vision compared with both twilight visions.

The Freidman test was applied to measure the significant difference between these vision conditions. By applying this test, the estimation error relationships were determined under different conditions. The results of Freidman test are furnished in Table 5 and since the significance value is greater than 0.05, it can be said that there is no significant difference between the estimation errors made under different visual conditions.

Table 5. Freidman test results of different vision conditions

	Mean ranks of estimation error of different vision conditions					
	DN	**DH**	**TN**	**TH**	**NVG**	**Asymp. Sig.**
Freidman test	2.57	3.14	3.02	3.20	3.07	0.284

Table 6. Correlation values of Spearman test

Vision conditions	**Values**	**Flight year**	**Total flight hrs**	**NVG hrs**
DN	Correlation coefficient	−.237	−.202	−.214
	Sig. (2-tailed)	.105	.168	.145
DH	Correlation coefficient	**−.338***	−.171	−.267
	Sig. (2-tailed)	.019	.245	.066
TN	Correlation coefficient	.163	−.012	.041
	Sig. (2-tailed)	.269	.934	.781
TH	Correlation coefficient	.124	.195	.178
	Sig. (2-tailed)	.401	.183	.225
NVG	Correlation coefficient	−.272	**−.291***	**−.285***
	Sig. (2-tailed)	.062	.045	.050

*Correlation was significant at the 0.05 level (2-tailed)

The correlation relationship with the increase in flight year, total flight hours and NVG flight hours is given in Table 6. When the values were examined, a high negative correlation was observed between flight year experience and DH. Moreover, the results between NVG conditions and total flight hours w/o NVG appeared to be negatively correlated.

The ratings of pilots using attack helicopters were compared with those of pilots using other helicopter types using the Mann–Whitney U test. However, the analysis did not reveal a statistically significant difference between the two groups, with mean ranks of 116.40 for pilots having attack helicopter ratings and 132.79 for pilots not having such ratings.

In Fig. 4, the estimated and real distance values are presented in meters, and histograms and bar graphs of error rates are depicted for different visibility conditions. From Figure 4a, it is evident that at short distances, the real and estimated values of all pilots were close to each other, whereas the errors in the positive and negative directions increased with the increase in distance. In Fig. 4(b) in which the estimated and real distances with night vision are displayed, the values were aligned closely with the linear line. Figure 4(c) presents the average error of NVGs on a per-pilot basis, which shows that Pilot 7 had the highest mean error with a value of 9.1667 meters. Figure 4(d) illustrates the mean estimation error of pilots operating each aircraft type under different visibility conditions. In this graph, the lowest mean error was measured as 3.83 mtrs with the T-129 Atak helicopter under normal daytime conditions.

The study findings indicate that the accuracy of distance estimation decreased as visibility conditions deteriorated. Table 4 demonstrates that the lowest error rate was observed in the DN condition (M = 3.92, SD = .50), whereas the TN condition resulted in the highest error rate (M = 5.33,

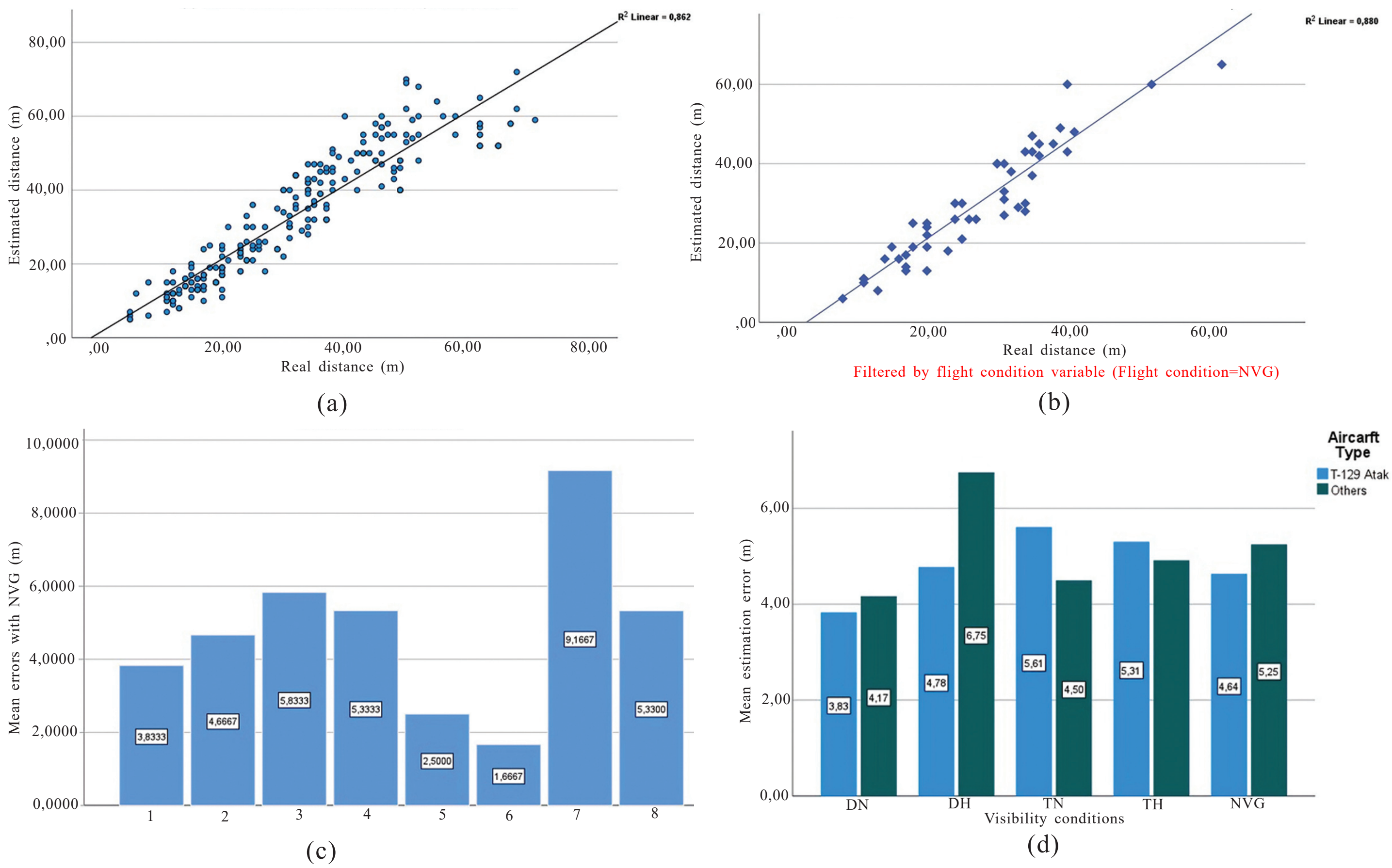

Figure 4. Graphical representation of estimated distance and estimation errors: (a) Scatter plot of estimated distance by real distance, (b) Scatter plot of estimated distance by real distance with NVG, (c) Pilot-mean error with NVG, and (d) Mean estimation error under different visibility conditions by aircraft type.

SD = .69). As the observation point was the same, it could have potentially resulted in self-feedback from the pilot. These results agreed with those from previous studies in the literature. When examining the twilight estimation values in Table 4, a notable increase in error values compared with other visibility conditions was observed. This result could be attributed to the inadequate utilization of cone and rod cells during this period. The NVG condition was associated with a lower error rate (M = 4.79, SD = .57) compared with DH, TN and TH. Despite being a monochromatic vision system, the NVG demonstrated better performance than twilight lighting conditions during the day. This finding suggests that cone and rod cells are underutilised during twilight, which leads to inaccuracies in the distance estimation. This study contributes to the literature by addressing this aspect of cone and rod cell underutilization for the first time.

Figure 4(c) shows that Pilot 5 and Pilot 6 had lower distance estimation error rates than the other pilots. Based on the statistics of Pilot 5 and Pilot 6 in Table 2, their flight years were 10 and 9, flight hours were 2374:00 and 2297:00 and NVG flight hours were 308:00 and 345:00, respectively.

In comparison with the figures for the other six pilots, these values are higher. Thus, the research shows that the accuracy of distance estimation increases as flight experience and flight hours increase.

The NVG distance estimation error rates of Pilot 5 and Pilot 6 were much lower when compared with those of other pilots (Fig. 4(c)). The significance of this finding is that it asserts that as flight experience and flight hours increase, so does the accuracy of distance estimation. This conclusion is supported by the very low correlation in Table 6 (Flight hrs r = 0.291, $p > 0.05$) and NVG flight hours (r = -.285, $p > 0.05$).

Another finding from this study was the correlation between the total number of NVG flying hours and the accuracy of the NVG distance estimation. An average correlation was observed when the values were investigated (r = -.538, $p < 0.01$). This shows that NVG flying time is closely related to improved distance estimation accuracy. This is considered to be an important result indicating how accidents can be prevented with NVG training under the previously described NVG flight conditions.

Pilots possessing the T-129 Attack helicopter rating were compared with other pilots without the rating. When the error values were analysed according to the type rating of an attack helicopter, a statistically significant difference was noted between those who had the rating (M = 116.40) and those who did not (M = 132.79). The TSU sensor, which measures the distance between the target and the helicopter and is frequently used by pilots flying attack helicopters, is considered to be

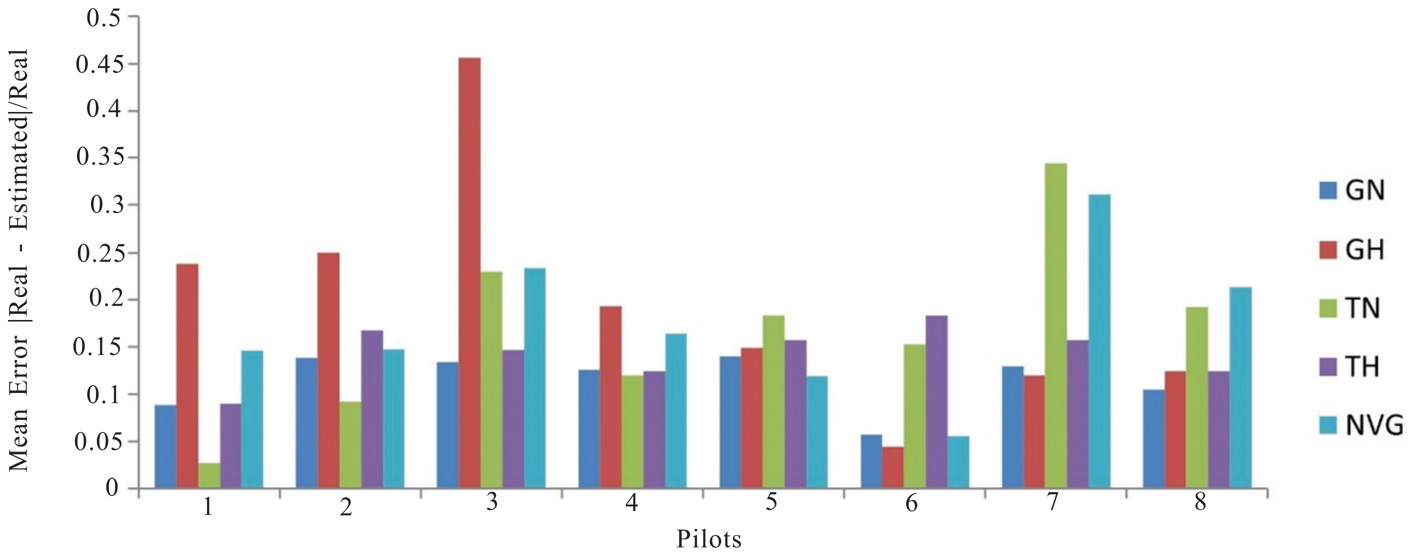

Figure 5. Mean error–types of estimation conditions.

one of the reasons for this difference in error. Another factor is that these pilots fly in formation, as standard practice (at least two helicopters). According to the leader's instructions, they come close to or farther away from one another in different patterns. Therefore, pilots flying in this regime may be capable of estimating distances precisely.

The mean of the error values ($|Real - Estimated| / |Real|$) of the total estimates of the pilots is presented in Fig. 5. The error rates of all pilots during DN were lower than when wearing NVG (except for Pilot 6). This result shows the negative effect of the limited field of view and night vision system on distance estimation. DH error rates were higher than DN error rates for all pilots (except for Pilot 6). This result demonstrates the detrimental effect of the limited field of view on distance estimation. Except for Pilots 3, 5, 7 and 8, TH resulted in a better estimation accuracy than TN. These findings indicate that under the same lighting condition (twilight), restricted vision has less effect on distance estimation accuracy than poor vision. In other words, in poor lighting conditions, limited visibility may not play an important role in accurate distance estimation. However, more research is needed to corroborate this finding.

The study lacked reference distance points for the pilots, the use of which could have potentially improved the precision of distance estimations. As shown in Fig. 4(a) and Fig. 4(b), an inverse relationship was observed between accuracy and the estimated distance, which indicates that the accuracy declined as the estimated distance increased. Both size and distance estimations serve the same purpose, and when estimating distance under poor lighting conditions, the target appears to move closer or farther away, which results in variations in the perceived size. Therefore, it is reasonable to assume that similar outcomes, such as accuracy in estimating the size under low lighting and restricted field of vision, can be expected.

Figure 4(b) clearly illustrates that the pilots had a tendency to overestimate the distance, particularly with regard to the NVG distance estimates. This finding is consistent with a previous study by Foyle and Kaiser[19] and adds valuable perceptions to the existing literature on the subject.

Misinterpreting size and distance not only reduces the work efficiency but also leads to potentially fatal situations. In 1997, the collision between the Russian Progress supply ship and the Russian Mir space station happened because of inaccurate distance and size estimations by humans [23]. Therefore, understanding the impact of restricted or absent visual cues on human spatial perception is important, especially in extreme circumstances, to prevent disastrous outcomes [24]. Considering these findings, it is advisable to postpone planned flights during the twilight period to ensure safety.

5. LIMITATIONS

This study has several limitations. First, the available twilight period was limited to 32 min., which restricted the number of pilots and the visibility conditions examined. Second, variations in NVG usage time owing to time constraints might have affected the quality of NVG vision. Third, sample diversity was limited because of high costs and the scarcity of pilot subjects. Finally, the absence of a simulator environment meant changing environmental factors as darkness fell, which limited the extension of our findings to complex operational scenarios.

6. CONCLUSION

The results indicate that compared with DH (M = 5.27, SD = .59), TN (M = 5.33, SD = .69,) and TH (M = 5.20, SD = .61), NVG (M = 4.79, SD = .57,) appears to have a lower error rate. In conclusion, as visibility conditions deteriorate and become limited, the accuracy of distance estimation decreases.

This study is the first in the literature to consider different flight experience groups and twilight conditions. Obstacle detection and distance estimation are crucial for pilots who control aircrafts. Similarly, detecting obstructions under the helicopter's body is important, especially during landing, an area that may be overlooked by the pilot during NVG flights.

Despite being two separate activities, depth perception and distance estimation are frequently linked as they are performed simultaneously and with the same tools. In this case, positioning and guidance assistance by the helicopter crewmember will aid in the aircraft safely approaching an appropriate landing point. A similar study should be conducted using height estimation by other crewmembers. By conducting the same research with other types of NVGs, particularly white phosphorus NVG, the differences between these NVG types used in recent years can be determined. Finally, owing to the low circadian rhythm [31] in the morning twilight, a similar study on the role of the pilot in decision-making or distance estimation may be conducted in the future.

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Dr Murat Akın obtained his PhD from Gazi University Computer Engineering Department. He has been working as a Lecturer at Gazi University. His areas of interest include: Data science, computer programming, big data, artificial intelligence, cyber security and intelligent transportation systems.
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