Scientific Research Publishing

**Open Journal of Safety Science and Technology, 2026, 16(1), 14-34**
https://www.scirp.org/journal/ojsst
ISSN Online: 2162-6006
ISSN Print: 2162-5999

# Industrial Hygiene in Virtual Reality Training Labs: A Tiered Exposure-Risk and ARECC Framework

**Riley Williams**

Independent Researcher, Calera, USA
Email: riley.denae.williams@gmail.com

**How to cite this paper:** Williams, R. (2026) Industrial Hygiene in Virtual Reality Training Labs: A Tiered Exposure-Risk and ARECC Framework. *Open Journal of Safety Science and Technology*, **16**, 14-34.
https://doi.org/10.4236/ojsst.2026.161002

**Received:** December 9, 2025
**Accepted:** January 10, 2026
**Published:** January 13, 2026

## Abstract

Virtual reality (VR) is increasingly used for occupational safety and health (OSH) training, yet the VR laboratory itself is seldom treated as an exposure environment requiring systematic industrial hygiene management. This paper proposes a conceptual framework that applies the Anticipate, Recognize, Evaluate, Control, and Confirm (ARECC) model to VR training labs, treating them as multi-hazard workplaces with physical, chemical, biological, ergonomic, electrical, and psychosocial exposures. The framework integrates a tiered exposure-assessment strategy ranging from qualitative screening to semi-quantitative scales and quantitative, sensor-based monitoring with engineering, administrative, and data-governance controls tailored to immersive environments. Real-time environmental, biomechanical, and physiological data streams from sensors, wearables, and eye tracking systems are used to construct multi-domain exposure profiles and to verify the effectiveness of control measures. The application of the framework is demonstrated through a VR confined-space entry training scenario in an industrial setting, showing how it can inform design decisions, operational policies, and continuous improvement across VR lab implementations. The paper concludes with implications for research and practice, highlighting needs for standardized VR-specific exposure metrics, empirical validation of the framework across sectors, and development of guidance that aligns VR training facilities with contemporary exposure-risk management principles.

## Keywords

Virtual Reality, Industrial Hygiene, Ergonomics, Safety, Psychosocial Hazards

## 1. Introduction

Immersive virtual reality (VR) systems are increasingly embedded in occupational safety and health (OSH) training across industries including construction, mining, manufacturing, transportation, and healthcare. Over the past several years, multiple reviews and empirical studies have shown that VR-based training can improve hazard recognition, procedural knowledge, and learner confidence compared with traditional lecture or slide based instruction, particularly for high risk and low frequency events such as confined space emergencies, chemical releases, or major equipment failures [1]. Recent work also suggests that VR can enhance knowledge retention and transfer by enabling realistic rehearsal of hazardous scenarios in a controlled environment, while supporting experiential and adult learning principles [2]. At the same time, regulatory and professional bodies generally treat VR as a supplement rather than a replacement for hands-on, job-specific instruction, emphasizing that training programs must still meet existing performance and competency requirements in the real workplace.

Despite these benefits, the rapid diffusion of VR into OSH training has outpaced the development of systematic frameworks for managing health and safety risks within the VR laboratories and training rooms themselves [3]. Reports from educational, industrial, and clinical deployments consistently highlight familiar adverse effects: cybersickness (including nausea, disorientation, and headaches), eye strain, balance disturbances and falls, musculoskeletal discomfort from awkward postures or heavy head-mounted displays, and psychological strain when scenarios depict highly realistic accidents or emergencies [4]. In addition, VR labs share many of the same hazards as conventional laboratory spaces such as electrical and fire risks from dense electronic equipment, trip hazards from cables and furniture, exposures to cleaning and disinfection agents used on shared headsets, and infection risks associated with high-touch surfaces [5]. Current literature and vendor guidance typically address these concerns through lists of practical precautions (for example, clearing play spaces, scheduling breaks, or screening users with certain medical conditions), but they rarely embed VR training environments within a formal occupational hygiene process [3].

In parallel, occupational hygiene and exposure science are undergoing their own transformation driven by real-time sensing, wearables, and analytics [6]. Direct-reading instruments, networked environmental sensors, and smart personal protective equipment increasingly enable continuous monitoring of physical and chemical agents, while advances in biomechanical sensing and physiological monitoring allow ergonomic and psychosocial exposures to be quantified at a level of detail that was not previously feasible [6] [7]. Professional frameworks now emphasize tiered, exposure-risk assessment and management cycles that integrate qualitative judgment, structured semi-quantitative tools, and quantitative data from direct-reading sensors, with explicit steps for verification and communication of control effectiveness [8]. However, these developments have largely been conceptualized for traditional industrial operations, laboratories, and field work, not for mixed digital–physical environments such as VR training labs.

The widespread adoption of VR for safety training and the maturation of sensor-enabled industrial hygiene creates both an opportunity and a gap. On one hand, VR technology offers powerful tools for simulating hazardous work, visualizing otherwise invisible exposures, and rehearsing safe behaviors [1]. On the other hand, the VR lab itself functions as an exposure environment where users, instructors, and technical staff may accumulate physical, ergonomic, and psychosocial loads that are seldom measured or managed systematically [3]. Existing work on "metaverse" and extended-reality applications in occupational health has begun to catalogue potential risks and ethical concerns, particularly around fatigue, cognitive overload, and intensive data collection, but has not yet articulated how these environments should be governed using established industrial hygiene principles [9].

This article proposes a conceptual framework that applies the Anticipate, Recognize, Evaluate, Control, and Confirm (ARECC) model to VR training labs [10]. The framework treats the VR lab as a multi-hazard workplace and integrates tiered exposure assessment with real-time sensor technologies to support evidence-based control of physical, chemical, biological, ergonomic, electrical, and psychosocial hazards. In this context, the framework adopts an expanded view of "exposure" that goes beyond traditional chemical and physical agents to include the ergonomic, cognitive, and psychosocial loads generated by immersive VR tasks and interfaces. By treating cybersickness, visual fatigue, cognitive overload, and stress responses as exposure domains alongside physical, chemical, biological, and electrical hazards, the model aligns VR labs with contemporary Total Worker Health (TWH) programs in industrial hygiene [11]. The aims of the paper are threefold: 1) to synthesize emerging evidence on VR-related health and safety risks and on sensor-based exposure assessment relevant to VR labs; 2) to adapt and extend contemporary exposure-risk management concepts into a structured model suitable for academic, industrial, and clinical VR training environments; and 3) to illustrate the application of this model through a worked example and practical design and operational guidance. By reframing VR safety training spaces as managed exposure environments subject to the ARECC process, the framework seeks to support safer and more sustainable adoption of immersive technologies in occupational safety and health practice.

## 2. Theoretical Foundations

### 2.1. ARECC

The contemporary industrial hygiene paradigm of ARECC formalizes exposure-risk management as a cyclical process in which practitioners anticipate potential hazards, recognize those that are present, evaluate exposures, implement controls, and then confirm effectiveness [10]. Recent guidance emphasizes that ARECC should integrate qualitative judgment, structured semi-quantitative tools, and quantitative exposure data, with explicit verification that control strategies achieve risk-reduction objectives. Applying ARECC to VR labs positions these environments within mainstream occupational hygiene practice rather than treating them as purely educational or technological domains.

### 2.2. Exposure-Risk Assessment and Tiered Strategies

Modern exposure-risk assessment frameworks promote tiered strategies that begin with qualitative screening and progress, as needed, to semi-quantitative and fully quantitative assessment [8]. Qualitative tiers rely on scenario analysis, checklists, and expert judgment to classify exposure potential, while higher tiers incorporate standardized scoring tools, exposure models, and direct-reading measurements to refine estimates and characterize uncertainty. These approaches are increasingly linked to risk-based decision-making, in which resource-intensive monitoring and controls are reserved for tasks, agents, or populations with greater potential for harm. Translating this logic to VR labs supports a scalable evaluation process that can grow with program maturity, allowing institutions to start with structured screening and move toward sensor-rich quantitative assessment as evidence or resources justify.

### 2.3. Metaverse and VR in Occupational Health

The emergence of the "metaverse" and extended-reality technologies has prompted new attention to occupational health risks and opportunities in immersive environments [9]. Recent reviews highlight applications of VR and related technologies for hazard visualization, safety training, remote collaboration, and rehabilitation, while also noting concerns about cybersickness, fatigue, cognitive overload, privacy, and psychosocial effects [1] [4] [5]. Regulators and professional agencies have begun to discuss how immersive visualization tools can be integrated safely into workplaces, underscoring the need to apply established OSH principles rather than developing entirely separate frameworks. However, most existing work conceptualizes VR primarily as a medium for representing external workplaces or for delivering training content, rather than as a physical–digital workplace where exposures occur and must be managed [1]. This theoretical gap motivates the present framework, which treats the VR lab itself as an occupational setting subject to structured exposure-risk management.

### 2.4. Sensor-Based Industrial Hygiene and Real-Time Monitoring

Rapid advances in direct-reading instruments, networked environmental sensors, and wearable technologies have transformed what industrial hygienists can observe in real time [6]. Parallel developments in smart personal protective equipment (PPE), inertial measurement units (IMUs), and physiological monitoring enable detailed characterization of ergonomic loads and physiological strain during work tasks, including heart-rate dynamics, motion profiles, and posture metrics [7]. These sensor-based approaches provide the conceptual and technical foundation for the quantitative tier of the VR-lab framework, where environmental conditions, biomechanical demands, and psychophysiological responses are treated as measurable exposures. Embedding such technologies within the ARECC cycle allows VR labs to function as data-rich testbeds for exposure-risk management, with monitoring outputs directly informing scenario design, lab configuration, and administrative controls.

## 3. Conceptual Framework

This section presents the conceptual framework for industrial hygiene in VR labs, integrating 1) the VR lab as a multi-hazard workplace, 2) the ARECC process, 3) a tiered exposure-assessment strategy, and 4) real-time sensor and analytics integration. Together, these elements form an iterative model for designing, operating, and evaluating VR training environments as managed exposure settings rather than purely educational spaces.

### 3.1. VR Lab as a Multi-Hazard Workplace

The framework begins by treating the VR training lab as a distinct workplace in which users, instructors, and support staff may be exposed to physical, chemical, biological, ergonomic, electrical, and psychosocial hazards during normal operation. Physical hazards include trips, slips, and collisions arising from dense equipment layouts, cable runs, and the mismatch between perceived and actual spatial boundaries, which have been flagged repeatedly in VR safety training studies [5]. Chemical and biological hazards stem from frequent disinfection of shared headsets and controllers, off-gassing from plastics and cleaning products in enclosed rooms, and contamination of high-touch surfaces, paralleling concerns in simulation centers and shared laboratory spaces [12]. Ergonomic hazards arise from the weight and fit of head-mounted displays, constrained movement areas, and repetitive or awkward postures, while electrical hazards relate to high equipment density, extension cords, and power strips [13]. Psychosocial hazards encompass cybersickness, visual fatigue, cognitive overload, and stress responses to realistic accident or emergency scenarios, all of which have been documented in recent reviews of VR and metaverse applications in occupational health [4]. Conceptualizing the VR lab as a multi-hazard workplace justifies the application of industrial hygiene approaches and aligns VR training environments with other occupational settings subject to exposure-risk management.

### 3.2. ARECC as the Core Process

Within this workplace framing, the ARECC model (anticipate, recognize, evaluate, control, and confirm) serves as the organizing process for managing exposures [10]. In the anticipate phase, planners perform a structured front-end review before systems are installed or training begins, drawing on scenario design, equipment specifications, and user population characteristics to forecast potential hazards [14]. Scenario design is examined to determine how virtual tasks, movements, and stimuli translate into real-world exposures: user actions such as walking, reaching, bending, rapid head turns, and emergency drills are mapped to potential physical and ergonomic hazards (trips, collisions, overreaching, awkward postures, repetitive movements) and to psychosocial stressors (graphic incident content, time pressure, high cognitive load) [15]. Visual and motion parameters—including field of view, locomotion method, and motion intensity—are evaluated for their likelihood of provoking simulator sickness, eye strain, or anxiety, with scenario variants or limits planned for sensitive populations [13].

Equipment selection is similarly reviewed not only for functionality but also for inherent exposure potential. Headsets, controllers, treadmills, haptics, and tracking systems are evaluated for weight, center of gravity, adjustability, and strap or handle design to anticipate ergonomic strain and skin-contact issues, while material composition and cleaning requirements are examined for compatibility with disinfectants and for risks related to off-gassing and microbial contamination of shared surfaces [12] [15]. Power supplies, cabling, and network hardware are assessed for electrical and physical hazards, including cable routing, trip risks, heat generation, and compatibility with protective devices and fire-safety systems [5]. User population characteristics—such as age, health status, motion-sickness susceptibility, and psychological vulnerability—are considered to anticipate how different groups may experience and amplify hazards, informing the need for medical screening, modified content, and alternative training pathways [14].

The recognized phase operationalizes this anticipation using structured tools to identify hazards that are actually present. VR-lab safety checklists, pre-use inspections, and expert walk-throughs are used to verify floor conditions, cable routing, equipment placement, ventilation, and hygiene practices [8]. Scenario-specific pilot sessions provide observational data on near-misses, posture extremes, balance losses, and visible distress, while post-session symptom questionnaires capture cybersickness, visual fatigue, and perceived workload, echoing methods reported in VR safety training evaluations [8]. These recognizing activities feed into the evaluate step, which is implemented via tiered exposure assessment, and into the control step, where engineering, administrative, and data-governance controls are selected and refined [10]. The confirm phase then uses monitoring results, incident reports, and user feedback to verify the effectiveness of controls and to disseminate lessons learned to stakeholders, reinforcing the cyclical nature of ARECC.

### 3.3. Tiered Exposure Assessment

The evaluation function is structured as a tiered exposure-assessment approach that can scale with laboratory maturity and resources. The main elements of this tiered structure are summarized in **Table 1**, which outlines representative tools, data outputs, and decision triggers at each level of assessment. At Level 1 (qualitative assessment), structured screening tools such as checklists, expert walkthroughs, and scenario-based reviews, are applied to classify exposure potential for each hazard category as low, medium, or high. This tier mirrors qualitative screening and control-banding strategies in occupational hygiene, where the priority is to rapidly identify tasks and scenarios that warrant additional analysis while limiting the need for instrumentation [8]. Level 1 may rely on brief pilot sessions with small groups of users, during which observers note near-misses, obvious strain, and early signs of cybersickness, supplemented by short symptom logs or comfort questionnaires. Outputs are summarized in scenario-by-hazard matrices that guide decisions about whether to proceed to Level 2 or implement immediate low-cost controls.

**Table 1.** Tiered exposure-assessment strategy for VR training labs.

| Tier | Primary purpose | Typical methods and tools | Data outputs | Example decision actions |
|---|---|---|---|---|
| Level 1 (Qualitative Assessment) | Rapidly screen VR scenarios and lab configurations to classify exposure potential by hazard category (physical, chemical, biological, electrical, psychosocial) as low/medium/high | Structured safety checklists; expert walkthrough; scenario task analyses; short pilot sessions with observational notes; brief symptom or comfort checklists. | Narrative descriptions of hazards; categorical rates (low/medium/high) for each hazard type per scenario; matrices linking scenarios to hazard ratings. | Identify scenarios needing immediate low-cost controls; decide whether to escalate a scenario or hazard category to Level 2; prioritize scenarios for redesign or monitoring. |
| Level 2 (Semi-quantitative Assessment) | Refine exposure estimates for scenarios or hazard domains flagged a Level 1 using standardized scales and limited measurements, enabling comparison across scenarios and user groups. | Simulator Sickness Questionnaire; workload and stress scales, ergonomic screening tools; short environmental spot measurement ($CO_2$, temperature humidity, noise); small-sample pilot runs. | Numeric scores and bands (e.g., symptom indices, workload scores, ergonomic risk scores); short-duration exposure metrics (e.g., peak $CO_2$, sound levels); semi-quantitative risk rankings. | Decide if engineering or administrative controls are sufficient; determine if Level 3 monitoring is warranted; compare alternative scenario designs; set provisional exposure thresholds. |
| Level 3 (Quantitative Assessment) | Develop detailed exposure time profiles for high priority scenarios and populations using continuous or high frequency data, supporting evidence-based control design and verification. | Fixed or portable environmental sensors ($CO_2$, VOCs, temperature, humidity, noise); wearables and tracking systems for posture, motion, and workload; biometric monitoring (heart rate, heart rate variability, skin conductance); VR-integrated eye tracking and usage analytics. | Time-stamped exposure curves for environmental, biomechanical, and psychophysiological indicators; peak and cumulative exposure metrics by scenario and user group; modeled relationships between scenario elements and exposure outcomes. | Optimize scenario design (e.g., motion profiles, task difficulty); reconfigure lab layout and ventilation; set or adjust length and peak policies; refine screening criteria and at-risk group protections; confirm effectiveness of controls in the ARECC cycle. |

At Level 2 (semi-quantitative assessment), standardized scoring systems and limited spot measurements provide more structured evidence. Tools such as the Simulator Sickness Questionnaire, workload scales (for example, NASA-TLX), stress or anxiety inventories, and ergonomic screening instruments generate numeric scores that can be compared across scenarios and user groups [16] [17]. Short-duration environmental measurements—such as spot checks of $CO_2$, temperature, humidity, and noise during peak use—are used to identify conditions approaching or exceeding institutional targets. These semi-quantitative data refine exposure classifications and support risk-based decisions about whether a scenario requires engineering modification, administrative controls, or escalation to Level 3 monitoring. The approach aligns with macro-level health and safety evaluation models that integrate subjective and objective indicators within a structured scoring framework.

Level 3 (quantitative, real-time monitoring) is reserved for scenarios, user groups, or hazard domains where Level 1 - 2 assessments indicate higher risk or greater uncertainty. At this tier, detailed quantitative data are collected and modeled, borrowing concepts from established occupational exposure modeling approaches but extending them to encompass ergonomic and psychosocial domains in VR labs [8]. Continuous or high-frequency data enable construction of exposure-time profiles for environmental conditions, biomechanical loads, and psychophysiological responses, which can then be analyzed for peaks, cumulative doses, and associations with scenario elements or user characteristics [18]. This tiered structure allows institutions to start with low-resource tools and progressively adopt more intensive monitoring as evidence and capacity justify, reflecting best practice in exposure-risk assessment.

### 3.4. Real-Time Sensors and Analytics

Real-time sensor and analytics integration operationalize the upper tiers of the framework and is central to its innovation for VR labs. The specific environmental, biomechanical, and biometric data streams used at these upper tiers are outlined in **Table 2**, along with example metrics. Environmental sensors track parameters such as air quality, temperature, humidity, and noise within and around the VR space, providing continuous records that reveal patterns not captured by occasional spot checks. For example, $CO_2$ measurements can indicate inadequate ventilation during high-occupancy periods, while acoustic monitoring can highlight short noise peaks associated with alarms or intense scenario segments that may require sound-level adjustments.

Wearables and tracking systems capture motion, posture, and physical workload in real time [18]. Inertial measurement units, smart garments, and existing VR tracking data can be used to quantify joint angles, repetition rates, walking distances, and acceleration peaks, enabling calculation of ergonomic exposure metrics such as cumulative time in non-neutral postures or frequency of rapid rotational movements. These metrics translate classical ergonomic risk concepts into the VR context and complement observational scoring conducted at lower tiers.

Biometric indicators—heart rate, heart rate variability, and skin conductance combined with VR-integrated eye tracking and usage analytics reflect physiological and cognitive strain during VR sessions [19]. Time-aligned with scenario events, these data can reveal segments that systematically elicit high arousal, disorientation, or visual fatigue, which have been linked to cybersickness, degraded performance, and reduced training effectiveness. Real-time analytics can then support dynamic control decisions, such as modifying camera motion, adding rest breaks, adjusting task complexity, or changing guardian boundaries, to keep exposure indicators within acceptable ranges.

Table 2. Real-time sensors and analytical components in VR training labs.

| Components | Example technologies | Primary exposure dimensions captured | Typical metrics | How data are used in the framework |
|---|---|---|---|---|
| Environmental sensors | Wall or ceiling $CO_2$ probes; VOC sensors; temperature and humidity loggers; integrated sound level meters. | Physical environment: ventilation adequacy, thermal comfort, chemical by-products, and noise in and around the VR space. | Time-stamped $CO_2$ and VOC concentrations; temperature and humidity traces; A-weighted sound levels and peaks during scenarios. | Identify periods or scenarios with inadequate ventilation, heat buildup, or high noise; trigger engineering changes (HVAC adjustments, equipment redistribution, alarm volume tuning) and verify their effectiveness in the ARECC "Confirm" step. |
| Wearables and motion tracking | Inertial measurement units (IMUs); smart garments; smart PPC; VR system pose tracking data exported for analysis | Ergonomic and physical workload: posture, joint angles, movement velocities, repetition rates, and walking distances during VR scenarios. | Cumulative time in non-neutral postures; frequency of high-velocity turns; step counts and path length; repetition counts for key motions. | Quantify ergonomic loads for specific scenarios and user groups; compare designs and lab layouts; inform engineering and administrative controls such as scenario redesign, play-area reconfiguration, and session length limits. |
| Biometric monitoring | Heart rate and heart rate variability sensors (chest straps, optical wearables); skin conductance sensors integrated into bands or controllers. | Physiological strain and arousal: autonomic responses to VR content, workload, and environmental conditions. | Heart rate profiles; variability indices; skin conductance peaks and tonic levels aligned with scenario events and tasks. | Detect segments that systematically elicit high physiological strain or cybersickness; adjust scenario pacing, intensity, and break schedules; refine screening criteria for at-risk populations. |
| Eye tracking and usage analytics | Headset integrated eye-tracking cameras; VR platform logs of gaze, interactions, and scenario progression. | Visual and cognitive load: gaze allocation, visual search behavior, fatigue indicators, and interaction patterns during training. | Fixation durations and locations; saccade rates; blink frequency; pupil size trends; error rates and time on task per scenario segment. | Identify visually demanding or confusing elements, regions of neglected hazards, and high workload segments; guide content redesign and instructional support while monitoring for visual fatigue and cognitive overload. |
| Integrated analytics and dashboards | Data pipelines and analytic dashboards that synchronize environmental wearable, biometric, and usage data with scenario timelines. | Multi-domain exposure profile: combined view of physical, ergonomic, and psychosocial indicators over time. | Scenario-specific exposure profiles; peak and cumulative indices across domains; flags for threshold exceedances; comparative reports across scenarios and cohorts. | Support evidence-based decisions across the ARECC cycle by prioritizing scenarios for control, evaluating control effectiveness, and communicating results to stakeholders as part of continuous improvement in VR lab design and operation. |

Overall, the framework integrates these four elements into an iterative model: the VR lab is conceptualized as a multi-hazard workplace; the ARECC cycle structures how hazards are systematically managed; exposure evaluation proceeds in tiers from qualitative to sensor-driven quantitative assessment; and real-time data and analytics supply ongoing feedback that drives refinement of controls and training design. This positions VR safety training not only as an educational intervention but as a managed exposure environment subject to modern industrial hygiene and exposure-risk management principles, with continuous improvement supported by data-rich feedback loops.

## 4. Application of the Framework: VR Confined Space Entry Training in an Industrial Setting Scenario

To illustrate application of the framework, consider a hypothetical VR training laboratory at an industrial plant that uses immersive modules to train maintenance workers on permit-required confined-space entry into large process vessels. The main module would simulate pre-entry checks, atmospheric testing, permit review, controlled entry, and emergency evacuation. Trainees would stand and move within a 3 m × 3 m tracked area while wearing a head-mounted display and hand controllers, navigating a virtual vessel interior that requires crouching, turning, and maneuvering through manways. In this hypothetical example, the VR lab is treated as an occupational setting in which trainees, instructors, and technical staff could experience physical, ergonomic, electrical, chemical/biological, and psychosocial exposures during routine operation.

### 4.1. Application of ARECC

The ARECC process is used as the organizing framework for describing what the systematic assessment.

#### 4.1.1. Anticipate

In the design phase, a multidisciplinary team would review the planned scenario, hardware, and user population to anticipate potential hazards. The team may identify:

- Physical hazards such as trips and collisions associated with furniture, room boundaries, and tethered headsets.
- Ergonomic hazards including prolonged standing, trunk flexion when simulating crawling through manways, and rapid turning during emergency evacuations.
- Electrical hazards related to cable entanglement and power distribution to desktop computers and displays.
- Psychosocial hazards stemming from high intensity, alarm-triggered emergencies and realistic incident simulations.
- Chemical/biological hazards from frequent disinfection of shared headsets and controllers and contamination of high touch surfaces.

These anticipated hazards would guide the choice of recognition tools and evaluation instruments.

#### 4.1.2. Recognize

Before full deployment, the team could apply a structured safety checklist and scenario-based task analysis. The checklist would cover room layout, cable routing, equipment placement, ventilation, and hygiene practices, while the task analysis would map user movements (stepping, bending, turning) and sensory demands (visual conditions, alarm characteristics) for each scenario phase.

The team might then run two short pilot sessions with a small group of experienced workers (e.g., n = 4). Observers would record near-misses, posture extremes, and visible signs of discomfort, and participants would complete a brief symptom checklist after each session. These recognition activities would provide initial qualitative risk ratings by hazard category and indicate which domains merit more detailed assessment.

### 4.1.3. Level 2 (Semi-Quantitative Evaluation)

For Level 2 assessment, the team could invite 10 maintenance workers to complete the confined-space module once under standard conditions. Four domains would be evaluated:

1) Ergonomics: A posture scoring tool would be applied to video recordings of the five most physically demanding minutes for each worker, focusing on trunk flexion, reach distance, and duration of non-neutral postures.

2) Simulator sickness: A Simulator Sickness Questionnaire (SSQ) would be administered immediately before and after each session to calculate total, nausea, and disorientation scores.

3) Workload and stress: NASA Task Load Index (NASA-TLX) ratings would be collected, with particular attention to physical demand, effort, and frustration during emergency segments.

4) Environmental conditions: Spot measurements of A-weighted sound levels near the headset during alarm sequences and short-duration $CO_2$ readings during back-to-back sessions would characterize ventilation and noise under typical occupancy.

Prior to data collection, the team would define cut points for each instrument (e.g., banded posture scores, SSQ change thresholds, NASA-TLX percentiles, and site guidance values for noise and $CO_2$) to determine when escalation to Level-3 monitoring is warranted.

### 4.1.4. Level 3 (Quantitative Assessment)

If Level-2 results suggested elevated risk in specific domains, a subset of sessions (for example, eight emergency-focused runs) could be instrumented for detailed monitoring. Planned measurements might include:

1) Environmental: Continuous logging of $CO_2$ concentration, temperature, and A-weighted sound levels throughout each session.

2) Biomechanical: Inertial measurement units (IMUs) on the trunk and upper arms to capture joint angles, movement velocities, and repetition counts.

3) Physiological and gaze: Wearable sensors for heart rate and skin conductance, plus the VR system's integrated eye-tracking to capture gaze position and blink rate.

All streams would be time synchronized with scenario events (alarm onset, gas monitor readings) to support exposure profiling.

### 4.1.5. Control and Confirm

Based on the hypothetical ARECC evaluation, the team would design engineering, administrative, and data-governance controls (for example, room reconfiguration, scenario adjustments, session-length limits, enhanced screening, and de-identification of biometric data). A follow-up Level-2 assessment with a new cohort, scheduled several months later, would be used to confirm effectiveness by comparing key indicators before and after control implementation.

## 4.2. Hypothetical ARECC Results

In this hypothetical application, checklist and task-analysis activities, combined with pilot observations, suggest that physical and ergonomic hazards are concentrated near the rear of the play area and during simulated entry and evacuation phases. The two pilot sessions reveal repeated near-misses with a chair positioned behind the user and frequent bending at the waist when trainees "enter" the virtual vessel. Brief symptom checklists indicate that several participants experience mild to moderate nausea and disorientation, while no acute electrical or fire issues are observed. On this basis, the team classifies physical and ergonomic hazards as "medium" and psychosocial exposure linked to emergency segments as "medium," while electrical and environmental hazards are initially rated "low." These qualitative ratings trigger a decision to proceed to Level-2 evaluation for the ergonomic and psychosocial domains.

### 4.2.1. Level 2 Findings

Under the hypothetical Level-2 assessment, posture scoring shows that trainees spend a notable fraction of the five-minute analysis window in moderate trunk flexion, with occasional awkward reaches required to interact with virtual controls and inspection points. Although extreme postures are rare, the duration of flexion suggests that cumulative musculoskeletal load could be meaningful over repeated training days.

SSQ scores increase from pre- to post-session for several workers, particularly in nausea and disorientation subscales, indicating that the scenario has the potential to induce cybersickness in susceptible individuals. NASA-TLX ratings indicate moderate–high physical demand and effort, and frustration scores are highest during emergency evacuation segments when alarms sound and virtual gas monitors display hazardous readings.

Spot environmental measurements show that alarm sequences briefly approach 80 dBA at the headset, while $CO_2$ readings increase during back-to-back sessions but remain below institutional concern thresholds. Applying predefined criteria, the team rates ergonomic and simulator-sickness categories as "medium–high," while environmental risk remains "low–medium." These results lead to a hypothetical decision to escalate to Level-3 monitoring focused on emergency phases of the scenario.

### 4.2.2. Level 3 Findings

In the hypothetical Level 3 phase, continuous environmental monitoring reveals a gradual increase in $CO_2$ concentration over the training day and short, distinct noise peaks aligned with alarm events, all within relevant guidance values. These patterns confirm that emergency segments are the dominant contributors to acoustic and ventilation load, even though absolute levels remain acceptable.

IMU data indicate that trainees spend a substantial portion of session time with trunk flexion greater than 30˚, particularly during entry and evacuation sequences. Motion traces also show clusters of rapid turns and lateral steps executed in quick succession when alarms are triggered, which could plausibly contribute both to balance disturbances and to additional musculoskeletal strain.

Physiological monitoring shows clear peaks in heart rate and skin conductance during simulated emergencies, especially at alarm onset and when virtual gas monitors indicate dangerous readings. Eye-tracking data for the same intervals reveal scattered gaze patterns, more frequent blinks, and transient loss of fixation on task-relevant cues, consistent with elevated cognitive load, stress, and visual strain. Taken together, these hypothetical Level 3 findings support the conclusion that the emergency portion of the confined-space scenario concentrates both ergonomic and psychosocial/physiological demands, while environmental and electrical conditions remain comparatively well controlled.

#### 4.2.3. Control and Confirm

On the basis of these hypothetical findings, the team would introduce targeted engineering, administrative, and data-governance controls. Engineering measures might include removing the chair from the active play area, installing a soft barrier behind the user, widening virtual passages to reduce required trunk flexion, and lowering and retuning alarm sound levels. Administrative policies could set a maximum session length of 20 minutes with mandatory 10-minute breaks, limit trainees to two sessions per day, add standardized pre-session briefings on symptoms and stop rules, and strengthen screening for prior motion sickness or severe anxiety. Data-governance measures would likely require de-identification of biometric and gaze data, short retention periods for raw traces, and explicit consent language emphasizing that data are used for exposure assessment and training improvement rather than performance evaluation.

A planned follow-up Level 2 assessment, conducted several months after these controls were implemented, would be expected to show reduced SSQ score changes, improved posture scores with less time in deep trunk flexion, and the absence of recorded near-misses with furniture or boundary structures. NASA-TLX ratings might demonstrate stable or improved perceived learning value with lower frustration during emergency segments, and trainee debriefings could reflect increased comfort and confidence with the training. Such hypothetical results would illustrate how the ARECC based framework could be used to iteratively refine VR confined-space training, reducing key exposures while preserving or enhancing instructional effectiveness.

The follow-up assessment results could be logged in an ARECC tracking table that links each control to specific indicators such as SSQ change scores, posture metrics, near-miss counts, and key NASA-TLX dimensions. These records would feed into routine VR-lab reviews, where predefined thresholds (for example, a resurgence of cybersickness in more than 10% of users or repeated ergonomic flags in a specific task segment) trigger a new ARECC cycle that revisits anticipation, recognition, evaluation, and the mix of engineering, administrative, and data-governance controls. By formally tying reassessment data to policy revisions and design decisions, the framework treats documentation not as a static requirement but as the mechanism that keeps VR confined-space training on a continuous improvement trajectory.

## 5. Practical Guidance for VR Lab Design, Operation, and Evaluation

### 5.1. Engineering Controls

From an ARECC perspective, engineering controls should be the primary means of reducing exposures in VR labs, with administrative and PPE measures layered on top. Table 3 summarizes example engineering, administrative, and data governance operational practices that can be applied when designing and operating VR training labs. For design, this means allocating sufficient unobstructed floor space per user, removing non-essential furniture from play areas, routing cables overhead or in low profile floor channels, and installing soft physical barriers that align with virtual boundary systems [5]. Ventilation and thermal control should be sized to handle heat and occupancy loads from headsets, computers, and users, with equipment racks and charging stations located away from air intakes and egress routes [14].

Hardware choices are equally important: headsets and peripherals should be selected for low mass, balanced weight distribution, and broad adjustability to reduce neck and shoulder strain; contact surfaces should use materials compatible with chosen disinfectants and with low allergenic potential [15]. Display and tracking technologies should be validated under the planned lighting conditions, and alarm and audio levels tuned so that cues remain salient without exceeding safe sound levels during peak scenarios. Treating these layout, ventilation, electrical, and hardware decisions as part of the exposure-control hierarchy embeds safety into the fabric of the VR lab before training ever begins.

### 5.2. Administrative Controls

Administrative controls govern who uses VR, for how long, and under what conditions, translating the framework into day-to-day practice [20]. Standard operating procedures should specify pre-session screening (including brief medical and motion sickness questions), maximum session durations, mandatory break intervals, daily and weekly exposure limits, and criteria for temporary exclusion (for example, acute illness, fatigue, recent concussion, or substance use) [14]. Age limits and informed-consent processes must be clearly defined, particularly for minors and vulnerable populations, with plain-language descriptions of potential symptoms and the right to stop at any time.

Operational policies should also address staffing and supervision: each active room should have at least one trained VR safety monitor responsible for fit checks, observation, and emergency response, with clear escalation pathways for medical or psychological events. Post-session debriefs and brief symptom checks enable early recognition of patterns in cybersickness, discomfort, or distress, feeding into the "recognize," "evaluate," and "confirm" steps of ARECC. Incident and near-miss reporting must explicitly cover VR-specific events (falls, collisions, severe cybersickness, panic reactions, equipment failures) and be integrated into existing occupational health and safety management systems so that VR related risks are not siloed from broader organizational learning.

### 5.3. Data Controls

Sensor-rich VR labs generate large volumes of personal and potentially sensitive data, making data governance controls an essential complement to engineering and administrative measures [21]. A written data management plan should inventory all data streams (environmental, motion, biometric, gaze, performance), classify them by sensitivity, and define specific, limited purposes for their use: exposure assessment, control verification, and training improvement. Informed consent materials must explain what is collected, how long it is kept, who can access it, and whether any data may be used for research, with clear options to opt out of non-essential collection where feasible.

Access to identifiable data should follow a least privilege model, restricted to roles with a legitimate occupational health or safety function, and de-identified or pseudonymized datasets should be used wherever possible for analytics and reporting [22]. Security measures (for example, encryption in transit and at rest, multi-factor authentication for administrative accounts, and regular access audits) are needed to protect biometric and behavioral records. Retention schedules should differentiate between raw traces and long-term aggregate indicators, ensuring that high granularity personal data are not kept indefinitely. By integrating data-governance practices into the ARECC cycle such as treating data handling itself as a potential source of risk to be anticipated, controlled, and periodically confirmed, the framework supports ethically robust, privacy-aware deployment of VR technologies in occupational safety and health.

**Table 3.** Practical control strategies for VR training labs.

| Control type | Design/configuration focus | Operational practices |
|---|---|---|
| Engineering controls | Clear play areas, minimal furniture, overhead or protected cable routing, aligned physical and virtual boundaries, adequate ventilation and temperature control, equipment and charging kept away from exits. | Periodic checks of clearances, cables, barriers, and ventilation controls; tuning alarm and audio levels; reviewing hardware whenever devices are added or changed. |
| Hardware and ergonomics | Light well balanced, adjustable headset and controllers; disinfectant resistant contact materials | Fit checks before sessions; scheduled replacement of pads and straps; tracking user complaints (pressure points, skin irritation) to trigger hardware changes. |

**Continued**

| | | |
|---|---|---|
| Administrative: exposure management | Session length limits, maximum sessions per day, mandatory breaks; extra rule for high intensity scenarios; criteria for pausing or stopping sessions. | Pre-session briefings on symptoms and stop rules; enforcing time limits; recording early terminations and reasons; revising limits using monitoring data. |
| Administrative: screening and staffing | Pre-use medical/motion sickness screening; age and consent rules; minimum staffing rations; SOPs for checks, active monitoring, and debriefs. | Applying screening checklists; real-time observation; brief post-session symptom checks; structured incident and near-miss reporting. |
| Data governance | Inventory and classify environmental, motion, biometric, gaze, and performance data; define uses (exposure assessment, control verification, training improvement) | Prefer de-identified or pseudonymized data; role-based access; limited retention of raw traces; encryption and authentication for storage and access. |
| Data consent and transparency | Clear information sheets and consent forms describing data collected, purpose, retention, and access; options to opt out of non-essential collection. | Recording consent; honoring opt-outs (e.g., disabling eye tracking when possible); sharing aggregate findings and changes made in response to monitoring. |

These control categories correspond primarily to the Control and Confirm steps of the ARECC cycle, with screening and data governance elements also supporting Anticipate, Recognize, and Control.

### 5.4. Framework Scalability and Phased Implementation

The tiered structure of the framework is intentionally designed to be scalable across organizations that differ in size, sector, and resource availability. Within this structure, Level 1 and Level 2 assessments can be implemented with relatively modest investments, relying primarily on structured checklists, standardized observation forms, short pilot sessions, basic posture or task-load screening tools, and intermittent environmental measurements obtained with commonly available instruments. These activities provide an initial classification of exposure potential across hazard categories and help identify scenarios, user groups, and lab configurations that warrant closer scrutiny. In most organizations, this qualitative and semi-quantitative information will be sufficient to support defensible decisions about engineering and administrative controls for the majority of VR training activities.

Escalation to Level 3 is not assumed by default but is instead triggered when Level 1 and Level 2 findings indicate persistent or uncertain risk that cannot be adequately characterized with lower-intensity methods. In practice, this may include scenarios in which near-misses or minor incidents continue to occur despite basic controls, semi-quantitative ratings for ergonomics, cybersickness, or workload remain in the medium–high range, or there is substantial variability in responses across different user groups. Under these conditions, the additional cost and complexity of continuous environmental sensing, wearable motion capture, and psychophysiological monitoring can be justified because they are targeted to well-defined questions about exposure–time patterns, peak loads, and the interaction between scenario elements and user characteristics. Organizations with limited resources can therefore prioritize a small number of high-risk or strategically important scenarios (for example, emergency response, confined-space entry, or workplace-violence prevention modules) for Level-3 monitoring, while managing lower-risk scenarios using only Level-1 and Level-2 approaches. In this way, the framework supports a graded, resource-sensitive implementation in which every site can adopt a consistent ARECC process, but the intensity of monitoring and analytics is matched to actual risk and operational capacity rather than applied uniformly.

## 6. Discussion

### 6.1. Implications for Research

Framing VR training labs as multi-hazard workplaces governed by an ARECC cycle opens several lines of empirical inquiry. The tiered exposure-assessment structure and worked examples suggest specific, testable hypotheses about how scenario design, lab configuration, and user characteristics shape physical, ergonomic, and psychosocial exposures over time. Studies can compare different tiers (for example, qualitative vs. semi-quantitative vs. sensor-rich assessment) to determine how much additional precision and decision value higher tiers actually provide, and under what conditions they are warranted. There is also an opportunity to examine how integrating real-time environmental, biomechanical, and physiological data into training design affects learning outcomes, transfer of training, and long-term health indicators, moving beyond current work that focuses primarily on performance or satisfaction.

The framework underscores the need for standardized metrics and protocols for VR-related exposures, particularly around cybersickness, cognitive load, and ergonomic load during immersive tasks. Harmonized measurement approaches would allow meta-analyses across sectors and platforms, and would support development of exposure benchmarks tailored to VR environments rather than borrowing thresholds from traditional industrial settings. Further research should also address equity and inclusion in VR training: for example, whether current hardware, content, and screening practices differentially impact workers with disabilities, older adults, or those with pre-existing health conditions, and how the ARECC process can be adapted to support diverse users without exacerbating stigma or exclusion.

### 6.2. Implications for Practice

For practitioners, the proposed model provides a structured roadmap for integrating VR labs into existing occupational safety and health management systems. Safety professionals can use the framework to justify VR-lab planning and monitoring activities in terms that align with established exposure-risk management expectations, making it easier to secure resources for engineering controls, sensor deployments, and specialized staffing. The tiered assessment and worked examples show how even modest programs can start with structured checklists and small pilot sessions, then scale toward real-time monitoring as risk, complexity, and capacity grow. Importantly, the inclusion of data-governance controls positions privacy and ethical data use as core elements of exposure management, rather than afterthoughts, which may help address organizational concerns about biometric and behavioral monitoring.

In practice, adoption of this framework can support more defensible decisions about how long workers should remain in VR, which scenarios are suitable for which populations, and when a lab is “safe enough” to operate at scale. It can also foster closer collaboration between industrial hygienists, human-factors specialists, instructional designers, and IT/security teams, since effective control of VR-lab exposures depends on design choices in all of these domains. Over time, organizations that systematically apply ARECC in their VR labs may develop institution-specific exposure profiles and control libraries that can inform procurement, scenario development, and training policies across multiple sites and applications.

The framework also underscores that VR lab safety is as much a human-factors challenge as a technical one. Instructors and safety monitors must be prepared to brief users, recognize subtle indicators of discomfort or overload, and intervene early, while designers and managers must anticipate how policies such as session limits, screening criteria, and biometric monitoring will be interpreted by workers. Treating these human-factors issues as explicit elements of the ARECC cycle rather than informal considerations can reduce variability in practice and support sustained acceptance of VR-based training programs.

Insights generated when applying the ARECC framework in VR labs can also inform operational risk assessments. Ergonomic or psychosocial stressors identified in simulation, such as sustained trunk flexion in a confined-space scenario, repeated rapid turns during emergency drills, or elevated stress responses to particular alarm configurations, may reveal previously overlooked hazards in the corresponding field tasks and prompt reevaluation of work methods, equipment layout, or staffing in the actual workplace. In this way, the VR lab functions not only as a controlled environment for training, but also as an instrumented testbed that helps organizations discover, prioritize, and control hazards in the operations that the simulations are intended to represent.

### 6.3. Limitations

This conceptual framework has several limitations. It is intentionally technology-agnostic and sector-agnostic, which means it may not capture all nuances of specific platforms (for example, fully wireless vs. tethered systems) or industries (for example, nuclear, aviation, or pediatric healthcare). The reliance on sensor technologies in the upper assessment tiers assumes access to suitable hardware, data-management infrastructure, and analytical expertise, which may not be available in smaller organizations or low-resource settings. Furthermore, while the framework integrates psychosocial and cognitive dimensions, current instruments and biomarkers for these constructs in VR environments are imperfect; misinterpretation of signals such as heart-rate variability or eye-movement patterns could lead to over- or under-estimation of risk.

Another limitation is that the framework does not prescribe specific exposure limits or "safe" thresholds for VR-related hazards, because such benchmarks are still emerging and may vary by population and use case. Instead, it offers a process for relative assessment and control, which could lead to variability in implementation and outcomes across institutions. Finally, although the worked examples demonstrate internal coherence, they do not substitute for empirical validation; real-world implementation may reveal unforeseen barriers, such as user resistance to monitoring, data-integration challenges, or conflicts with existing training schedules and regulatory requirements.

### 6.4. Summary and Implications

This paper proposes a tiered ARECC-based framework that treats VR training laboratories as multi-hazard workplaces and integrates engineering, administrative, and data-governance controls into a single process. The worked example and practical guidance illustrate how organizations can start with qualitative and semi-quantitative assessments and selectively deploy sensor-rich monitoring where risk and capacity justify it. By embedding human-factors and privacy considerations alongside traditional exposure controls, the framework is intended to support defensible, scalable adoption of VR safety training across varied organizational settings and contexts.

Future research should focus on empirically validating the framework across multiple sectors such as industrial plants, healthcare, and construction using mixed-methods designs that combine exposure metrics, learning outcomes, and qualitative user feedback. Longitudinal studies could investigate whether applying ARECC in VR labs affects rates of adverse events (for example, falls, severe cybersickness) and downstream safety performance in the field. Comparative work could evaluate different configurations of the tiered assessment (for instance, Level-1-only vs. Level-1 + 2 vs. full Level-3 monitoring) to determine cost-effective combinations for organizations with varying risk profiles and resources.

On the methodological side, there is a need to refine and validate sensor-based indicators of ergonomic and psychosocial exposure specific to VR, including robust algorithms for deriving actionable metrics from motion, physiological, and eye-tracking data. At the policy level, collaboration between occupational hygiene bodies, VR standards organizations, and regulators could translate elements of this framework into guidance documents, recommended practices, or even formal standards for VR training facilities. Finally, future work should explore how artificial intelligence and adaptive systems might use real-time exposure data to dynamically adjust scenarios in response to individual user responses, creating VR training that is not only pedagogically adaptive but also exposure-aware and health-protective.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

## References

[1] Scorgie, D., Feng, Z., Paes, D., Parisi, F., Yiu, T.W. and Lovreglio, R. (2024) Virtual Reality for Safety Training: A Systematic Literature Review and Meta-Analysis. *Safety Science*, **171**, Article ID: 106372. https://doi.org/10.1016/j.ssci.2023.106372

[2] Evangelista, A., Manghisi, V.M., De Giglio, V., Mariconte, R., Giliberti, C. and Uva, A.E. (2025) From Knowledge to Action: Assessing the Effectiveness of Immersive Virtual Reality Training on Safety Behaviors in Confined Spaces Using the Kirkpatrick Model. *Safety Science*, **181**, Article ID: 106693. https://doi.org/10.1016/j.ssci.2024.106693

[3] Bernabei, M., Colabianchi, S., Carli, M., Costantino, F., Ferrarotti, A., Neri, M., *et al.* (2024) Enhancing Occupational Safety and Health Training: A Guideline for Virtual Reality Integration. *IEEE Access*, **12**, 154349-154364. https://doi.org/10.1109/access.2024.3481668

[4] Simón-Vicente, L., Rodríguez-Cano, S., Delgado-Benito, V., Ausín-Villaverde, V. and Cubo Delgado, E. (2024) Cybersickness. a Systematic Literature Review of Adverse Effects Related to Virtual Reality. *Neurología* (*English Edition*), **39**, 701-709. https://doi.org/10.1016/j.nrleng.2022.04.007

[5] Jelonek, M. (2023) VRtoER: When Virtual Reality leads to Accidents: A Community on Reddit as Lens to Insights about VR Safety. *Extended Abstracts of the* 2023 *CHI Conference on Human Factors in Computing Systems*, Hamburg, 23-28 April 2023, 1-6. https://doi.org/10.1145/3544549.3585783

[6] Babangida, A.A., Caraballo-Arias, Y., Decataldo, F. and Violante, F.S. (2025) Advancing Occupational Medicine through Wearable Technology: A Review of Sensor Systems for Biomechanical Risk Assessment and Work-Related Musculoskeletal Disorder Prevention. *ACS Sensors*, **10**, 5410-5432. https://doi.org/10.1021/acssensors.5c01578

[7] Alenjareghi, M.J., Sekkay, F., Dadouchi, C. and Keivanpour, S. (2026) Wearable Sensors in Industry 4.0: Preventing Work-Related Musculoskeletal Disorders. *Sensors International*, **7**, Article ID: 100343. https://doi.org/10.1016/j.sintl.2025.100343

[8] Jahn, S.D., Bullock, W.H. and Ignacio, J.S. (2024) A Strategy for Assessing and Managing Occupational Exposures. 4th Edition, American Industrial Hygiene Association (AIHA).

[9] Tang, Y., Liang, H. and Zhan, J. (2024) The Application of Metaverse in Occupational Health. *Frontiers in Public Health*, **12**, Article 1396878. https://doi.org/10.3389/fpubh.2024.1396878

[10] (2020) Understanding and Applying ARECC to Occupational and Environmental Health and Safety. American Industrial Hygiene Association (AIHA), 1-16.

[11] Tamers, S.L., Chosewood, L.C., Childress, A., Hudson, H., Nigam, J. and Chang, C. (2019) Total Worker Health® 2014-2018: The Novel Approach to Worker Safety, Health, and Well-Being Evolves. *International Journal of Environmental Research and Public Health*, **16**, Article 321. https://doi.org/10.3390/ijerph16030321

[12] Roberts, S.C., Havill, N.L., Flores, R.M., Hendrix II, C.A., Williams, M.J., Feinn, R.S., *et al.* (2022) Disinfection of Virtual Reality Devices in Health Care Settings: *In Vitro* Assessment and Survey Study. *Journal of Medical Internet Research*, **24**, e42332. https://doi.org/10.2196/42332

[13] Souchet, A.D., Lourdeaux, D., Pagani, A. and Rebenitsch, L. (2022) A Narrative Review of Immersive Virtual Reality's Ergonomics and Risks at the Workplace: Cybersickness, Visual Fatigue, Muscular Fatigue, Acute Stress, and Mental Overload. *Virtual Reality*, **27**, 19-50. https://doi.org/10.1007/s10055-022-00672-0

[14] Souchet, A.D., Lourdeaux, D., Burkhardt, J. and Hancock, P.A. (2023) Design Guidelines for Limiting and Eliminating Virtual Reality-Induced Symptoms and Effects at Work: A Comprehensive, Factor-Oriented Review. *Frontiers in Psychology*, **14**, Article 1161932. https://doi.org/10.3389/fpsyg.2023.1161932

[15] Chen, Y. and Wu, Z. (2023) A Review on Ergonomics Evaluations of Virtual Reality. *Work*, **74**, 831-841. https://doi.org/10.3233/wor-205232

[16] Sevinc, V. and Berkman, M.I. (2020) Psychometric Evaluation of Simulator Sickness Questionnaire and Its Variants as a Measure of Cybersickness in Consumer Virtual Environments. *Applied Ergonomics*, **82**, Article ID: 102958. https://doi.org/10.1016/j.apergo.2019.102958

[17] Xi, N., Chen, J., Gama, F., Riar, M. and Hamari, J. (2022) The Challenges of Entering the Metaverse: An Experiment on the Effect of Extended Reality on Workload. *Information Systems Frontiers*, **25**, 659-680. https://doi.org/10.1007/s10796-022-10244-x

[18] Naranjo, J.E., Mora, C.A., Bustamante Villagómez, D.F., Mancheno Falconi, M.G. and Garcia, M.V. (2025) Wearable Sensors in Industrial Ergonomics: Enhancing Safety and Productivity in Industry 4.0. *Sensors*, **25**, Article 1526. https://doi.org/10.3390/s25051526

[19] Kriklenko, E., Kovaleva, A., Klimenko, A., Dukuev, U. and Pertsov, S. (2022) Multimodal Assessment of Changes in Physiological Indicators When Presenting a Video Fragment on Screen (2D) versus a VR (3D) Environment. *Behavioural Neurology*, **2022**, Article ID: 5346128. https://doi.org/10.1155/2022/5346128

[20] Biswas, N., Mukherjee, A. and Bhattacharya, S. (2024) "Are You Feeling Sick?"—A Systematic Literature Review of Cybersickness in Virtual Reality. *ACM Computing Surveys*, **56**, 1-38. https://doi.org/10.1145/3670008

[21] Magee, P., Ienca, M. and Farahany, N. (2024) Beyond Neural Data: Cognitive Biometrics and Mental Privacy. *Neuron*, **112**, 3017-3028. https://doi.org/10.1016/j.neuron.2024.09.004

[22] Spivack, J., Givens, A., O'Hara, J., Heller, B. and Valladares, C. (2024) Data Privacy Experts Dive into the Data Uses and Risks for XR on Latest Webinar. XRA Association.