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How Extreme Environments Can Impact the Training of Industrial Operators

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Extreme environments, either natural or artificial, can greatly affect the effectiveness and safety of operators. Scope of the paper is to provide a rather detailed list of extreme working environments and the effects produced on the workers in terms of disturbances, efforts, and misrepresentation of real operating conditions. These elements can influence the operators' awareness and therefore call for the definition of dedicated training methods. The concluding part of the article discusses the recommended features that a training simulator for extreme environments should implement to improve the situational awareness and safety of operators.

1. Introduction

Extreme environments (EE) are "*environments to which humans are not naturally suited and which demand complex processes of physiological and psychological adaptation*" (Manzey et al., 1998). EE can be experienced in either natural or artificial sites. When Nature plays a direct role on EE then temperature, pressure, gravity, and winds are the elements that most make them severe. In case of artificial EE, the main players are noise, harsh conditions, lighting, pollutants, toxic substances, and extended strain. Some elements can characterize both natural and artificial EE. For instance, tornadoes, hurricanes, sea storms, and eruptions can produce high volume noises likewise compressors, pneumatic hammers, impellers, turbo fans, and turbines. These high volume noises can impair the communication among operators, increase the workers' fatigue, reduce their ability to carry out complex and dangerous operations, and have a negative impact on the worker´s health. The worker's promptness to respond to emergencies can be significantly worsened by both direct and indirect effects produced by external disturbances such as those characteristic of EE. EE affect operators directly by making the workers' operation more difficult and challenging as the abnormal features of EE negatively affect human operators (Newman and Lathan, 1999). Similarly, the indirect effect produced by EE is the increase of tiredness and distraction, leading to decreases in attention and concentration compromising the operators' efficiency and promptness. Another byproduct of the indirect effect by EE is the possible negative impact on situational awareness and teamwork (Nazir *et al.*, 2015). A straightforward example of distorted situational awareness is given by space activity, where, just to cite two items, the absence of gravity and the lack of external sounds play a key role in spatial orientation (*e.g.*, what is over and what is under) and environmental feedback (*e.g.*, the noise produced by friction and stiction of equipment cannot be used in extravehicular activity as clues for imminent failure) with a consequent alteration of situational awareness (Patrick and Morgan, 2010). Likewise, the lack of light coupled to high wind velocities and extremely low temperatures may severely affect the operations in Artic zones. However, the presence of EE can change across a work space. In the case of offshore platforms for crude oil extraction, where the extracted oil contains gases with high contents of hydrogen sulphide, the oil rig can feature separate safety zones (usually three) where people can live (i) without breathing masks, (ii) with breathing masks at hand, and (iii) donning breathing masks. Performing the same operation, either donning or not donning safety devices

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(such as a breathing mask or a protective overall), can make the difference in terms of endurance, comfort, agility, and weariness as well as affecting communication, vision and mobility (Bensel et al., 1987).

1.1 Operator training in extreme environments

Process/plant/equipment simulators often support training of industrial, maritime, and space operators where trainees learn how to perform specific operations either in the control room or in the field. At present, operator training simulators (OTS) mainly focus on the process/plant features in terms of equipment dynamics and units response but largely ignore the environmental factors that can alter the operating conditions and how the operators' actions and decisions are executed. Environmental conditions may radically impact, reduce, and impair the efficacy of operators' performance (Bensel *et al*., 1987). These critical points should be considered by trainers who shape the training activities of industrial operators before they go in the field and start working on real stuff (Saus *et al.*, 2010). The paper provides an overview of the role played by the temperature, pressure, wind, gravity, lighting, and harsh conditions on the performance of operators and of how these factors should shape the design of OTS for extreme environments.

2. Extreme environments

High/low temperatures and pressures, low oxygen contents (for aerobic organisms), high exposure to radiation, acid/basic/salty conditions, water deficiency, and presence of polluting/toxic substances are just a few examples of EE, which can be either limited to Earth or extended to outer space. The exposure of operators to EE may vary greatly from only seconds to days (*e.g.*, operators living and working at high altitudes for prolonged time). EE conditions may be somehow mitigated by specific clothes and wearable devices (*e.g.*, overalls, helmets, protective shields, earplugs, air bottles). At the same time, these devices may play a hampering role respect to normal operating conditions (Bensel *et al.,* 1987).

2.1 The role of temperature in EE

Both low and high temperatures are responsible for difficult life conditions of people living in extreme regions. Temperatures above 40 °C and below -20 °C characterize the places where to work can be life-threatening and where the operators must be protected from exposure to hazards. Operators may also work in abnormal environments where people do not live (*e.g.*, oceans, deserts, poles, high mountains, and space). High temperatures may be experienced also in or at artificial environments such as engine rooms, furnaces, and combustion engines. In case of polluted sites or support to antiterrorism chemical, biological, radiological, and nuclear threat, the ambient temperature may be even mild but the necessity to don specific sealed overalls amplifies the effect of discomfort due to the increase of transpiration and buildup of moisture in contact with skin. Similar arguments can be applied to operation in water (*e.g.*, rivers, lakes, seas, but also artificial ponds and basins) where heat dissipation is higher than on-land and therefore less extreme water temperatures may all the same lead to significant discomfort and fatigue. Table 1 reports the most extreme temperatures registered on Earth.

Table 1: Extreme temperature conditions officially and ever registered on Earth.

Condition	Place	Year	Temperature [°C]
Highest temperature	Furnace Creek in Death Valley (USA)	1913	56.7
Lowest temperature	Vostok Station (Antarctica)	1983	-89.2

Conversely, the thermal inertia of sea water is much higher than that of air. Indeed, Figure 1 shows how the zonal mean sea surface temperature ranges only 30 °C for hot/cold waters respect to 80 °C for hot/cold land temperatures as reported in Figure 2. It is worth observing how the extreme ranges of hot/cold air temperatures on Earth span a 140 °C interval (see also Table 1). The thermal inertia of water is also preserved with depth. The dependence of water temperature from sea depth is significant in the first 1000 m below the surface with drops of 20-25 °C and temperature profiles that asymptotically reach a value of 1-4 °C at greater depths. It is worth observing that in case of aquatic operations there is usually a dispersion of body heat as almost all seas are cooler than human-body temperature. Therefore, protective wet suits are highly recommended as soon as water temperatures fall below 15-18 °C. Conversely, the temperature profile of air versus altitude may be considered constantly decreasing as the adiabatic expansion gradient is -1 °C every 100 m of elevation for the whole troposphere (*i.e.* up to 18 km of elevation). The mesosphere, between 18 and 50 km altitudes, shows a reversed positive gradient. A further negative gradient is measured in the mesosphere up to 80-100 km altitudes. The air temperature decreases about 80 °C if one moves from sea level to the top of highest mountains. This decrease is definitely more significant than the one observed in the sea. Indeed, the Mariana trench in the western Pacific Ocean is the deepest in the world, at almost 11 km below sea surface, but the recorded temperature is just 1-4 °C.

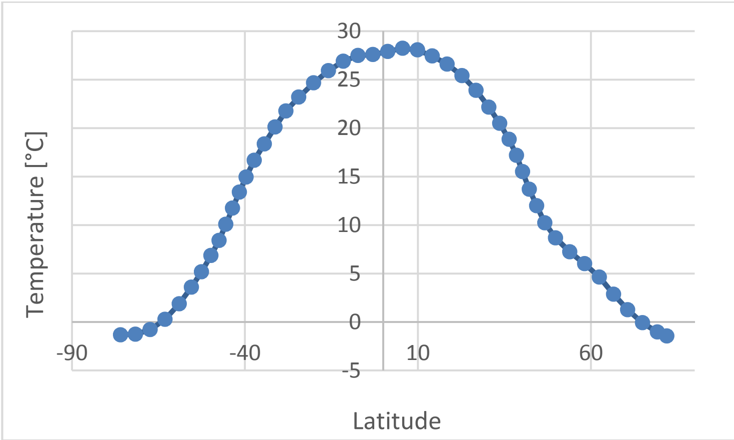

Figure 1: Mean sea surface temperature as a function of latitude (averaged values, Jan 1982- Dec 2011).

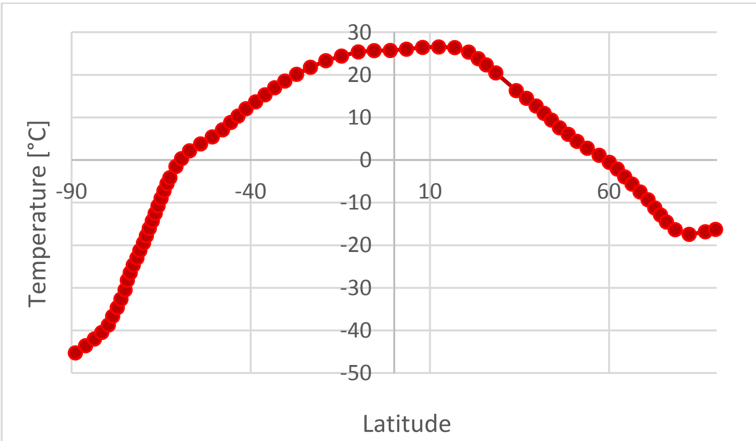

Figure 2: Air temperature at sea level as a function of latitude (averaged 2009 values).

2.2 The role of pressure in EE

Ambient pressure compresses or dilates the organism as a function of its positive or negative value respect to the internal body pressure. In addition, the atmospheric pressure modifies the air density, which decreases with elevation and produces a reduced supply of oxygen to lungs. For instance, at the top of Mount Everest at 8848 m the pressure can be as low as one third (*i.e.* 33.7 kPa) of that at sea level. The proportional decrease of air density with atmospheric pressure is responsible for breathing problems at high altitudes.

Apart from the so-called "death zone" at altitudes over 8000 m, even much lower altitudes may call for the adoption of special protective measures such as air bottles. For instance, the operators responsible for moving, configuring, and maintaining the equipment of the astronomical observatory in the Atacama Desert (Chile), at an altitude of 2635 m, don air bottles, as they have to carry out precision maneuvers and coordinate with team operators to position the telescopes array. The ambient pressure increases significantly whenever one plunges into water (*i.e.* 1 atm increase either every 10.33 m of suit water or 10.07 m of salty water). For instance, the pressure is 1072 atm at the Mariana trench. The linear dependency of pressure with depth calls for air bottles whenever one has to operate underwater. The gas-liquid equilibria between breathed air and blood is of paramount importance and embolism must be contrasted by suitably regulating the decompression procedure of divers. This issue plays a significant role in affecting the time a diver can operate at different depths, which is also a function of pressurized air and the percentage of breathed oxygen. As initially mentioned in the Introduction, space environments are characterized by the absence of atmosphere and consequently by a null pressure. The operation in space (*e.g.*, extravehicular activity) requires special overalls to compensate/regulate not only the absence of external pressure, but also the internal temperature, which is affected by the positive/negative radiative heat fluxes respectively exchanged with the sun and the vault of heaven.

2.3 The role of other elements in EE

A number of further effects play a primary role in making extreme the environments. This paper cannot devote enough space to them. However, for the sake of brevity, we can summarize the key issues of wind, gravity, light, harsh conditions, and noise. Winds amplify the effects of pressure and temperature on EE. Indeed, wind intensifies both mass and heat exchange fluxes. Likewise, high wind velocities produce significant drag forces that can impair the operators' work. Winds can also reduce visibility as in sand/snow storms. Reduced gravity is typically experienced in outer space activities/travels. In addition, (i) aeronautical pilots under free-fall maneuvers experience it shortly, and (ii) scuba divers are subjected to reduced gravity as they operate underwater. Excess of lighting (either natural or artificial) can produce asthenopia (*aka* eyestrain) with nonspecific symptoms such as fatigue, pain, blurred vision, and headache. Likewise, the absence/reduction of lighting, *i.e.* darkness reduces the operators' fitness. Besides reduced visibility, darkness can reduce the sense of direction and the proficiency to differentiate among objects. The direct effects of lack of proper lighting conditions are reduced/impaired consciousness, preparedness, and vigilance. Poor lighting may cause eye discomfort and headaches and thus reduce the operation efficiency. Harsh conditions (HC) are somehow connected to EE. They are either artificial environments or artificially induced situations that drive the operators far from standard working conditions. For instance, HC can be experienced in the engine room of a ship, in mines, in chemical plants with toxic atmospheres, and on oil platforms. HC can induce uneasiness, irritation, suffering, and troubles and limit the operators' capability to carry out ordinary tasks. HC can limit/diminish the situation awareness of workers, can affect their efficiency, and bring to slips and human errors. Industrial, maritime, and aviation activities often expose operators to loud and strident noises (*e.g.*, manufacturing, mining, aeronautics, construction, metallurgy, drilling, and wood/textile works). Exposure to loud noises has negative effects on several physiological systems. Indeed, the operators that work in noisy environments suffer from circulatory, digestive, metabolic, and neurological complications (Singh *et al.*, 1982). The operators that perform regular tasks breathe on average 12-18 times per minute although stress conditions increase the respiration rate. Oxygen decreases naturally with altitude and artificially in case of combustion processes, pollutants, and inert atmospheres. For instance, inert gases (*e.g.*, nitrogen) may replace oxygen to avoid the formation of flammable/explosive mixtures. In case of low oxygen content in the breathed atmosphere, the human body can rely on both short- and long-term adaptation methods. The partial pressure of oxygen decreases with elevation and is about half of the sea-level value at 5000 m and one third at 8848 m (i.e. at the top of Mount Everest). Low oxygen levels cause medical diseases such as mountain sickness and can be responsible for potentially fatal high altitude pulmonary and cerebral edema. The scientific literature describes high risks of permanent brain damage when operators work at extreme altitudes without donning air bottles.

3. Operators training in EE

Training operators for normal operating conditions has long been considered as a common practice in the industry with rapid development especially since last decade (Kluge et al., 2014). However, training simulators designed for tackling extreme conditions represent a relatively new concept. Operators can experience very atypical conditions in EE, which makes their coaching/training highly recommended if not mandatory respect to standard environments. If on one hand, it takes some time to train the operators for conventional operations, on the other hand, the time required to experience and understand EE is far higher and the coaching sessions become more challenging and demanding (as also shown in Figure 2). OTS cannot be simply modified to cover the nonconforming features of EE. Conversely, an in depth study of recommended features of OTS in EE is preparatory to release the specifications of dedicated software for this task. Most EE require the interaction/presence of both control-room and field operators. This is the case of industrial, maritime, aviation, and space operators. One could think that control-room operators are less exposed to EE than field operators are. If this is often true, nonetheless control-room operators must achieve a mental representation of EE so to cope with the limitations, requirements, and obligations that characterize the in-the-field operations. When the environment is changed from normal to extreme/harsh, the physical and mental workload of the operators required to perform simple tasks increases manifold. Unfortunately, such challenges are ignored in current training practices, which are mostly focused on normal operations. At the most, some emergency scnerios are simulated in training phase, which can not gurantee appropriate training for EE. The importance of simulating industrial accidents by advanced OTS was discussed in Brambilla and Manca (2011) and Nazir and Manca (2014). This allows training operators to cope with abnormal, near misses, and real accidents (Manca *et al.*, 2012). Brambilla and Manca (2011) listed a few technical specifications focused on the simulation of liquid/gas emissions, pool spreading/shrinking, evaporation, gas dispersion, ignition, pool fire, and heat radiation.

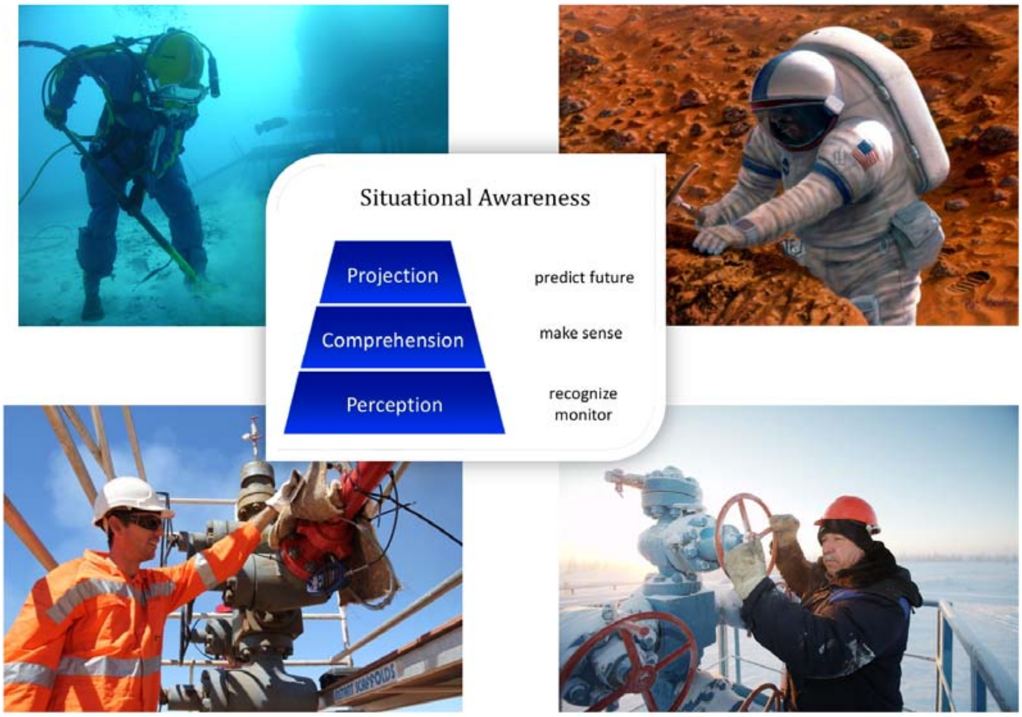

Figure 2: Extreme environments (underwater, space, very hot, and very cold sites) can significantly modify the situational awareness of field operators, alter their understanding and representation of surrounding equipment, and degrade their capability to carry out the requested tasks.

Afterwards, Nazir *et al.*, 2012b, examined the need for training field operators with the support of specific tools such as virtual reality in 3D immersive environments. Manca *et al.*, 2012 discussed also the benefits produced by augmented virtual reality, which is a promising support to enhance the situational awareness of field operators and perfect the workers' perception of the environment and equipment where they operate. These elements can be used as the foundations to design OTS targeted to EE. We suggest naming such simulation tools as ETS, *i.e.* Extreme Training Simulators. ETS may be used to allow operators adapt to working in EE, to facilitate physiological and psychological adaptation and also adapt to working with protetive clothing. Immersivity is a key feature that must be inherited from advanced 3D OTS so to induce stress in the operators and make them live a realistic experience of what may happen in EE. A preliminary analysis for the design of ETS should select the so-called "stressors", which characterize the EE and make them different from the conventional environments. A priority list should identify the stressors that are more able to play a role in the formation of operators and affect both individual and distributed situational awareness (Nazir *et al.*, 2012a). Once this priority list is defined and accepted, it is possible to select the features to be implemented in the ETS according to a cost-benefit criterion. It is worth observing that it can be more problematic to implement some stressors as they depend on the intrinsic characteristic of the training laboratory where they will be installed/operated. For instance, it may be complex and expensive to simulate, reproduce, and implement elements such as thermal, mechanical, and gravity stressors. Objectively, some extreme conditions are more difficult to implement than others are. Indeed, most of the difficult-to-implement stressors are centered on physical qualities and cannot be simulated only within a virtual reality environment. Actually, such stressors call for the implementation/reproduction of real features such as air temperature, humidity, oxygen, wind, and ambient pressure. On the contrary, it is easier and cheaper to simulate/implement noise, reduced visibility, and darkness. Likewise, extreme temperatures and humidity can be reproduced and even amplified by personal protective devices (*e.g.*, sealed overalls, breathing masks).
The ETS design should be based on an accepted priority list and implemented using a relevant subset of the possible stressor elements. As a case example, we propose a few stressor elements and their implementation for work in chemical processing facilities in hot, windy, and humid environments with significant vibrations.

- Visual stressors: light, weather, harsh conditions, and reduced visibility could be implemented in the IVR environment and experienced by the trainees with head-mounted displays.
- Audio stressors: the sounds of the process equipment, other loud and strident noises, and the weather

effects could be implemented in the IVR environment by using stereoscopic headsets.

- Mechanical stressors: physical work including walking, running, crouching, jumping, rotation and vibration could be implemented by using omnidirectional treadmill.
- Wind stressors: a set of directional fans could be used to simulate the effect of wind.
- Thermal stressors: a set of infrared lamps could be used to simulate the effect of heat sources (*e.g.*, sun, fire, ambient temperature, radiative chambers, furnaces, kilns).
- Pressure and humidity stressors: humidity and air pressure changes could be implemented by using training garment with embedded HVAC (*i.e.* Heating, Ventilating and Air Conditioning) features.
- In order to keep the implementation costs as low as possible, low-cost, commercially available equipment should be considered.

Further research work is needed to optimally design the stressors, and deploy the ETS equipment for the reproduction of the EE experience. The design of optimal learning strategies and the implementation and testing of realistic training scenarios in ETS represent further challenges to achieve a consistent product.

4. Conclusions

The exploitation of resources (*e.g.*, raw materials) in unconventional and difficult-to-live places on Earth is just one of the reasons that make EE relevant. More in general, the term EE gathers not only natural environments but also artificial ones and can be extended to outer space. The atmospheric and operating conditions of EE are quite challenging and call for a high level of training by the involved operator. The intrinsic limitations of conventional OTS must be overcome by means of a dedicated design and implementation of simulation tools capable to introduce the stressors inside the training procedure so to accustom the operators and make them ready for real operations. Trainers have to redesign the training sessions to cope with the features of EE and allow the trainees to become experts of those demanding operating conditions. In addition, the assessment of operators in EE must be rethought to cope with the challenges proposed by these environments.

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