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The usability and technology acceptance of immersive virtual reality simulation for critical infrastructure workers

Wyniki badań użyteczności rzeczywistości wirtualnej do szkoleń kadry infrastruktury krytycznej

Słowa kluczowe: immersyjna rzeczywistość wirtualna, symulacja szkoleniowa, uczenie się poprzez gry, infrastruktura krytyczna.

Streszczenie: Jednym z głównych zastosowań wirtualnej rzeczywistości (VR) w infrastrukturze krytycznej są szkolenia. Szkolenia mają kluczowe znaczenie dla zapewnienia bezpieczeństwa, ochrony i wydajności systemów infrastruktury krytycznej i ich pracowników. VR można także wykorzystać do szkolenia kadr infrastruktury krytycznej odpowiedzialnych za zapewnienie ciągłości jej działania i przywrócenie efektywności po awarii. Niewiele jest jednak badań na to, jak taka wciągająca wirtualna symulacja może wpływać na pracowników infrastruktury krytycznej zwłaszcza pod kątem użyteczności i akceptacji technologii, bo to bardzo ważne z punktu widzenia praktycznego wdrożenia. Z tego powodu badania przeprowadzono z udziałem 20 ekspertów aktywnych zawodowo w zakresie różnych obiektów infrastruktury krytycznej. Oprócz użyteczności i akceptacji technologii sprawdzono poziom choroby symulatorowej, realizm symulacji, obciążenie i stres powodowany przez narzędzie szkoleniowe, a także ogólną ocenę jakości szkolenia. Szczególnie istotny jest bardzo wysoki wynik wskaźników zamiaru użycia, postrzeganej przydatności i zaangażowania (ok. 90% wartości maksymalnej). Oznacza to, że zdecydowana większość użytkowników końcowych powinna być chętna do korzystania z opracowanych symulacji szkoleniowych VR.

Key words: immersive virtual reality, training simulation, game-based learning, critical infrastructure.

Abstract: One of the main applications of Virtual Reality (VR) in critical infrastructure is training. Training is crucial for ensuring the safety, security, and efficiency of critical infrastructure systems and their employees. VR can also be used to train critical infrastructure personnel responsible for ensuring CI business continuity and disaster recovery. However, there is little research on how such an immersive virtual simulation can affect critical infrastructure staff especially in terms of usability and acceptance of the technology, as this is very important for practical implementation. For this reason, the research was carried out with 20 experts active in various critical infrastructure facilities. In addition to the usability and technology acceptance, the level of simulator sickness, the realism of the simulation, the workload and stress caused by the training tool, as well as an overall assessment of the training quality were examined. The very high score for the indicators of intention to use, perceived usefulness, and engagement (around 90% of the maximum value) is particularly important. This indicates that the vast majority of end users should be willing to use the VR training simulations developed.

Introduction

Virtual reality (VR) is a technology that simulates a realistic and immersive environment for users. VR can be used for various purposes, such as entertainment, education, health care, and training. This article will focus on the use of VR in the domain of critical infrastructure, which refers to the systems and assets that are essential for the functioning of a society and economy, such as transportation, energy, water, and communication.

One of the main applications of VR in critical infrastructure is training. Training is crucial for ensuring the safety, security, and efficiency of critical infrastructure systems and their employees. Traditional training methods may have some limitations, such as high costs, logistical challenges, safety risks, and lack of realism. VR can overcome these limitations by providing a cost-effective, flexible, safe, and realistic way of training critical infrastructure employees.

For example, VR can be used to train employees on how to operate and maintain complex equipment, such as power plants, pipelines, or railways. VR can also be used to train employees on how to respond to emergencies or disasters that may affect critical infrastructure systems, such as fires, floods, cyberattacks, or terrorist attacks. VR can create realistic scenarios that mimic the conditions and challenges that employees may face in real situations. VR can also provide feedback and assessment to help employees improve their skills and performance.

The result of research suggests that virtual reality training simulators can be effective in increasing worker awareness, eg. in the firefighting (Grabowski 2020). It was found that VR training was more effective than traditional classroom training in identifying and assessing construction safety risks (Sacks 2013). The results of a review show many benefits of integrating virtual reality with operator training simulators in the process industry, including improved safety and increased productivity (Patle 2018).

Virtual reality training has several advantages in the field of crisis management. Virtual environments that can be used to support crisis management training, allowing personnel to rehearse for real crises using the same tools they would have available to them in a real crisis were presented in (Walker 2011). A hazard simulation system using virtual reality and discrete-event simulation technologies, which allows organizations to conduct emergency drills inside a virtual world having a close correspondence with their real physical apparition was presented in (Kwok

2019). Later it was found that users' acceptance of virtual reality technology for practicing crisis management was determined by perceived usefulness, perceived ease of use, perceived behavioral control, application-specific self-efficacy, and attitude (Kwok 2020). Most simulations for training typically focus on mono-professional teams, however, there are some approaches to developing a model for multi-professional emergency management education that involves the use of virtual reality simulations, which can provide efficient and safe training for various user groups (Prasolova-Førland 2017).

In the field of critical infrastructure virtual reality training can be a useful tool for power plant staff training. Results of a study on the training of field operators in two Finnish nuclear power plants show that VR-based solutions could facilitate and advance the training process (Koskinen 2022). A virtual reality platform for the evaluation, design, and training of physical protection systems in nuclear power plants was proposed in (Bowen 2018). A novel approach to the training of power substation operators based on interactive virtual reality, which enables operators to gain realistic operational experience without the anxieties of causing blackouts and damage in a real grid, was presented in (Nasyrov 2018). VR training can improve the training of power plant staff, providing a safe and effective way to gain realistic operational experience. However, it should be noted that some research shows different results, for example, it was found that a VR simulator for power substation operational training was marginally acceptable in terms of usability (Bernal 2022).

The methodology

Research question

Despite that VR is very often used for training, its use in industry is focused mainly on machine operators or training of various maintenance procedures. This is observed also in the case of training of people working in Critical Infrastructure facilities such as power plants. However, VR can be also used to train Critical Infrastructure staff responsible for ensuring the continuity of CI's operation and restoring its efficiency after a failure. Such training is addressed primarily to the management staff so that persons responsible for the operation of the critical infrastructure facility gain greater awareness of the processes taking place in this facility, the procedures necessary to carry out to prevent failures as well as the effects of actions taken by them and the effects of possible omissions (e.g. related to ignoring measurement results suggesting possible failure). However, there is little evidence of how such immersive virtual simulation may be assessed by Critical Infrastructure's staff. Especially in terms of usability and technology acceptance, because it's very important from the point of view of practical implementation. For this reason, research was carried out with the participation of professionally active experts in the field of various Critical Infrastructure facilities.

Measurements

The following research tools were used in the form of standard questionnaires:
- Simulator Sickness Questionnaire (SSQ) (Kennedy 1993).
- Spatial Presence Questionaire (SPQ) (Vorderer 2004).
- Questionnaire for assessing the level of technology acceptance (TAM – Technology Acceptance Model) (Venkatesh and Davis 2000). Components: Intent to use (behavioral intention), Perceived usefulness, Perceived ease of use, Subjective norm, Adequacy (relevance).
- System Usability Scale(SUS) questionnaire (Brooke 2013).
- Evaluation of the training simulation load (NASA TLX – Task Load Index) (Hart 1988).
- Assessment of stress related to training, Dundee Stress State Questionnaire (DSSQ) (Matthews 2013).
- Training and Work Assessment (TWA) questionnaire.

Procedure

The study was conducted with 20 volunteers using Meta Quest 2 goggles with wireless PC image transfer (Figure 1). Volunteers were recruited among professionally active people, employees of CI facilities (mainly power plants and combined heat and power plants), and CI experts. Questionnaires were used in the research, e.g. assessing the usefulness of the developed training applications.

The course of the research was as follows:
- completing questionnaires for assessing the state of the research participant before immersion in a virtual environment,
- launching four training simulations (one for each environment)
- completing questionnaires to measure the assessment of training simulations and the state of the research participant after immersion in a virtual environment.

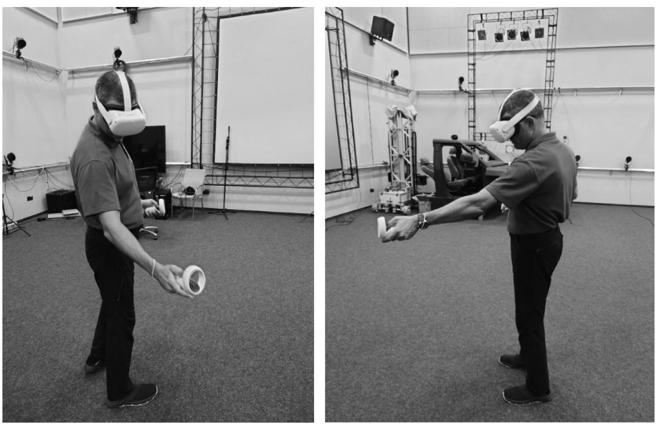

Fig. 1. The research was conducted in the VR laboratory using Oculus Quest 2 goggles

VR-based simulations

A set of scenarios of the development of crisis situations in critical infrastructure facilities was prepared on the example of a power plant, combined heat and power plant, gas compressor station, and water treatment plant. In all scenarios, the simulation involves playing the role of an employee of a Critical Infrastructure (CI) facility, similar to non-computer RPG simulation games used to practice crisis management. However, the type of tasks performed by the simulation participant is different. Depending on the simulation scenario, the trainee supervises the functioning of the CI facility or takes part in activities aimed at restoring the efficiency of the CI facility and neutralizing the effects of failure.

The three scenarios concerning the virtual environments of the CHP plant, the natural gas compressor station and the water treatment plant concern primarily maintaining the continuity of the CI facility's operation. The participant of the simulation stays in the control center of the CI facility, where he receives various information about the functioning of individual components (Figure 2). The source of information may be video monitoring, sensor indications, measurement results (e.g. flow meter indications), as well as CI facility employees. The scenario

Fig. 2. The VR environments

is focused on the right procedure when a situation indicating possible damage or cyberattack occurs. The task of the simulation participant is to react quickly to sensor indications or information from employees so that the functioning of the CI facility is not stopped. This is an important part of the training, as many failures or malfunctions of IK components result from management errors, neglect, or improper maintenance. Another advantage of the simulation is the indication of the possible causes and effects of the situation in the training part and the presentation of the process of responding to improperly functioning telemetry, e.g. The simulation participant also has the option of giving instructions to various employees of the CI facility (Figure 2).

A different approach is used for the five variants of the power plant scenario. The simulation then has a more dynamic character and concerns the conduct of activities by one of the employees who were on the premises of the CI facility during the failure. The task of the simulation participant who can move freely around the CI facility is to carry out activities aimed at assessing the consequences of failure, securing individual components of the CI facility, neutralizing threats, and helping the injured (Figure 2). These are typical actions necessary to be carried out in a situation where it is necessary to restore the efficiency of the CI facility. To simplify, this scenario can be said to be „tactical" in nature, in contrast to the previous scenarios, where the „strategic" level of action was dominant.

Results of the experiment

As part of the research involving 20 experts associated with critical infrastructure, results were obtained on the impact of training simulation on the emergence of symptoms of the so-called. simulator sickness. The Simulator Sickness Questionaire (SSQ) was used for the measurement, which was completed before and immediately after the training simulation in the VR environment. The results obtained on a scale from 1 (no symptoms) to 4 (maximum symptoms) are shown in Figure 3. Looking at the average value for the whole group, it can be seen that the values before and after exposure to the VR environment are very similar, and even the value after contact with VR is slightly lower. In addition, the value after the simulation is very small, slightly (by 17%) higher than the minimum value. The obtained result indicates that the training simulation in a virtual environment has been prepared correctly and does not cause negative effects related to the so-called. simulator sickness, even though the participants took part in several training simulations for several different Critical Infrastructure facilities.

The next research tool was the SPQ (Spatial Presence Questionaire) questionnaire used to measure the level of spatial presence related to the realism of the simulation. The values are on a scale of 1 (worst value) to 7 (best value). The questionnaire has 7 different components. The obtained results are shown in Figure 4. The average value is relatively high, 76% of the maximum value. The lowest value was obtained for the indicator of suspension of disbelief – only 40% of the maximum value. Participants of the research were aware that they were taking part in a simulation, and the world presented in VR was not the real world. This is because activities at the level of managing the functioning of a CI facility are necessarily presented in a slightly simplified way. In addition, high values of this indicator are observed for productions that strongly engage the user on an emotional level, such as entertainment productions, and are not achievable in the case of training simulations, which may not be so interesting for the user.

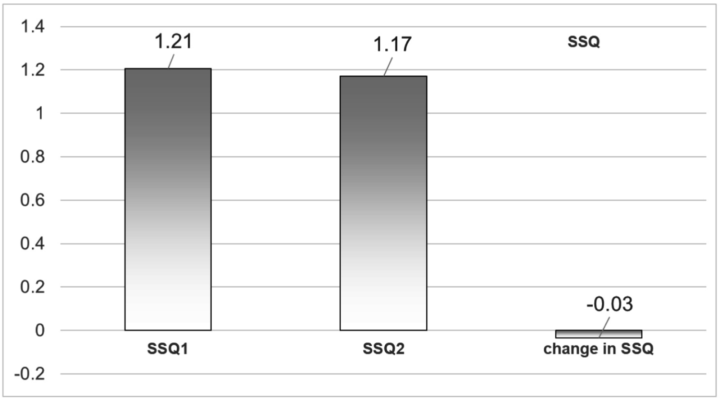

Fig. 3. The results of research obtained using the SSQ questionnaire used to measure the level of symptoms of the so-called simulator sickness

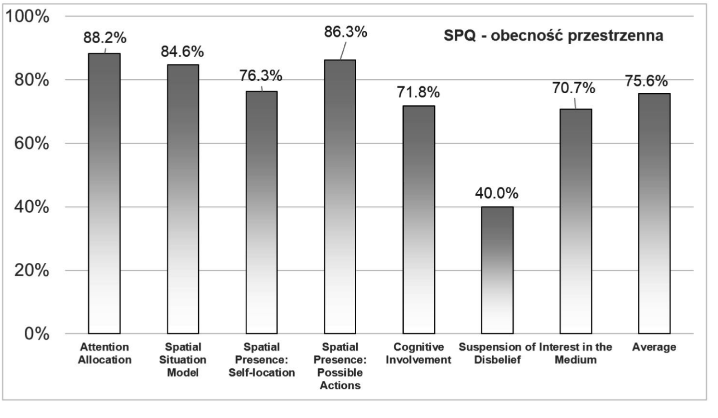

Fig. 4. The results obtained using the SPQ questionnaire measuring the level of simulation realism. The results are presented as a percentage of the maximum achievable value

From the point of view of training, the most important indicator is the involvement of attention (attention allocation), because only when the involvement of attention is high, effective and efficient transfer of knowledge and skills is possible. A disengaged trainee does not efficiently memorize the information presented. For this reason, the simulations were designed to make the value of this indicator as high as possible. The obtained results confirm that it was successful, as the highest score, as much as 88% of the maximum value, was obtained for the attention allocation indicator.

The high value of the Spatial Presence: Possible Actions indicator, 86% of the maximum value, clearly shows that the training scenarios and their implementation in VR enable the trainee to perform a wide range of activities in the context of tasks related to maintaining the continuity of CI facility operation. In other words, the training simulation has been prepared in a way that allows a wide range of activities and performing various tasks, which results from the amount of work devoted to the implementation of a wide range of types of interaction with elements of the virtual environment.

The NASA-developed Task Load indeX (NASA TLX) questionnaire was used to measure the training load of the interactive VR simulation. Values on a scale from 1 (least burden) to 20 (heaviest burden) were collected in the following categories: mental demand, physical demand, tempral demand (time pressure), performance (efficiency), effort, and frustration. The obtained results are illustrated in Figure 5. The average value of the load is relatively low, as it is 25% of the maximum value. The physical load (demand) is almost the same as average value (24%). Values for tempral demand, effort, and mental demand were lower than the average value. The lowest value has the indicator of mental load (15% of the maximum value), and the highest indicator of the level of frustration (43% of the maximum value). It should be noted that only values above 50% are negative, so the obtained results do not indicate that the participants of the training simulation were frustrated.

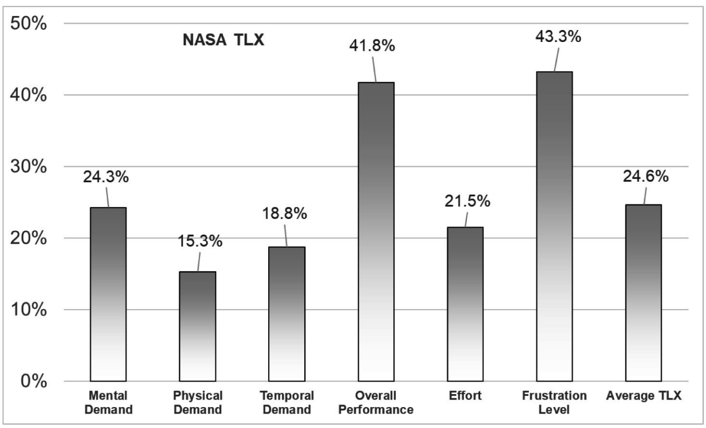

Fig. 5. The results of research obtained using the NASA TLX questionnaire used to measure the level of load related to the training simulation being carried out. The results are presented as a percentage of the maximum achievable value

The relatively high value of the frustration index (against the very good values of the physical and mental stress indicators) is associated with the result of the index determining the subjective assessment of performance during the training simulation, for which a value close to 42% of the maximum value was obtained. Relatively high (but still positive) values of these indicators may be due to the lack of experience in using virtual reality interfaces.

To sum up, the obtained results in terms of the training process load indicate that the VR training simulation was prepared correctly, i.e. the interface itself and the hardware and software solutions used do not cause a significant burden, especially mental. This is a positive result, as it is conducive to remembering information and acquiring skills by trainees. It should be emphasized that people who are overburdened with the training process itself, including frustrated people, do not have enough resources, especially cognitive resources, and do not have the will to focus on the substantive content of the training and effectively acquire new knowledge and skills.

The assessment of stress caused by the training process, including the stress related to the human-computer interface used, was performed using the Dundee Stress State Questionnaire (DSSQ). The questionnaire includes a subjective rating on a scale from 1 (least stress level) to 7 (highest stress level) in three categories. The obtained results are shown in Figure 6. The average value of the stress level is very low, as it is 32% of the maximum value. The lowest value has the indicator of stress related to involvement in the task (26% of the maximum value), which may be partly because the pilot training was attended by people who were well acquainted with the specificity of the Critical Infrastructure facilities. The highest value was recorded for the distress index, but it is still a relatively low value, lower than the average value (40% of the maximum value).

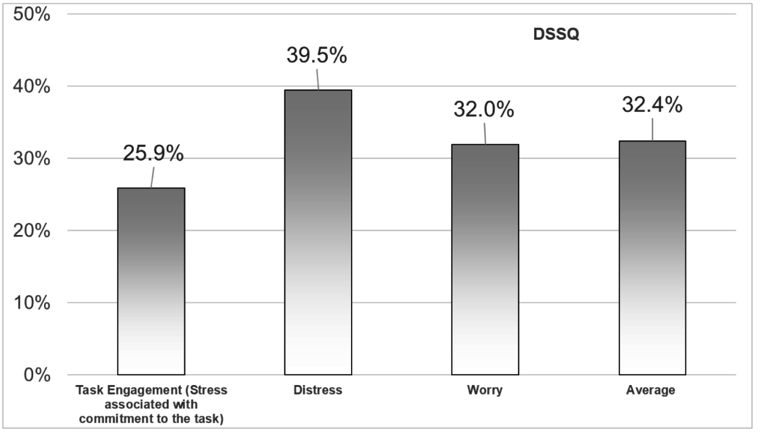

Fig. 6. The results obtained using the DSSQ questionnaire measuring the level of stress associated with the training simulation. The results are presented as a percentage of the maximum achievable value

The results of the subjective assessment of stress are consistent with the results of the load obtained using the NASA TLX questionnaire – a low level of stress (especially in terms of the frustration index) cannot occur together with high values defining the level of stress. This is important information, as it indicates that the tests were carried out correctly and the results obtained are reliable. The obtained results overlap with the two most similar indicators: frustration with NASA TLX (43% of the maximum value) and distress with DSSQ (40% of the maximum value).

The results obtained using the DSSQ questionnaire (low level of stress related to the training process) indicate that the training application was prepared correctly. As in the case of the load, the high level of stress caused by the training process (including, for example, the human-computer interface used) negatively affects the process of remembering information. It should be emphasized that the tools used do not measure stress induced on purpose, i.e. resulting from the substantive issues of tasks performed during the simulation – this type of stress is of great importance in the case of some types of training (especially for uniformed services officers), as it increases the realism of the simulation (uniformed services officers often work under stress), but this stress should not be caused by the training process itself, e.g. by an improperly selected human-computer interface (e.g. the use of cables could cause fear of entanglement in them and falling over, which is not a source of stress related to the substantive content of the tasks performed during the simulation).

From the point of view of practical implementation of the developed training simulations, the subjective usability assessment is important. The usability assessment was carried out using the System Usability Scale (SUS) questionnaire. Based on the answers to 10 questions, a subjective usability rating is determined on a scale of 0 (minimum usefulness) to 100 (maximum usefulness). The obtained value of 80.6 (81% of the maximum value) shows that the VR system was considered useful by users. According to data from 206 studies presented in (Bangor 2008), the median SUS value is 70.91 (the usefulness of the developed training simulation is higher than for most other systems). According to the results of the review studies, the fourth quarter ranges from 78.51 to 93.93. The obtained result is within this range. According to the data presented in (Bangor 2008), a higher result was obtained only in 12% of studies. This indicates that the usability of the developed VR system, assessed by experts, is very high.

The possibility of practical implementation is also affected by the level of acceptance of the technology by users. Even the most technologically advanced solutions will not be accepted and willingly used by end users if the level of technology acceptance is low. Technology acceptance was measured using the Technology Acceptance Model (TAM) questionnaire consisting of the following indicators: intention to use, perceived usefulness, perceived ease of use, subjective norms, and adequacy. From the point of view of practical implementation, the first three components are the most important, especially the assessment of intention to use and the assessment of subjective usability. The obtained results are shown in Figure 7. The average TAM value is high and amounts to 81% of the maximum value (answers are on a scale of up to 7). The highest values were obtained for the most important components from the point of view of implementation and acceptance of the product by end users. In order of greatest value, these are perceived usefullness (90% of the maximum value), intention to use (89% of the maximum value), and ease of use (87% of the maximum value). The perceived usefullness score in terms of technology acceptance is even higher than the usability level using the SUS questionnaire. The obtained results indicate that the training simulation has been prepared correctly, as the acceptance of the technology is at a high level, which should facilitate implementation among end users. The very high score for the indicators of intention to use and perceived usefulness (around 90% of the maximum value) is particularly important. This indicates that the vast majority of end users should be willing to use the developed VR training simulations.

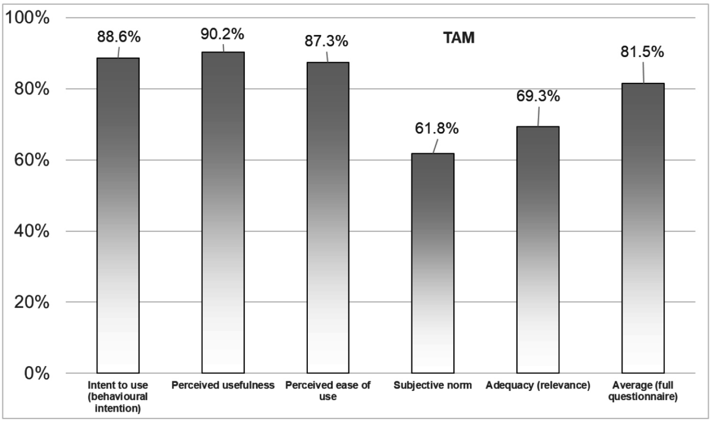

Fig. 7. The results obtained using the TAM questionnaire measuring the level of acceptance of technology. The results are presented as a percentage of the maximum achievable value

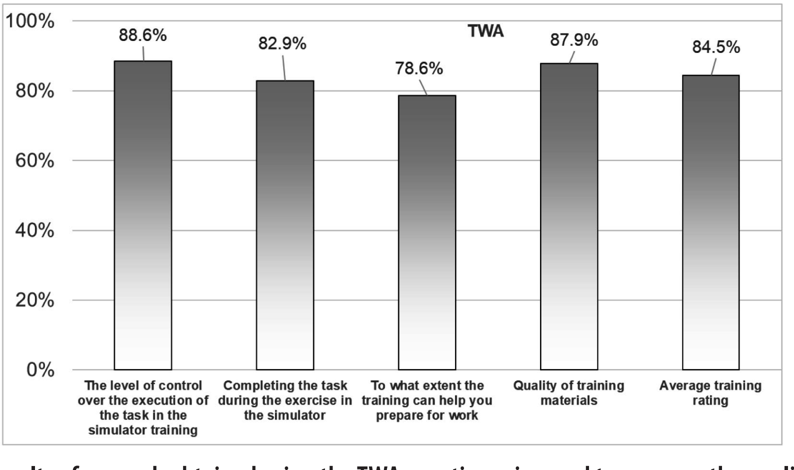

Fig. 8. The results of research obtained using the TWA questionnaire used to measure the quality of training. The results are presented as a percentage of the maximum achievable value

The last questionnaire that was used in the study was the Training and Work Assessment (TWA) tool for assessing the quality of training and training, consisting of the following indicators: level of control over task performance in the training simulator, task performance during the exercise in the simulator, degree of assistance of the training in preparation to work and the quality of training materials. The values of individual indicators are on a scale from 1 (the worst training evaluation) to 7 (the best training evaluation). The obtained results as a percentage of the maximum value are shown in Figure 8.

Conclusions

VR has the potential to revolutionize the training methods and outcomes for critical infrastructure systems. VR can provide a more effective, efficient, and engaging way of learning and practicing the skills and knowledge that are essential for ensuring the reliability and resilience of critical infrastructure.

The results of the pilot training with 20 CI experts indicate that the developed training tool is:
- useful,
- is characterized by a high level of technology acceptance,
- realistic and engaging (high level of components of spatial presence and simulation realism),
- does not cause symptoms of the so-called simulator sickness,
- does not cause unnecessary burdens on the training process.

The obtained results indicate that the training simulations have been prepared correctly and are suitable for implementation. High values of usability and intention to use prove that this type of training tool should be well received by end users.

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