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Principles for Safe Use of Virtual Reality, Augmented Reality, and Mixed Reality in Flight Training

O. Zavila*, P. Michenka, J. Bořil, and P. Engelová

Department of Air Force, University of Defence, Brno, Czech Republic

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Abstract:

The present article focuses on key flight safety issues in the use of virtual reality, augmented reality, or mixed reality technologies in military flight training. It summarizes what is known and traceable to date about the potential benefits and dangers of using virtual technologies. In relation to these findings, the article then presents options for effective recovery from work in virtual environments, a set of safety recommendations to reduce the likelihood of negative impacts on the user's health and fitness, and groups of potential at-risk users for whom working in virtual, augmented, or mixed reality environments should be carefully considered and, where appropriate, subjected to increased supervision. Finally, the article summarizes the logical principles and recommendations for effective and safe work with virtual technologies, not only in the flight training.

Keywords:

human factors, flight training, flight safety, virtual reality, augmented reality, mixed reality

1 Introduction

Virtual reality has emerged as a prominent technological trend, permeating diverse domains such as industry, medicine, and military technology. Although its origins can be traced to the United States in the 1960s [1] and it has been extensively utilized by millions of users worldwide for nearly four decades across various computing platforms, its technical and user limitations remain under-promoted.

The potential user risks resulting from these limitations and the effectiveness of the work always depends on the user's way of thinking, values, and goals.

* *Corresponding author: Department of Air Force, University of Defence, Kounicova 156/65, CZ-662 10 Brno, Czech Republic. Phone: +420 973 445 206, E-mail: ondrej.zavila@unob.cz. ORCID 0000-0002-9283-0399.*

The effectiveness of working with virtual technologies depends less on the quantity of time spent in the virtual environment and more on the quality of engagement – specifically, how the work is conducted within a strictly limited timeframe – while always considering the type of application and specific objectives.

In this particular instance, more than in others, the maxim that *"technology can sometimes be a good helper, but without adequate regulation of its use it is almost always a bad master"* applies.

Before delving into subsequent principles, it is appropriate to establish the foundational framework of the terminology used. In the course of examining virtual technologies, one may encounter four fundamental terms: virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) [2]. Each of these terms represents a slightly different group of technologies (see Fig. 1).

Virtual reality (VR) is defined as a fully virtual environment created by a computer. There are three forms of VR:

- non-immersive VR refers to an environment in which users can move and control the environment, but do not interact with it directly and are not removed from the sensations of the real environment (e.g., laptop, mobile phone),
- semi-immersive VR refers to an environment in which users can move and are able to control it, but the environment does not reflect their own physical movements and users are only partially removed from the sensations of the real environment (e.g., flight simulators with virtual image projection but with realistic plastic cockpit design),
- fully immersive VR refers to an environment in which users can physically move, control it, and interact with it in full motion using special helmets, goggles, or gloves, with the perception of the surrounding real environment completely removed.

Augmented reality (AR) is defined as a real environment with virtual elements that cannot be interacted with, leaving the user as an observer.

Mixed reality (MR) is defined as a real environment with virtual elements that can be interacted with using the user's hands and feet.

Extended reality (XR) is a common name for augmented reality (AR) and mixed reality (MR) technologies [2].

Fig. 1 Virtual technologies: (A) Virtual reality – non-immersive; (B) Virtual reality – fully immersive; (C) – Augmented or mixed reality

The motivation for this study stems from the authors' objective to provide a balanced assessment of the capabilities and limitations of virtual technologies in military flight training, with top priority being safety and training effectiveness.

In selecting information sources for this study, the authors considered:

- the systematic nature of published research and experience (results must always be obtained in a systematic way and interpreted in sufficient context to avoid mystification),
- the comprehensiveness of the view on the problem (the view on the problem should accept the pros and cons, the advantages and limitations, the limits of validity of each claim, etc.),
- logic and transparency of published conclusions (published results and experience must have a clear basis in facts, not emotions or conjectures),
- the profession and motivation of the authors (the potential conflict of interest of the authors of many publications was assessed – the motivation for objectivity of insight may even differ significantly, for example, between manufacturers or distributors of these technologies versus medical doctors of various specialties who have no commercial interests in the field),
- the identity of the publisher (any emotionally-conceived company promotional material, tabloids, anonymous websites or publishers were excluded automatically from the selection of sources).

The selection of information sources was not carried out quickly. It was essential to fully understand the content of each source in context.

2 Methods

The information obtained from the available literature was grouped and subjected to examination using standard methods of scientific work such as: analysis, synthesis, deduction or comparison. The aim was to explain the key concepts and principles in a broader context and to find logical interrelationships in order to form the basis for a safety management system of virtual flight training.

In formulating recommendations for the safe use of virtual technologies in a logical sequence, selected principles of sports training theory were used for inspiration, such as: the principle of gradual loading (adaptation) of the organism, principles for activation of the organism (warm-up) or for recovery of the organism after exercise.

3 Known Benefits

The promotion of VR, AR, and MR technologies is typically supported by six arguments, including the following:

- *realism* of the experience,
- *variability* of application environments,
- *user safety*, even when training dangerous activities in “unsafe” environments,
- *efficiency* of the training,
- *availability* on the market,
- low acquisition and operating *cost* [3].

However, for the sake of fairness, it is appropriate to complement these arguments with a clarifying comment and to put them into context.

The *realism* of a VR, AR, or MR working environment can be defined as the degree of correspondence with the real-world model it represents (i.e., as the number of common features the simulated model shares with its real-world counterpart). However, such an assessment can be quite relative, as it depends on the objectives that users wish to achieve through training. The assessment of realism, therefore, must always be evaluated in relation to the specific objectives of the training. To this end, it is essential that the objectives should be defined with the utmost precision by the users. Only when such objectives are well-defined can one determine the appropriateness of the technology and training methodologies. The degree of realism can only be determined for a particular task and the utilization of a specific technology. It is therefore far from being just an evaluation of a single, usually visual perception, which is most often appraised by image sharpness, the vividness of colors, the fluidity of movement, or the exoticism of the simulated environment.

The *variability* of application environments constitutes a clear advantage of these technologies. It is possible to generate virtually an almost infinite variety of application environments; nevertheless, it is also important to consider the realism of these environments. When the degree of realism of the working environment is low in relation to the training purpose, the variability of mentioned environment becomes less significant.

The *safety* of training in VR, AR, and MR must be evaluated from at least two perspectives. The first one is the user's safety in relation to the trained scenario in the virtual working environment. The second one is the user's safety in relation to the need to maintain physical and mental health and fitness. When considering the former one, the utilization of VR, AR, and MR technologies are indeed safe in a simulator environment; for instance, users cannot sustain bodily injury from enemy missile fire or die in the event of an air accident. However, from the latter perspective, these technologies may carry potential risks, contingent on the manner and extent to which they are employed by individuals. Inadequate or improper usage of these technologies has the potential to result in adverse physical and mental health consequences for the users, as well as a possible decline in work performance that may be either temporary or permanent (see Section 3 for more details).

Efficiency can be broadly defined as the ratio between the benefits of any activity and its costs. Thus, the higher the rate of benefits received relative to their cost, the higher the efficiency. In the case of simulation technologies, this concept can be understood as the ratio between the amount of knowledge or skills gained by users and the amount of money spent. From this perspective, VR, AR, and MR technologies have a clear advantage over training in a real environment. However, this is only true under the condition that a sufficient level of realism and a sufficient level of safety in terms of fitness and health protection of the users are guaranteed for a particular project. Otherwise, training conducted using these technologies is not efficient.

The market *availability* of these technologies for civilian and military users is determined by current technological, commercial, and political trends in some countries worldwide.

The acquisition and operation *cost* of these technologies must always be evaluated in the light of the expected guaranteed benefits, especially in terms of realism for specific training objectives, user safety, and efficiency.

To summarize the preceding section, it can be concluded that the indisputable benefits and promising capabilities of VR, AR, and MR technologies should be recognized and evaluated within a comprehensive framework, while concurrently considering their possible limitations.

4 Known Disadvantages

According to the available information sources [4-19], four main groups of potential disadvantages (dangers) of VR, AR, and MR technologies for users can currently be identified. These disadvantages include the following:

- risk of harm to physical health and fitness,
- risk of harm to mental health and fitness,
- risk of misuse for cyber-attacks, and
- legal liability issues in case of harm to the user's health.

These potential disadvantages arise from several factors, including: the practically non-existent safe use policies for the user (who may not know what to look out for and how to manage their security); the unregulated distribution on the market (devices based on these technologies can be purchased by practically any legally competent individual, despite the fact that they may be users at increased risk of harm to their health – see Section 6 below); the absence of legal restrictions on the form, content, and distribution of these technologies and their application products (inappropriate content operating in a fully immersive form can reach high-risk users without restriction – again, see Section 6 below); and the unnatural stimulation of the human body.

The different groups of disadvantages are described in more detail in the following sections.

4.1 Risk of Harm to Physical Health and Fitness

Available information sources suggest that five groups of physical problems can manifest (in isolation or combined) when working in VR, AR, or MR environments: an increased physical fatigue; visual function alterations; disruptions to the circadian rhythm; various forms of nausea, pain, and other specific physiological responses within the body (collectively termed "simulator sickness", "cyber sickness", or "virtual reality sickness" – VRS); and epileptic and photosensitive seizures.

Increased physical fatigue results from the human body's constant need to adapt to stimuli from its unnatural environment. These stimuli may conflict with many of the natural sensations to which the human organism is evolutionarily adapted (e.g., different spatial perception and situational awareness, conflict between visual perception and proprioception – the sense of body position in space, or lack of complex sensory perception). The human body is then forced to gradually recalibrate its evaluation of sensory stimuli in order to adapt to the new (unnatural) environment, and, as a result, it cannot save energy by using habitual procedures [4-10].

Visual function alterations may be transient or even permanent, with various authors noting the potential for asthenopia (eye strain syndrome manifested through symptoms such as eye fatigue, pain in and around eyes, ocular muscle strain etc.), accommodative insufficiency (inability of the eye to focus properly on an object), convergence insufficiency (reduced ability of the eyes to turn towards each other), and impaired binocular vision (ability of three-dimensional vision and to perceive depth of space). In practical terms, these alterations can result in impaired distance estimation and spatial perception, which can be a life-threatening incapacitation for pilots [4-10].

Circadian rhythm disorders (i.e., disturbances in the periodic alternation of natural activity and rest of the human body over time) can be caused by an inadequate amount of work in virtual environments at inappropriate times of the day. The human body is evolutionarily adapted to regulate its activity in relation to sunlight, or more precisely, according to the frequency spectra of sunlight passing through the atmosphere at different angles at different times of the day. This results in fluctuations in the light spectra throughout the day, which elicit physiological responses in the human body. Consequently, certain types of light promote increased activity, while others induce a decrease. The issue arises from the fact that virtual technology displays emit light spectra that approximate those of midday sunlight, which physically and mentally stimulates human body to activity. If this occurs during a period when the body should naturally be transitioning into a state of decreased activity in preparation for sleep, this preparatory phase is disrupted, which results in the user's inability to fall asleep until they have fully recovered. This disruption can potentially delay sleep by several hours, which can lead to a decline in both cognitive and physical performance in the short term. Additionally, it can contribute to long-term health complications and a reduction in lifespan. A more comprehensive overview of the impact of light on human health and performance can be found in the literature [11].

Simulator sickness, also known as cyber sickness or virtual reality sickness (VRS), is associated with symptoms that include nausea, dizziness, lightheadedness, pale skin, cold sweat, vomiting, headache, difficulty concentrating, and eyestrain, among others. The cause of these symptoms is typically a conflict of sensations between different sensory organs or an increased sensitivity to certain unnatural characteristics of the virtual environment (e.g., the type of light). Resilience to these “diseases” is commonly diminished by fatigue, stress, and temporary or permanent health indispositions [12, 13].

Epileptic seizures can be triggered by a discordance between visual perception and proprioception, and are usually characterized by unconsciousness, convulsions, disturbances of consciousness, tingling of the limbs, dizziness, and nausea. Photosensitive seizures are a type of epilepsy (photosensitive epilepsy) occurring in response to certain types of light and their alternation at short intervals (intermittent flicker at a specific frequency), and are characterized by dizziness, alternations in vision, tics in the eyes or face, disorientation, confusion, and loss of attention. In both cases, the user is unable to continue working in the virtual environment [14, 15].

4.2 Risk of Harm to Mental Health and Fitness

According to the available information sources, the deleterious effects of protracted improper use of virtual technologies on the user’s mental health are primarily manifested by various perceptual disorders, changes in experience, and a reduction in the level of social skills. The user loses the ability to communicate and interact with the real environment [16, 17].

Perceptual disorders include dissociation (a psychological disorder manifested as a feeling of “disconnection” from one’s own thoughts, memories, emotions, activities, and self-awareness), depersonalization (a psychological disorder or condition in which the affected person perceives their body, thoughts, emotions, or sensory stimuli as alien, distant, unreal, or not their own), and derealization (a perceptual or experiential disorder in which a person’s subjective dissociation from the environment occurs and the sufferer feels as if everything were “like in a movie”, “behind glass”, “behind a curtain”, or “like in a dream”).

Changes in experience can manifest in various ways, such as in a reduction in empathy, an increase in aggression, and the emergence of mental trauma. This, in turn, can affect the user’s decision-making process and their reactions.

In summary, the users may gradually lose the ability to perceive their body, thoughts, and feelings, and lose the ability to communicate with their real environment. In the more favorable scenario, recovery requires a certain amount of time and a specific set of conditions. In the less favorable scenario, professional psychological or psychiatric assistance may be necessary.

4.3 Risk of Misuse of Virtual Technologies for Cyber Attacks

A cyberattack is any intentional action carried out in cyberspace that targets and threatens the interests of another individual or entity. In the case of flight simulators operating on the principle of virtual technologies, this may include the danger of unauthorized acquisition and analysis of sensitive personal data of users, the danger of psychological manipulation, or the danger of psychological attacks to influence the personal or professional performance of the user.

In the absence of adequate cyber protection, the possibility of unauthorized access by foreign entities to sensitive personal data from the training of military pilots cannot be excluded. Such access could provide, for example, an overview of the current professional and personal performance of entire air units, combat tactics, trained flight tasks, and professional know-how.

The introduction of logical errors in the software has the potential to manipulate the flight routines of crews, thereby affecting the course and quality of flight training.

Furthermore, the implementation of subliminal visual cues or sound distractions could influence the performance and reactions of flight crews in standard situations over an extended period. Such actions could be classified as a psychological attack [18].

4.4 Legal Liability Issues

In the event of harm to the physical or mental health of the user as a result of the use of virtual technologies, the Czech Republic relies on the legislation currently in force, in particular Act No. 262/2006 Coll., the Labor Code [19].

In such cases, when assessing legal liability, it is necessary to distinguish whether the harm to health occurred to a person in an employment relationship while performing a work activity, to a self-employed person, or to a private individual. Different laws and related legislation apply to each of these categories. In principle, it is required to demonstrate that the employer's duties towards the employee were breached, that the product safety information provided by the distributor (seller) was inadequate, or that a manufacturing defect was present.

However, the primary requirement is the establishment of a causal link between the exposure to the virtual technology and the damage inflicted. This causal link is particularly challenging to substantiate in cases involving harm to mental health. The injured individual would have to undergo a series of specialized medical examinations at sufficiently short intervals before and after working with the virtual technologies for the work with these technologies to be directly related to the changes recorded in the medical examinations. In many cases, however, even this would not make the argument conclusive, as many physical and especially mental health problems can arise from multiple causes. Unfortunately, in most cases, the proportion of specific causes cannot be clearly established retrospectively.

In conclusion, the legal liability of technology manufacturers, distributors, or employers is challenging to enforce and cannot be relied upon. In light of these considerations, users must primarily protect their health by exercising caution and sound logical judgment.

5 Recovery Options

Recovery can be defined as the process leading to the regaining of the original physical and mental condition after a load. Specifically, in the case of recovery following work in VR, AR, and MR environments, efforts should be concentrated on the restoration of visual functions, proprioception (the sense of one’s own body position in space), spatial orientation, the circadian rhythm of the body, perception of one's own feelings and stimuli from the environment, and the ability to interact socially in the real environment.

The fundamental prerequisite for initiating the recovery process is the disengagement from the VR, AR, or MR environment and re-entry into the tangible environment.

The recovery process can be accelerated in a number of ways, particularly by activities that increase the volume of fluids in the body, improve blood circulation to all parts of the body (especially the brain), increase the amount of oxygen in the blood, restore spatial orientation, and restore proper coordination of movement and position of the body in the natural environment. Increased consumption of appropriate beverages, light physical activity (ideally walking at a slow or moderate pace), breathing exercises, or exposure to certain types of natural or artificial light can facilitate this.

The liquids consumed should not contain any stimulants (no energy drinks etc.) or cause dehydration (no coffee or certain types of tea). The ideal beverage is plain water or beverages with the lowest possible content of fructose or fructose-containing sugars (fructose is a type of sugar that stimulates the body energetically in the short term, thus reducing the feeling of fatigue, but then very quickly causing a decrease in energy in the body) [20, 21]. Light physical activity should not exert undue strain on the vestibular apparatus, nor should it place augmented demands on movement coordination or spatial orientation. Movement should facilitate safe, gradual adaptation to the natural environment. Breathing exercises should lead to the stabilization of breathing, the calming of the organism, and the reduction of stress (for more detailed information, refer to the relevant literature [22, 23]). It is also possible to promote recovery by using natural sunlight, wavelength spectra of which correspond to specific times of the day and can help to stabilize the user’s potentially disturbed circadian rhythm. The most problematic is working in a virtual environment at times that are not naturally associated with blue light production by solar activity (i.e., early morning, evening, and nighttime). At these times, one should be waking up or preparing for sleep or asleep. If an individual is exposed to the blue light component (i.e., light with a wavelength of 430 to 500 nm) emitted from virtual technology displays for more than a few seconds during these times, the body’s natural circadian rhythm is disrupted (the ability to fully sleep and recover is thereby impaired). It is therefore advisable to refrain from working in virtual environments during these specific timeframes. A technical point of interest is that there are now methods to artificially generate light with a frequency spectrum corresponding to natural sunlight at different times during the day. Suitably chosen artificial lighting acting as natural sunlight can therefore be used for recovery, despite any unfavorable weather conditions that may occur (see [24-26] for details).

The duration of recovery can vary from individual to individual and is typically influenced by several factors which include:

- the complexity of the task being practiced,
- the intensity of effect of the technology utilized (fully immersive virtual reality technologies are the most potent),
- the duration of exposure to the technology,
- the health status of the user,
- the current fitness level of the user,
- the recovery options and conditions.

When training typified activities (e.g., certain types of flight tasks) under comparable conditions (e.g., time of day, pre-training workload), the approximate time and methods of effective recovery can be estimated for a particular user or group of users by observation. These may of course change over time and therefore need to be updated periodically. If feedback is consistently solicited from users, the main trends in recovery can be seen after a certain period of time and then incorporated into the management system for the safety of flight training in VR, AR, and MR of specific work groups (squadrons, units, etc.).

The comprehensive recovery of physical and mental fitness ought to be substantiated through a series of specialized assessments. As regards physical fitness, the assessments should encompass visual function tests and balance tests (i.e., vestibular tests). In terms of mental fitness, the assessments should include tests of perception, experience, and social skills.

It is essential that activities in VR, AR, or MR are not integrated with actual flight operations until the user has been clearly demonstrated to have fully recovered.

6 At-Risk User Groups

Pursuant to the information contained in Sections 2 and 3, it is possible to specify the risk groups of users of virtual technologies (i.e., VR, AR, or MR) in general terms as follows:

- individuals with temporary or newly developed physical limitations (e.g., illness, physical injury, physical fatigue, on medication, etc.),
- individuals with temporary or newly developed psychological limitations (e.g., psychological trauma, mental illness, mental fatigue, burnout syndrome, on medication, etc.),
- individuals with permanent physical limitations (e.g., epilepsy, vestibular disorders, eye disorders, etc.),
- individuals with permanent psychological limitations (e.g., congenital personality disorders–psychopathic characteristics, low IQ, low EQ, etc.),
- individuals demonstrating a disregard for safety rules (e.g., workaholic or over-motivated individuals, individuals violating training rules-time, recovery, etc.),
- children and immature persons (i.e., individuals with incomplete physical and mental development).

At-risk users, with regard to their specific problems, should refrain from working with virtual technologies entirely, or alternatively, they should operate under closer supervision, or their workload should be restricted relative to that of individuals considered “healthy”, who do not currently fall within these risk categories. However, even a person initially considered to be in good health may transition into one of these

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risk categories (particularly those classified as A and B) if they engage in prolonged, inappropriate work.

Items A, B, D, and E of the list above are of particular relevance to military flight crews, irrespective of their specialization.

7 Proposal for Safety Principles of Use

At the outset of this section, it is useful to provide an explanation of the fundamental logic of the effect of virtual technologies on humans and the principles of limited human resilience to these technologies (see Fig. 2).

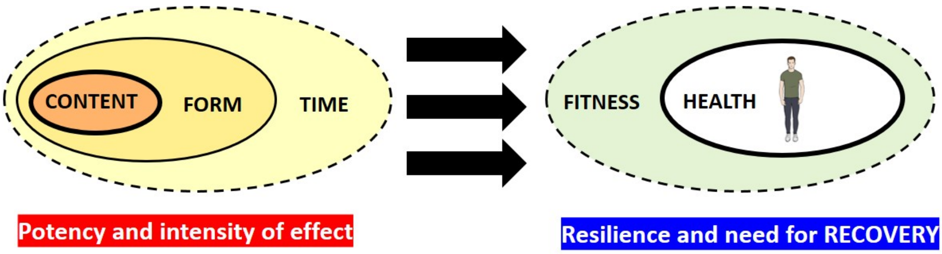

Fig. 2 The principle of the effect of virtual technologies on humans

In a virtual environment, the most significant element is invariably its "content" (i.e., the visual and auditory elements of the environment, the principles of operation, the thematic focus, and the range of activities available to users). The distribution of this content is amplified by the "form" (the more immersive the form, the more quickly, strongly, and with longer persistence it affects the user). The form is then further amplified by the "time" the user spends in the environment (the longer the time, the more strongly and with longer persistence the content affects the user). In summary, the more dangerous or inappropriate the content, the more immersive the form, and the longer the user's time spent in the virtual environment, the faster, stronger, and longer the persistence of the content on the user.

In contrast, a person's resilience to the potential negative effects of this environment on their health and fitness is determined by their "state of health" (physical and mental health) and "current fitness" (physical and mental fitness in relation to natural circadian rhythms). The healthier and fitter a person is, the longer they remain resistant to all potential negative effects and the shorter their recovery period is. However, no human being can resist the aforementioned negative influences indefinitely. The temporality of human resilience is a factor that must be considered.

In establishing principles for the safe use of VR, AR, or MR technologies, it is possible to draw on the known benefits (see Section 2) and disadvantages (see Section 3) of these technologies in relation to the human user, as well as several principles underlying, for example, sports training theory. In a figurative sense, working in a virtual environment can be described as a form of sporting performance, the achievement and sustainability of which, while maintaining health, is subject to several rules. A list of these principles (for the general user) is provided below:

- familiarize oneself beforehand with the principles of the virtual environment and the previous user experience,
- reflect on one's current health status (the user should not belong to any of the risk groups),

- incrementally increase the workload (work/training) and time spent in the virtual environment:
    - from intervals of minutes to tens of minutes (time aspect),
    - from static tasks to dynamic tasks (movement aspect),
    - from simple tasks to more complex ones (stimulus quantity aspect).
- respect one's personal performance limits or current limitations (in the event of sudden health complications, cease all work in the virtual environment until the issue is resolved),
- monitor user reactions (i.e., user health and fitness in relation to the type and time of workload in the virtual environment) on a long-term basis,
- ensure sufficient recovery periods for both duration and effectiveness,
- specify the duration and content of safety breaks between virtual and real flying (i.e., minimum mandatory recovery time and permissible activities during this time),
- after prolonged breaks, transition to a higher workload gradually.

In summary, as with any sport performance (e.g., athletics), it is necessary to familiarize oneself with the principles of the sport and the environment in which it is to be performed (see point I.). In addition, it is necessary to reflect on the current state of health which the expected athletic performance is based on, both quantitatively and qualitatively (see point II.). In order to achieve the desired increase in performance, the volume and intensity of training should be increased incrementally, also to avoid injury (see point III.). This incremental increase in training load should respect the athlete's current individual capabilities and limitations (see point IV.). In instances where the coach lacks the capability to assess the effectiveness of the training and the limits of harm to the athlete's health according to objective criteria, feedback from the athlete should be sought (see point V.). Following each training session, effective form of and time for recovery are necessary (see points VI. and VII.), so that the training can be further developed and the athlete's performance can continue to improve. Finally, after a prolonged break in training, it is crucial to initiate a gradual reintroduction of training loads to prevent injury (point VIII). These principles are well-supported by numerous publications in the field of sports training theory, including [27].

8 Benefits and Limitations for Flight Training

First of all, the basic differences between civilian and military flight training need to be explained. Civilian flight training is usually focused on routine flights at high altitudes without aerobatic elements in non-combat zones. Thus, there is no need to include a range of tasks related to the use of air tactics, weapon systems or, for example, radio electronic warfare systems. In contrast, military flight training may include all of these attributes, and in addition, the aerial activity may be located at near-ground altitudes (i.e., low level flying in complex terrain) where the requirements for speed of decision making, accuracy of piloting, and consistency in execution of procedures may vary significantly. All these differences should also be respected when planning and implementing virtual training.

The benefit of military flight training on simulators that utilize virtual technologies is the capacity to acquire a specific set of flight skills without risking life. Nevertheless, such a set of skills is limited as no flight simulator has yet been capable of entirely supplanting training in a real environment [28, 29]. The degree of benefit then depends on the effectiveness of the training process, which is further dependent on the realism of the working environment, the selection of appropriate (non-risk) users, and the safety of their work.

The disadvantages of military flight training that utilizes virtual technologies include the risk of possible harm to the user's health in case of inappropriate use of the technology, the risk of sensitive personal data loss, particularly regarding the user's personality and professional performance, and the risk of technology misuse for manipulation and psychological attacks on the user in order to affect their performance in the event of inadequate cyber security measures.

Therefore, the utilization of virtual technologies needs to be approached in a comprehensive and objective manner without overestimating their benefits and underestimating their limitations. Otherwise, their employment can be not only ineffective but also dangerous. Simulators, due to their current limited level of realism, should be utilized exclusively as a complement to actual flight training, not as its basis. The disparities in human perception and physiological responses to virtual environments may potentially contribute to aviation accidents in real-world flying situations.

9 Conclusion

The primary objective of this article was to provide an objective and comprehensive contextual view of the benefits and limitations of virtual technologies (VR, AR, and MR) for military flight training. The available information suggests that there are not only benefits but also numerous limitations of these technologies in relation to human health and performance that need to be considered. It has been identified that there are also at-risk groups of potential users that require increased attention, as well as the ever-evolving possibilities of effective recovery for end-of-work in virtual environments.

Based on the summarized facts, a proposal of general safety principles for working with VR, AR, and MR technologies has been drafted. These principles are fundamentally based on the principles of sports training theory, with consideration of the specific needs and objectives of military flight training. This foundational concept of principles can be further elaborated into a distinct "Safety Management System for Military Aviation Training in Virtual Environments", which would take account of: specific training objectives, specific aviation technology, specific application environment of a potential battlefield and a specific group of users with their specialized portfolio of knowledge, skills, and health status.

In summary, VR, AR, and MR technologies can provide an excellent range of benefits, but only if users understand their training objectives and adhere to the principles of safe usage to prevent harm to their health or unintended decline in their fitness. Given the current limitations on the level of realism (at least in the field of military flight training), it is preferable to use these technologies as an adjunct to flight training, rather than as the basis of it, and only where absolutely necessary and feasible for the benefit of training. If the boundaries of its safe and effective application are delineated and despite the aforementioned challenges, it is a promising trend in military flight training for the future.

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