A Review on Education and Training Needs for Military Space Operations

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ABSTRACT

Space is a dynamic and rapidly evolving domain, driven by the increased engagement across the commercial, scientific, governmental and military sectors. Particularly, operations in low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary Earth orbit (GEO) play a vital role in sustaining infrastructures for daily on-Earth activities, e.g., global positioning system (GPS) and 5G. In 2019, a significant milestone was reached with the adoption of NATO's Space Policy, officially recognizing space as a distinct operational domain alongside land, air, sea and cyberspace. This integration positioned space capabilities as an integral part to military strategies, supplying vital information for secure operations.

Due to the growth of space activities and dependency of their infrastructure, the number of military personnel involved naturally increases, leading to a corresponding rise in educational sessions and training programs. Consequently, this study investigated the current type and quality of educational sessions and training programs within military space operations through an online survey among 42 respondents. Moreover, the survey assessed other factors related to the current and desired frequency, the current and desired knowledge and capabilities in specific topics such as space situational awareness (SSA), the favored type of teaching and training methods, as well as the integration of emerging technologies such as virtual reality (VR) and augmented reality (AR). Findings indicated a need for improvement in both the quality and frequency of educational and training sessions. Additionally, significant disparities were observed between current and desired knowledge and capabilities across the various space operations topics. Finally, the respondents provided important insights regarding the best educational and training methods, along with the combination of technological methods and their possible improvements and discouragements to use them.

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1. INTRODUCTION

Since the beginning of the space age with the launch of Sputnik 1 by the Soviet Union in 1957, space emerged as a critical domain for military operations. The strategic significance of space became increasingly important during the Cold War, as the United States and the Soviet Union raced to develop and deploy military satellites, reconnaissance systems and ballistic missile defense capabilities. Thus, the military's involvement in space activities and operations began with the recognition of space as a new frontier for subjects such as strategic advantage, surveillance and communications (Coletta & Pilch, 2009; Hays, 1994; Lambeth, 2004; Mowthorpe, 2001; B. Wang et al., 2022; Q. Wang et al., 2021). Currently, operations in low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary Earth orbit (GEO) play a vital role in sustaining infrastructures for daily on-Earth activities, e.g., global positioning system (GPS) and 5G (fifth generation mobile network) (Pardini & Anselmo, 2021; Vatalaro et al., 1995). Satellite-based technologies developed for communication, navigation and reconnaissance purposes have not only transformed our daily lives, but also contributed significantly to the strategic and defensive capabilities of nations (Grest, 2022). This dual-use aspect underscores the interconnectedness of civilian and military space efforts, showing the broader impact of space activities on both everyday existence and national security. Accordingly, in 2019 the U.S. Space Force was established (USSF) (Godshall & Thomas, 2021) and the North Atlantic Treaty Organization (NATO)'s Heads of State and Government recognized space as a distinct operational domain on par with air, land, maritime and cyberspace. Moreover, there is a growing need for improved coordination of orbit assignments and a shift from passive space situational awareness (SSA) to active space domain awareness (SDA) (*NATO's Approach to Space*, 2024). Since the exponential growth in number of debris (e.g. rocket and satellites) pieces exceeding 10 cm, surpassing 16000 (Kanazaki et al., 2017; B. Wang et al., 2022). This surge in space debris poses a significant threat, escalating the risk of collisions to unprecedented levels and jeopardizing space security. Recognizing the gravity of this challenge, nations, including the Netherlands, have prioritized SSA and space traffic management (STM) as top priorities in their long-term space agenda (Klimaat, 2024).

Accordingly, the military, as one part of the national security organization, became a very active actor in space in many nations, besides the United States. Consequently, as military space activities continue to expand and evolve, the number of personnel involved increases, leading to a corresponding rise in educational sessions and training programs (Godshall & Thomas, 2021). This growth is essential for maintaining high-quality standards and ensuring that personnel (e.g., space operators) is adequately prepared to fulfil their roles effectively (Fahnestock, 2020; Jenkins et al., 2018; Stouch et al., 2021, 2023). Educational sessions are considered activities that aimed at developing knowledge. Conversely, training programs are considered as a planned process intended to modify attitudes or skills through experiential learning, with the objective of achieving effective performance in any activity or range of activities (Manpower Services Commission, 1981; Masadeh, 2012). Therefore, this paper aimed to investigate via a survey the current effectiveness and frequency level of the educational sessions and training programs within the military space operations. Furthermore, among the array of factors potentially impacting the perceived effectiveness of educational and training programs, years of experience may lead to significant influence. Hence, the differences across various experience groups were analyzed to identify any notable trends and disparities. Additionally, there has been a significant increase in the use of technologies and applications during these educational sessions and training programs in recent years (Fahnestock, 2020; Kasım et al., 2021; Stouch et al., 2021, 2023). For example, Fahnestock (2020) studied that virtual reality (VR) as an effective tool for training complex concepts within the USSF. Whereas, Stouch et al. (2023) and Jenkins et al., (2018) examined the use of augmented reality (AR) for training topics such as SSA and STM. Meaning that VR and AR tools, in addition to other simulation tools, are becoming essential methods for educating and preparing military personnel for space operations (Kasım et al., 2021). Thus, the survey examined the state of the current integration of technologies within the operations and explored needs for future integrations and enhancements. Lastly, the survey delved into potential future operational developments and identified increasing needs within specific topics.

2. METHOD

To examine a small sample of military personnel and civilians, data were obtained about the educational and training experiences by means of a survey. Although the survey primarily focused on questions regarding actual military space operations, as it is a relatively new and small scale domain especially in Europe, there was a limited representation of specific military space operators. Therefore, the survey also involved individuals engaged in space operations as those conducted by military personnel, such as SSA and STM operations. Hence, several questions pertaining to military space (e.g., training programs and exercises) were either made optional or provided with the response option 'I do not know'.

Given the limited number of respondents, this study aimed for a small effect size as well as significant effects in the analysis. An a priori power analysis (with $\alpha = 0.05$, $1\text{-}\beta = 0.80$, $p = 0.5$) indicated that a minimum of 21[1] participants were necessary. However, a total of 42 respondents (41 male) completed the survey, with a mean age of 42.3 years (SD = 10.8) and a mean working experience of 9.6 years[2] (SD = 8.4), which 13 were space operators with a mean age of 45.1 (SD = 10.8) and a mean working experience of 7.2 years[2] (SD = 5.7). A total overview of the characteristics is presented in Table 1. The survey was made available online to respondents via a website called LimeSurvey[3]. Potential respondents received an email with a link that gave them access to the survey. All data were collected anonymously.

Table 1 - Overview of characteristics of the total sample (Mean and SD between parentheses).

	Total n = 42
Gender	
Men	41
Women	1
Age (years)	42.3(10.8)
1) Country	
Brazil	1
India	1
Italy	3
France	1
South Korea	1
The Netherlands	27
United Kingdom	1
United States	5
Germany	2
2) Type of the organization	
Educational	2
Governmental	1
Mid Cap	3
Military	10
Research and Technology O.	17
Small and Medium E.	8
Start up / Scale up	1
3) Domain of the organization	
Aerospace	6
Cyberspace	1
Military	12
Multidomain	2
Space	21
4) Role / Position	
Military	6
Operator	1
Policy maker	2
Program manager	4
R & D engineer	11
Other	18
5) Years (experience) in the space domain	
Less than 2 y.	11
Between 2 and 5 y.	6
Between 5 and 10 y.	10
Between 10 and 20 y.	8
Over 20 y.	7
6) Year (experience) as space operator	
I have never worked as military space operator	29
Less than 2 y.	4
Between 2 and 5 y.	2
Between 5 and 10 y.	3
Between 10 and 20 y.	4

2.1. Survey Design

In consultation with experienced military space operators, a survey was developed that measured the current status of the military space educational sessions and training programs, the potential needs for improvement and the current use of technologies. The survey contained six sections: “Descriptive information”, “Education”, “Emerging technologies in the educational context”, “Training”, “Emerging technologies in the training context” and “Future military space operations”. The section “Descriptive information” contained seven questions concerning gender, age, the nation’s organization, the type (e.g., governmental, military etc.) and the domain (e.g., military, space etc.) in which the participant works, the working position, years’ experience in the space domain and as military space operator. Prior to each section, a definition was provided, except for the sections “Descriptive information” and “Future military space operations” considered as standard parts of surveys. Prior to the education (Appx. 1, section I) and training (Appx. 1, section II), a definition was provided adjusted to the context from previous literature (Manpower Services Commission, 1981; Masadeh, 2012). Similarly, prior to the two emerging technologies and applications section (Appx. 1, section III and V), a definition was provided adjusted to the context from previous literature (Tsien et al., 2003). 11

[1] Due to optional questions, respondents did not answer all the questions, resulting in few questions where statistical tests were conducted, a minimum of 21 responses. This was mentioned this in the discussion section.

[2] To facilitate quantitative analysis of the qualitative responses regarding years of experience, numeric values were assigned to each experience range. "Less than 2 years" was represented as 1 year, "Between 2 and 5 years" as 3.5 years, "Between 5 and 10 years" as 7.5 years, "Between 10 and 20 years" as 15 years, and "Over 20 years" as 25 years. This approach was chosen to approximate the central tendency of each range, providing a more precise estimation of the average experience level within each category.

[3] https://www.limesurvey.org/

questions were open questions, 15 were closed ones and two tables (by questions 8 and 17, appx. 1) were semi-closed questions with the possibility to add information on the answer provided. Closed questions (7, 12, 16 and 21, appx. 1) provided the same possibilities in the answers, that were “very poor”, “below average”, “average”, “above average”, “excellent” and “I do not know”. Whereas, the questions number 9 and 18 were related to the frequency of educational sessions and training programs and they had the possible following answers: “daily”, “weekly”, “monthly”, “quarterly”, “semi-annually” and “annually”.

2.2. Data analysis and statistics

To analyze our data, several statistical tests were used. Firstly, the Likert scale responses, ranging from 1 (indicating 'very poor') to 5 (representing 'excellent'), were utilized to examine the effectiveness of education and training and the respondents' space experience (years) groups. Secondly, to gauge whether respondents’ aspirations for knowledge exceeded their current levels, a paired samples t-test was conducted. The hypothesis posited that respondents aimed to enhance their knowledge, thus an one-tailed test was specified, indicating that the desired knowledge would surpass the actual knowledge (Measure 1 < Measure 2). Thirdly, due to the low sample sizes in the actual and desired frequencies across various education and training topics, statistical tests were not conducted and instead focused on examining the answers in percentages. Responses were converted into percentages, facilitating a comparative analysis of respondents preferences. For instance, if five respondents selected 'daily' out of 20 responses, it represented 25%. Fourthly, within the domain of technological trends, encompassing both education and training, the effectiveness of technological applications among respondents’ space experience (years) groups were analyzed also using the Likert scale responses, ranging from 1 ('very poor') to 5 ('excellent'). Since some respondents with 2 to 5 years of experience did not provide responses to several questions, the groups were subdivided into three categories: less than 5 years, between 5 to 20 years and more than 20 years of experience. To assess whether there were significant differences between these groups, a Kruskal-Wallis H test was used. Following the test, which indicated a significant difference between the groups, a post hoc pairwise comparisons using the Mann-Whitney U test with Bonferroni correction was conducted. The Bonferroni adjustment was applied to control for Type I errors across the multiple comparisons, ensuring that the significance level was maintained at 0.05 for the family of comparisons. Furthermore, the discrepancy between current and desired knowledge and capabilities within the 14 topics was calculated separately by subtracting the current values from the desired ones. This approach was taken to provide additional insight into specific values if interesting discrepancies were identified. Finally, concerning the answers towards the open question, the suggestions were categorized aligned with the same topics. A second person who was not involved in this study performed a reliability check by repeating the same procedure for statements of at least 10% of the respondents.These analyses were conducted utilizing the statistical software JASP 0.18.3.0.

3. RESULTS

A total overview of respondents’ gender, mean age and SD, work related information and years of working experience are presented in Table 1. From the 42 respondents, 12 filled the entire survey (i.e., up to section future military space operations, *see Appendix I – section VI*). Figure 1 shows the averages of the individual educational and training scores among the experiences groups. The average score for education effectiveness was 3.3 (i.e., average) (SD = 1.3) and for training effectiveness was 3.9 (i.e., above average) (SD = 1.1). Possible differences among work experience groups were examined. Within the educational effectiveness scores, the means and standard deviations were as follows: for less than five years of experience (n = 7), M = 2.7, SD = 1.3; between 5 and 20 years (n = 10), M = 3.4, SD = 1.2; and over 20 years (n = 3), M = 4.7, SD = 0.5. Kruskal-Wallis H test showed a significant difference between the groups, X^2 (2) = 6.526, p = 0.03. Post-hoc comparisons using the Bonferroni correction a significant different between the group with less than five years of experience with the group with more than 20 years. Whereas, within the training scores, the findings were as follows: for less than five years of experience (n = 3), M = 2.7, SD = 0.5; between 5 and 20 years (n = 6), M = 3.4, SD = 1.2; and over 20 years (n = 3), M = 5. Kruskal-Wallis H test did not show any significant difference between the groups, X^2 (2) = 4.958, p = 0.08.

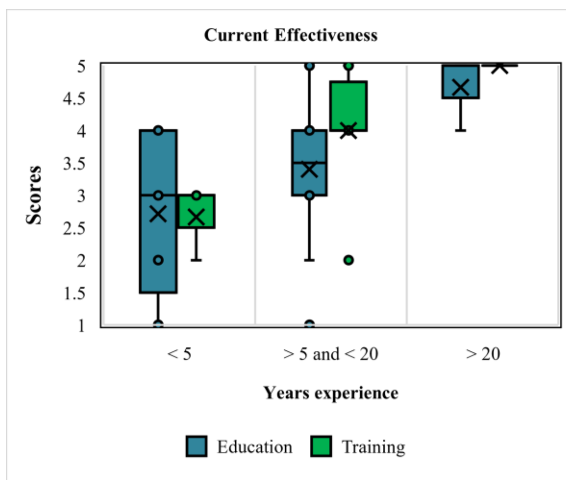


Figure 1 - Education and training effectiveness scores among years’ experience

3.1. Education

The survey included an open question about respondents' experiences in educational sessions. Results showed that 56% did not follow any specific program, some being self-taught. 9% attended the NATO School Oberammergau Space Course and NATO Space Support Coordinator Course, along with various university courses. 15% only followed university courses and 12% learned on the job. The remaining took the Coalition Space Course by the USSF, the Space Operations Qualification Course by the USSF and completed the Space Weather course by the Royal Netherlands Air Force.

3.1.1. Current and Desired Knowledge

A paired samples t-test was conducted to compare the current and desired knowledge averages scores among the respondents across several topics. The highest discrepancy were in STM (1.1) and secondly in rendezvous operations (1); whereas the lowest ones were satellite communication (SATCOM), space weather and launch operations (0.7). Moreover, the results showed that all 14 topics exhibited significant differences. In the domain of SSA, the paired samples t-test showed a significant difference between the two measures $t(40) = -6.02$, $p = .001$. Similarly, significant differences were found between the current and desired knowledge averages in STM $t(40) = -6.25$, $p = .001$, space weather $t(40) = -4.46$, $p = .001$, Global Navigation Satellite System (GNSS) use for Positioning, Navigation & Timing (PNT) $t(38) = -4.81$, $p = .001$, early warning (threats) $t(37) = -5.7$, $p = .001$, Intelligence, Surveillance & Reconnaissance (ISR) $t(37) = -5.7$, $p = .001$, SATCOM $t(38) = -4.9$, $p = .001$), secure communication $t(37) = -5.5$, $p = .001$, cyber security $t(37) = -5.1$, $p = .001$, counter (counter) space $t(36) = -5.9$, $p = .001$, satellite operations $t(37) = -5.8$, $p = .001$, payload operations $t(37) = -5.2$, $p = .001$, rendezvous operations $t(37) = -6.2$, $p = .001$ and launch operations $t(37) = -4.7$, $p = .001$) (See Fig. 2). In the option 'other', the following topics were suggested: allied space, cislunar and lunar operations, dual use (military and civil), meteorology and oceanography (METOC), navigation warfare, object characterization, policy, sensors (EO, IR, SAR and others), supply chain, space power theory, asteroid mining, electromagnetic warfare, interoperability, joint military operations and wargames. Moreover, the respondents suggested various means to achieve the desired knowledge level, including the use of technological tools like VR and AR, educational videos, reading materials, self-education, hands-on experience, simulation-based training, university courses, conferences, expert guest lectures and wargames.

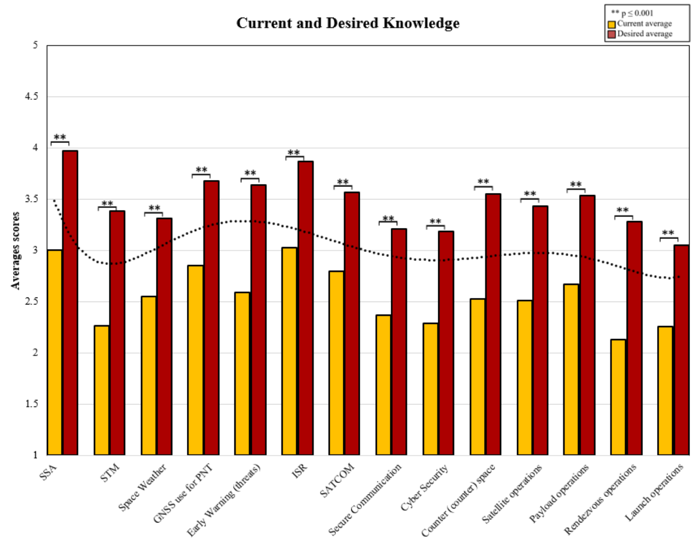


Figure 2 - Averages of current and desired knowledge

3.1.2. Current and Desired Frequency

Figure 3 shows the percentage of the current and desired frequencies for each topic for educational sessions. The left column for each topic represents the current frequency, while the right column represents the desired frequency. Overall, the percentage of 'none' sessions decreased for each topic from the current to the desired frequencies. Rendezvous operations had the highest percentage (76%) and the respondents also expressed the highest desire for an annual frequency sessions, from 16% to 52%. A similar pattern emerged for STM, payload and launch operations. Whereas, the

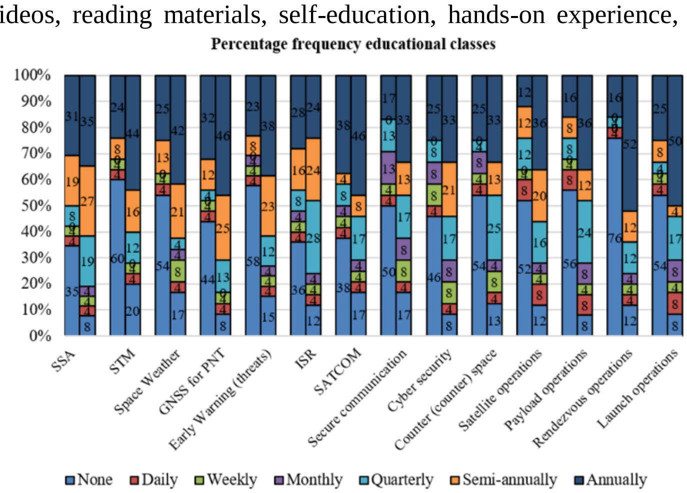


Figure 3 - Percentage frequency educational classes

percentage of annual sessions increased for each topic from the current to the desired frequency, except in the ISR operations.

The options of daily, weekly and monthly frequencies were consistently low for both current and desired frequencies. Notably, satellite, payload and launch operations showed the highest preference for daily frequencies in the desired category. Regarding weekly frequencies, the highest levels of interest were found in space weather, secure communication, cyber security and counter (counter) space. Meanwhile, SSA, GNSS for PNT and ISR recorded the highest percentages of desired frequency sessions for the semi-annual option. The respondents who selected the "others" option provided additional topics, along with their corresponding desired frequencies. These topics included dual use (military and civil), which was desired on a daily basis; METOC, with a desired annual frequency; policy, also with a desired annual frequency and space power theory, with a desired quarterly frequency.

3.2. Training

The survey included an open-ended question about the training programs followed. 50% did not participate in any specific program. The remaining mentioned university courses and on-the-job learning such as practical training in cybersecurity, as well as in various aspects of satellite operations such as payload management, link planning, network coordination, communications and electronic warfare. Moreover, other respondents reported participating in training programs and military exercises that simulated real-world scenarios, including the Fundamentals of Space Operations Course at the Netherlands Ministry of Defense, the advanced SSA course at European Space Agency (ESA), NATO Exercise Steadfast Jupiter, USSF exercise Global Sentinel and the French Space Command exercise AsterX. Lastly, some mentioned taking graduate-level electives at the US Army Command and General Staff College.

3.2.1. Current and Desired Abilities

A paired samples t-test was conducted to compare the current and desired abilities average scores among the respondents across several topics. The highest discrepancy was in SATCOM (1.2) and the lowest one was early warning (threats) (0.2). In the domain of SSA, the paired samples t-test revealed a significant difference between the two measures, $t(7) = -1.53$, $p = 0.08$. Significant differences were also found between the current and desired abilities in the domains of space weather $t(7) = -1.528$, $p = 0.08$, GNSS use for PNT $t(6) = -2.121$, $p = 0.04$, ISR $t(6) = -1.987$, $p = 0.04$, SATCOM $t(5) = -2.076$, $p = 0.05$, cyber security $t(6) = -1.987$, $p = 0.05$ and rendezvous operations $t(6) = -1.987$, $p = 0.05$. In the domain of STM, no significant difference was found $t(7) = -1.871$, $p = 0.05$, as well as in early warning (threats) $t(6) = -1.000$, $p = 0.18$, secure communication $t(6) = -1.922$, $p = 0.05$, counter (counter) space $t(6) = -1.549$, $p = 0.09$, satellite operations $t(6) = -1.922$, $p = 0.05$, payload operations $t(6) = -1.444$, $p = 0.10$ and launch operations $t(6) = -1.922$, $p = 0.05$ (see Fig. 4). An extra comment in the option 'other' was provided as "Joint Military Operations".

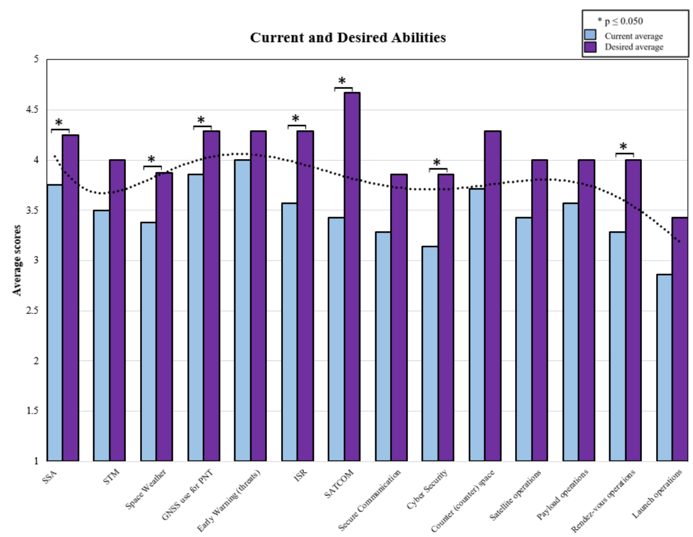
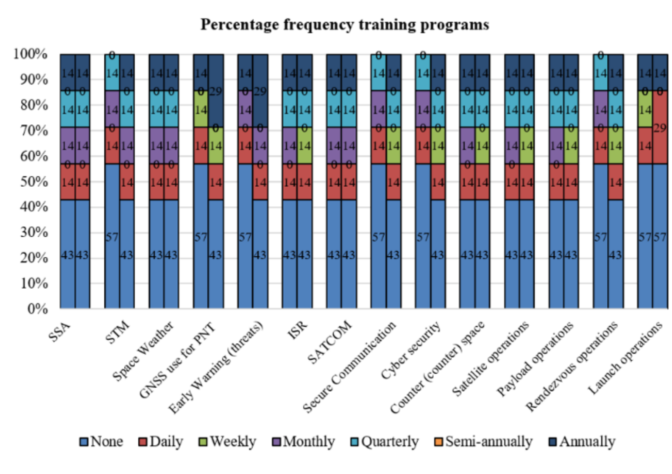


Figure 4 - Averages of current and desired abilities



3.2.2. Currently and Desired Frequency

Figure 5 shows the percentage of current and desired frequencies for each topic within the training domain. The left column for each topic represents the current frequency, while the right column represents the desired frequency. For each topic, the percentage of 'none' training sessions was the highest and for the topic STM, GNSS use for PNT, secure communication and rendezvous operations decreased in the desired frequency. In launch operations, the daily option was the highest in the desired frequency, among also the other topics. Interestingly, the monthly frequency option was no longer preferred for ISR, counter (counter) space, satellite operations and payload operations in the desired frequency, with respondents instead opting for the weekly frequency option. No further comments were provided by the respondents in other type of trainings.

3.3. Technological Applications

Figure 6 shows the averages and the individual educational and training scores regarding technological applications among the experiences groups. The average score for application of technologies in educational sessions was 3.1 (SD = 0.9) and for the training effectiveness was 3.91 (SD = 1.1).Within the educational effectiveness scores, the means and standard deviations among the work experience groups were as follows: for less than five years of experience (n = 5), M = 3.2, SD = 1.3; between 5 and 20 years (n = 10), M = 3.1, SD = 0.8; and over 20 years (n = 4), M = 3, SD = 0.7. Kruskal-Wallis H test did not show any significant difference between the groups, X^2 (2) = 0.211, p = 0.90. Whereas, within the training effectiveness scores, the findings were as follows: for less than five years of experience (n = 4), M = 3.7, SD = 0.8; between 5 and 20 years (n = 7), M = 4.2, SD = 1; and over 20 years (n = 1), M = 2. Since the 'over 20 years' group contained only one respondent, it was not possible to perform the Kruskal-Wallis H test.

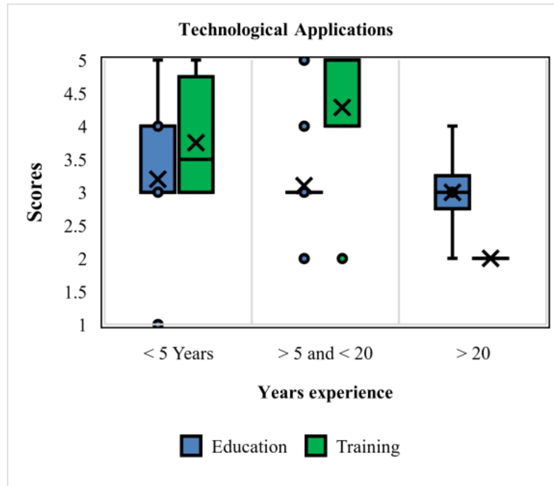


Figure 6 – Technological applications in education and training effects settings among years' experience

3.3.1. Technological Applications in Education

Practice hands-on training and classroom-based lectures were scored as the most effective educational methods (see Table 2). Furthermore, respondents could explain their choices. Most emphasized the importance of hands-on training for real system experience. Others mentioned that classroom lectures are seen as fundamental for theoretical knowledge, while simulations were valued for replicating real scenarios, aiding practical training and understanding complex operations. Opinions varied among AR/VR and games. Some see potential for illustrating concepts like orbits, while others doubt their utility for space operations conducted in control rooms. Games are seen as helpful for knowledge retention, but opinions differ on their effectiveness in educational sessions. Many believe that interactive elements (e.g., visual representations) aid in understanding, retention and they also advocate for a mix of lectures, hands-on sessions, simulations and games.

Table 2 - Ranking type of educational methods

Ranking type of educational methods (from 1 to 5)	Mean rank (SD)	Median	Mode
- Classroom-based lectures	2.3 (1.2)	2	1
- Games (tabletop, wargames)	3.1 (1)	3	3
- Practice hands-on training	1.9 (1)	2	1
- Simulation exercises in AR/VR	3.2 (1.2)	3	3
-Other	4.4 (1.1)	5	5

3.3.2. Technological Applications in Training

Classroom-based lectures and practice hands-on training were scored as the most effective training methods (see Table 3). Moreover, respondents provided reasons for their choices. One respondent mentioned that gaming helps to train the intel operators and developers for intel-algorithm development. One emphasized the need for theoretical and practical military training before involving other organizations. Another mentioned the Socratic Method for critical thinking skills. Lastly, it was mentioned that training should ideally reflect current systems and procedures, with simulations and games used for "potential situations" and hands-on training prioritized for practical scenarios.

Table 3 - Ranking type of training programs

Ranking type of training methods (from 1 to 5)	Mean rank (SD)	Median	Mode
- Classroom-based lectures	2.1 (1.4)	1	1
- Games (tabletop, wargames)	2.9 (1.2)	2	2
- Practice hands-on training	2.3 (1.2)	2	1
- Simulation exercises in AR/VR	2.8 (1.1)	3	3
- Other	4.4 (0.8)	5	5

3.3.3. Tech Combos for Education & Training

Many respondents found a combination of educational methods beneficial, including methods such as classroom lectures, practical exercises, VR simulations, table-top games and hands-on training. After classroom lectures, practical hands-on exercises were the most mentioned, including simulations, table-top games and direct experiments. Simulated operational environments, VR simulations and table-top games were noted for their effectiveness. Combining these methods with military exercises were also suggested for the training programs. Moreover, pre-readings, online videos, computer-based instruction and multimedia elements like pictures and movies were suggested to enhance visualization and therefore understanding, laying the foundation for interactive methods. Lastly, interactive discussions with experts, particularly for subjects like cybersecurity, were favored by some respondents.

3.3.4. Tech Improvements for Education & Training

Responses regarding improvements in educational methods varied. Suggestions included better visualizations for teaching complex topics like cybersecurity and secure communication, such as 2D/3D animations. Many respondents emphasized the enhancing of AR/VR for teaching and visualizing complex concepts like orbits (e.g., orbital mechanics) and celestial mechanics and other specific topics like SSA. Passthrough VR glasses were suggested to keep trainees connected. PowerPoint and e-learning were noted for theoretical knowledge, but interactive methods like VR and simulations were seen as complementary for practical experiences. Robotics and interactive simulations were mentioned for space operations training, providing hands-on demonstrations and gaming approaches. Simulation of control room environments was favored for realistic practice, covering both normal and contingency procedures without expensive physical models. Similar inputs were provided for training methods, including artificial intelligence (AI), scenario analysis with 3D tools and gaming. Specific suggestions included improving situational awareness for decision-makers and training datasets for spacecraft maneuver planning.

3.3.5. Tech Discouragements for Education & Training

Responses on discouraging specific technologies emphasized concerns and preferences. Several respondents cautioned with using VR and AR due to discomfort and sickness, especially with low-fidelity devices. They worry about these technologies' inability to support mathematical understanding in astrodynamics, essential for space operations interpretation. AI, particularly chatbots, raised skepticism for potentially promoting surface-level learning over critical thinking. One respondent doubted the use of text prompt AI in military space activities, while another suggested scenario analysis with 3D tools, albeit noting their high cost. Lastly, written exams were criticized for emphasizing recall rather than deep understanding, while non-interactive presentations were seen as ineffective for engaging learners.

3.4. Future Military Space Operations

For future operations, a significant 87% of respondents emphasized the necessity of specialized personnel in SDA, crucial for comprehending and monitoring the space environment and informing decision-making. SDA plays a vital role in mitigating threats from malicious actors, guiding decision-making and underlining its foundational importance in all space operations. Collaborations among NATO nations and entities, including ESA, National Aeronautics and Space Administration (NASA) and USSF, are seen essential to further bolster space-based services and threat surveillance. Additionally, 70% of respondents highlighted the importance of in-space operations, as space evolves into a warfighting domain and the necessity of safeguarding owned assets cannot be overstated. The implication of security was emphasized by 65% of respondents, with satellites being prime targets for hacking due to the sensitive data they handle. Furthermore, 57% underscored the importance of space-based services, which are crucial for military operations. Space’s role in cyber infrastructure and across terrestrial domains emphasized the need for knowledgeable personnel and therefore for more educational sessions and training. A notable 39% of respondents mentioned the importance of 'access to space', most likely due to the lack of launching capabilities in Europe. Other topics mentioned included cybersecurity, electromagnetic spectrum operations, space power theory and space weather.

The survey also explored the expected future developments and threats. Respondents expressed concerns about personnel availability for military operations and the trend of integrating commercial services into military space endeavors. They stressed the need for automation to meet operational demands and flagged challenges such as competition for lunar resources and space piracy. Cybersecurity emerged as a significant threat, alongside risks of collisions with space debris. Key areas of focus included SDA, denial of services and vulnerabilities in large LEO constellations. Respondents also identified developments in digital twinning and autonomous decision-making, while expressing concerns about spying, anti-satellite (ASAT) weapons and electronic warfare. Initiatives for European strategic independence and immediate threats like jamming and cyberattacks were highlighted. Finally, the survey solicited input on prioritizing potential space military training to counteract emerging threats. The training priorities spanned a wide range of threats, necessitating specialized expertise. Enhancing the identification capabilities of SDA sensors was identified as a key area of focus, along with bolstering cybersecurity to counter the growing threat of cyberattacks. Addressing geopolitical challenges and their implications for space operations was also deemed essential. Furthermore, respondents emphasized the need for specialized training to counter ASAT weapons, electronic warfare and other advanced threats. Collaboration with European assets was considered vital, alongside measures to mitigate insider threats and protect against unauthorized satellite maneuvers.

4. DISCUSSION

As military space activities continue to expand and evolve, the demand for well-educated and trained personnel increases proportionally. Educational sessions and training programs are crucial in preparing personnel. Educational sessions focus on developing knowledge, while training programs aim to enhance capabilities of the personnel. This study aimed to investigate the current effectiveness of educational sessions and training programs for military space operations. This was accomplished through a survey that collected data on the current status, existing and desired knowledge and expertise, the current and desired frequency of sessions and preferred teaching methods. Finally, the survey explored future specializations for military space personnel, anticipated developments and threats in the coming years and the threats to prioritize.

The respondents shared a diverse range of experiences regarding both the educational sessions and training methods. Most respondents in the educational sessions and training programs did not follow a specific program; instead, they engaged in self-directed learning, attended university courses or received training from entities such as NATO and the USSF. In the training domain, respondents reported participating in programs and military exercises simulating real-world scenarios, conducted by the Dutch defense forces, the USSF and NATO (e.g., the AsterX exercise). The overall score for current educational effectiveness was average; whereas, for the current training effectiveness was above average. A few respondents mentioned that the need for and growth of space activities within NATO are increasing, and current courses are either insufficient or need to improve in quality to keep up with this growth. Looking at the years of space experience across both domains, a trend of increasing scores with greater experience was found. Individuals with less than five years of experiences rated the level of education between below average and average; whereas, individuals with over 20 years of experience rated the level between above average and excellent, showing a significant difference compared to the group with less than 5 years of experience. Except for the group with the least years of experience, the training effectiveness score was slightly higher in the other two groups. Yet, it is important to note that only 12 respondents completed the training section. Thus, in contrast to the educational component, which encompassed a broader audience involved in space operations, the training responses may be provided solely by specialized individuals who had undergone specific training programs and exercises (e.g., NATO exercises).

Interestingly, for both questions regarding the effectiveness of the use of technological applications within educational sessions and training programs, an inverse trend was observed. The fewer the years of experience within the groups, the higher their scores tended to be. This phenomenon may be attributed to factors such as the younger generation's quicker adaptation to new technologies and their familiarity with these technologies, having grown up using them. For example, recently the USSF emphasized important strategies to leverage commercial tech innovations (Erwin, 2024b) largely invested to develop a virtual and mixed-reality training environment (Erwin, 2024a) and is also collaborating with company to deploy AI and machine learning models (Erwin, 2024c). Accordingly, the Chief of U.S. Space Operations recently discussed technological innovations, noting that the current space domain is vastly different from the one he grew up with (Erwin, 2023). Consequently, as new cadets join the American forces, they will naturally be introduced to space operations through more interactive and technologically advanced tools. Simultaneously, individuals with more experience may exhibit a greater degree of discernment and discomfort regarding the use of these new technologies. Indeed, several respondents highlighted the importance of enhancing these technologies, particularly AR/VR tools, to mitigate discomfort and motion sickness.

Numerous respondents emphasized the benefits of combining classroom lectures with practical exercises, VR/AR simulations, table-top games and hands-on training to create a complete learning experience. Therefore, they were not in favor of relying solely on one method. When asked to rank the most effective educational and training methods, respondents rated practical hands-on exercises and classroom-based lectures as the highest. By recognizing the benefits of combining different educational and training methods and addressing concerns about specific technologies, educators and trainers could develop more effective and engaging programs that cater to the needs of participants, especially during joint exercises such as the military space exercises AsterX (NATO, 2024).

Based on the findings, STM and rendezvous operations showed the largest gap between current educational practices and desired areas for enhancement, whereas SATCOM was identified as the primary area for improvement in training. This highlighted a need for improvement in these specific domains. Previous studies have effectively utilized AR/VR tools and simulators to enhance skills like SSA and STM (Jenkins et al., 2018; Kasım et al., 2021; Stouch et al., 2023). Therefore, using combined educational and training methods, along technological tools such as VR/AR and simulations, may be an efficient approach to reduce the gaps. Such methods could be applicable to any military space activity, as the survey revealed a significant desire among respondents to enhance their knowledge and capabilities across the 14 topics. Furthermore, certain technological methods, as long as they maintain a high level of fidelity, may increase the frequency of both educational sessions and training programs, as respondents expressed a desire for more frequent sessions (Stoffregen et al., 2003). In particularly, the rendezvous operations, STM, payload and launch operations had the similar pattern of having a high absence in educational sessions and the respondents also expressed the highest desire for annual frequency sessions. There was also notable lack of training sessions (e.g., exercises) for each topic. No specific topic stood out with significant changes in the desired frequencies. The trend is towards varying training frequencies across different topics. For instance, in the topics of counter (counter) space, satellite operations and payload operations, current session frequencies were monthly, but there is a desire for more frequent weekly sessions. However, prior to introduce a tool like VR within training sessions, within the organizations, conducting a training media analysis alongside a training needs analysis would be crucial to determine the appropriate steps to take (Training Media Analysis; Training Needs Analysis - NLR, 2024).

Finally, most of the respondents highlighted the importance of specialized personnel in SDA for future military space operations, for monitoring the space environment to mitigate potential threats. Hence, security concerns, along with cybersecurity, were mentioned by many respondents, who also highlighted the vulnerability of satellites to hacking and the sensitive data they handle. To address these challenges, it is important to educate and train personnel in these areas to ensure they are well-prepared to handle the evolving threats and complexities of space operations. This could be done also via collaborations between NATO nations and entities, including ESA, NATO and USSF which they were mentioned to be essential to further overall bolster the space security. Furthermore, the results also highlighted concerns regarding personnel availability. European space forces could consider adopting practices similar to those of the U.S. Air Force Academy, which offers internship opportunities for undergraduate students with the USSF as an example (Scrapchansky et al., 2024). Lastly, respondents expressed concerns about spying, ASAT weapons and electronic warfare. Initiatives for European strategic independence and immediate threats like jamming and cyberattacks were highlighted, emphasizing the multifaceted nature of space security challenges. To effectively address these multifaceted security challenges, the education and training of personnel should be prioritized in these fields.

4.1 Strengths and Limitations

This study is the first that examined the current efficiency of educational sessions and training programs within military space operations, along with factors such as the frequency and the application of technologies. It provided several areas of improvements; however, several limitations must be considered. Firstly, this research focused on military space operations. Given the small population of military space personnel, especially in Europe, a broader audience of individuals in our study was included. Consequently, while the information gained are valuable, they may not fully represent the unique challenges and needs of military space operations personnel. Secondly, respondents came from various types of organizations and countries, leading to diverse experiences with educational sessions and training programs. For instance, the USSF operates over 200 satellites, while the Netherlands Ministry of Defense currently operates three (Heinrich et al., 2021). As a result, the legacy and knowledge related to educational sessions and training programs may differ significantly, potentially affecting the quality of them. Another example is that the highest percentage of respondents were from research and technology organizations, which may have influenced the results, particularly regarding their knowledge in the application of technologies. Furthermore, some respondents were specialized in particular domains (e.g., cybersecurity), which might have influenced the overall results, including their judgments on other topics. Consequently, future studies should investigate specific military organizations and their unique challenges and advancements to provide a more detailed understanding of the differences within the domain. In the meantime, a survey with a larger sample size, possibly facilitated by organizations such as NATO, would yield more comprehensive information. For instance, including a broad group of respondents could have enabled the examination of fundamental factors related to education and training, such as generational disparities and their varied learning styles. This, in turn, would allow for the tailoring of educational and training programs to better meet the diverse needs of participants (Shepherd, 2020; Urick, 2017). Finally, although the number of respondents exceeded the initial power analysis requirements, some questions used in statistical tests did not reach the minimum sample size needed. Future studies should take this into consideration to ensure more robust results.

In conclusion, this study highlighted the need for improvement in the current educational sessions and training programs within military space operations, particularly in addressing the diverse learning styles and preferences of experienced professionals and newer generations. By recognizing the benefits of combining different educational and training methods, leveraging technological advancements and tailoring programs to meet the expectations of both groups, military space organizations could enhance the effectiveness and impact of their initiatives. Furthermore, prioritizing more frequent educational sessions and training opportunities, especially those that incorporate innovative technologies, will be crucial in supporting the professional development of military space personnel. Ultimately, this study underscored the importance of continued research and investment in educational and training programs to ensure that military space personnel are adequately equipped to address the evolving challenges and opportunities in the domain.

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DATA SHARING STATEMENT

The data that support the findings are available in Open Science Framework at https://osf.io/wqkzp/.

APPENDIX

Appendix I - The survey is available in Open Science Framework at https://osf.io/npb8d/.

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