TESIS DOCTORAL

ESCUELA INTERNACIONAL DE DOCTORADO

Programa de Doctorado de Ciencias de la Salud

Potencial de la realidad virtual en contextos de emergencias y, desastres: formación, evaluación y análisis neurofisiológico de la percepción del riesgo y la toma de decisiones.

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AUTORIZACIÓN DEL DIRECTOR DE LA TESIS
PARA SU PRESENTACIÓN

El Dr. D. Manuel Pardo Ríos, Dr. D. Federico Semeraro como Directores de la Tesis Doctoral titulada ***Potencial de la realidad virtual en contextos de emergencias y desastres: formación, evaluación y análisis neurofisiológico de la percepción del riesgo y la toma de decisiones*** realizada por Dña. Carmen Amalia López López en el Programa de Doctorado de ciencias de la salud, **autoriza su presentación a trámite** dado que reúne las condiciones necesarias para su defensa.

Lo que firmo, para dar cumplimiento al Real Decreto 99/2011 de 28 de enero, en Murcia a 20de mayo de 2026.

Dr. D. Manuel Pardo Ríos

Dr. D. Federico Semeraro

A Martín y Amalia.

RESUMEN

Introducción: Los entornos de emergencia, desastres y alta complejidad sanitaria demandan una formación específica que no solo se centre en la adquisición de conocimientos teóricos, sino que también prepare a los profesionales para actuar con eficacia y rapidez bajo presión. La Realidad Virtual (RV) emerge como una herramienta innovadora que permite simular escenarios críticos en entornos controlados, seguros y repetibles, favoreciendo el entrenamiento tanto en habilidades técnicas como no técnicas, como la toma de decisiones en situaciones de alta incertidumbre.

Objetivo: Evaluar el potencial de la Realidad Virtual (RV) como herramienta educativa en contextos de emergencias, desastres y alta complejidad, centrándose en su eficacia para la formación, evaluación y análisis neurofisiológico de la percepción del riesgo y la toma de decisiones.

Metodología: Esta tesis se presenta como un compendio de publicaciones indexadas en el Journal Citation Report (JCR), compuesto por cinco estudios científicos que exploran el uso de la RV en diferentes contextos: conducción en condiciones extremas, toma de decisiones en escenarios de incidentes con múltiples víctimas y medicina táctica, y reanimación en hipotermia accidental. Cada estudio integra métodos experimentales y cuasi-experimentales, así como el análisis de variables neurofisiológicas y fisiológicas.

Resultados: Los resultados muestran que la Realidad Virtual mejora la percepción del riesgo y la toma de decisiones en situaciones críticas en comparación con los métodos tradicionales. Los participantes en los entornos virtuales demostraron una mayor implicación emocional, mejor regulación del estrés y una activación neurofisiológica más intensa, asociada con áreas cerebrales clave para la toma de decisiones y la regulación emocional. Además, la RV mostró ser eficaz en la evaluación de decisiones bajo presión, identificando errores críticos que pasaron desapercibidos en simulaciones convencionales.

Conclusiones: La Realidad Virtual es una herramienta educativa de alto potencial en el ámbito de la formación y evaluación en contextos de emergencias y alta complejidad. Su capacidad para recrear escenarios de alta presión, involucrar emocionalmente al usuario y registrar respuestas fisiológicas y cognitivas la posiciona como un complemento a los métodos tradicionales de formación. La integración de la RV en la formación de primeros intervinientes, especialmente en la medicina táctica y situaciones de desastre, constituye una estrategia eficaz para mejorar la toma de decisiones y la preparación ante emergencias.

PALABRAS CLAVE

Reanimación cardiopulmonar, realidad virtual, toma de decisiones, percepción del riesgo, medicina de emergencias, medicina táctica en combate, análisis neurofisiológico, aprendizaje inmersivo, primeros intervinientes, regulación del estrés, toma de decisiones complejas.

ABSTRACT

Introduction: Emergency, disaster, and high-complexity healthcare environments demand specialized training that not only focuses on theoretical knowledge but also prepares professionals to act effectively and swiftly under pressure. Virtual Reality (VR) emerges as an innovative tool that allows the simulation of critical scenarios in controlled, safe, and repeatable environments, promoting training in both technical and non-technical skills, such as decision-making in high-uncertainty situations.

Objective: To evaluate the potential of Virtual Reality (VR) as an educational tool in emergency, disaster, and high-complexity contexts, focusing on its effectiveness for training, assessment, and neurophysiological analysis of risk perception and decision-making.

Methodology: This thesis is presented as a compendium of publications indexed in the Journal Citation Report (JCR), consisting of five scientific studies exploring the use of VR in different contexts: driving in extreme weather conditions, decision-making in mass casualty incidents and tactical combat casualty care, and resuscitation in accidental hypothermia. Each study integrates experimental and quasi-experimental methods, as well as the analysis of neurophysiological and physiological variables.

Results: The results demonstrate that immersive Virtual Reality improves risk perception and decision-making in critical situations compared to traditional methods. Participants in virtual environments showed greater emotional engagement, better stress regulation, and more intense neurophysiological activation, linked to brain areas crucial for decision-making and emotional regulation. Additionally, VR proved effective in assessing decisions under pressure, identifying critical errors that were overlooked in conventional simulations.

Conclusions: Virtual Reality is a highly valuable educational tool for training and assessment in emergency and high-complexity contexts. Its ability to recreate high-pressure scenarios, emotionally engage users, and record physiological and cognitive responses makes it an invaluable complement to traditional training methods. The integration of VR in training first responders, especially in tactical medicine and disaster scenarios, constitutes an effective strategy to enhance decision-making and preparedness in emergencies.

KEYWORDS

Cardiopulmonary resuscitation, Virtual Reality, Decision-making, Risk perception, Emergency medicine, Tactical Combat Casualty Care, Neurophysiological analysis, Immersive learning, First responders, Stress regulation, Complex decision-making.

AGRADECIMIENTOS

La mejor parte de este camino ha sido la gente con la que lo he compartido. Por eso quiero empezar estas páginas dando las gracias.

A **Manuel,** gracias. Por tus constantes "hazlo, yo te ayudo". Porque sabías que podía hacerlo sola, pero aun así no me has dejado ni un segundo. Por quemar rueda en el asfalto conmigo y enseñarme que las locuras también se trabajan. Por tu bondad, tu enorme humildad y tu amor por la vida. Por tu paciencia y tu exigencia. ¡Lo conseguimos! Ojalá esta tesis esté a la altura de todo lo que me has dado. Eternamente agradecida. Que siga el juego…y que a los locos nos sigan viendo bailar.

A **Federico Semeraro,** mi co-director de tesis, por su generosa orientación, su rigor académico y el apoyo brindado a lo largo de este trabajo

A **Dani** y **Javi.** Porque con vosotros no existen los imposibles ni los "no". Gracias por tanta vida y tantos momentos que han hecho el camino más bonito. Qué bien lo hemos pasado. A **Manu Pons**, bendito el momento en el que me liaste en esta aventura. Hoy estoy aquí por ti. A todo el grupo de investigación de nuevas tecnologías. Gracias por ser familia. Este trabajo también es vuestro.

A mis **compañeros** y amigos de guardia, gracias por mis "cinco minutos más" que tantas veces terminaron siendo horas. Porque vosotros sabéis mejor que nadie cuánto trabajo hay detrás de estas páginas. Os debo mucho.

A **Fran**, gracias por hacerme sentir capaz de cualquier cosa sin dejar nunca que me pierda demasiado lejos. Mi equilibrio, mi calma, mi hogar. Que nunca nos falte el champagne.

A mi **padre**. Cada vez que trabajo en una idea que parece una locura y requiere mucho trabajo… siento que tengo un poquito más de ti. Gracias, papá. Te admiro profundamente.

A mi **madre**, mi ángel de la guarda. Sin ti, todo sería muy difícil. Gracias por darme la vida una y mil veces.

A mis hermanos: **Toñi**, **Trini, Fran, Alejandro, Jesús, Cristina y Carmen**. Sois la suerte de mi vida.

A mis abuelos **Fajardo, Esteban y Trini**. El cielo brilla más desde que estáis allí. Gracias por cuidarme desde arriba. Y a **Antonia**, por seguir abrazándome aquí abajo.

A mis hijos, **Martín** y **Amalia**. Todo lo hago por y para vosotros. Ojalá siempre estéis orgullosos de mí.

A mis **pacientes**, a mis **alumnos** y mis **amigos** gracias.

"«*Abbiate il coraggio di essere felici.*»
— Papa Francisco

ÍNDICE GENERAL

SIGLAS Y ABREVIATURAS

XR: extended reality

RV: Realidad virtual

RA: Realidad aumentada

RM: Realidad mixta

RCP, Resucitación Cardiopulmonar

SUS: System Usability Scale

MARCH: acrónimo que representa los pasos secuenciales del protocolo: M: Massive Hemorrhage (Hemorragia masiva**)** A**:** Airway (Vía aérea) R**:** Respirations (Respiración) C**:** Circulation (Circulación) H**:** Head (Cabeza)

EEG: Electroencefalograma

ECG: Electrocardiograma

CAMIL: Cognitive Affective Model of Immersive Learning

IMV: Incidente de Múltiples Victimas

HR (Heart Rate): Se refiere a la frecuencia cardíaca

HRV (Heart Rate Variability): Se refiere a la variabilidad de la frecuencia cardíaca

ECLS (Extracorporeal Life Support): soporte vital extracorpóreo

ECMO Extracorporeal Membrane Oxygenation

RPD: hace referencia al modelo de toma de decisiones Recognition-Primed Decision Model (RPD) desarrollado por Gary Klein.

EMS Emergency Medical Services (Servicios Médicos de Emergencia).

TCCC: Tactical Combat Casualty Care.

ÍNDICE DE ANEXOS

COMPENDIO DE PUBLICACIONES

A continuación, se presentan las citas completas de los cinco artículos que constituyen esta tesis doctoral por compendio de publicaciones.

ARTÍCULO I.

Título: *"Meta-health: a national swot analysis for the development of a metaverse and virtual reality in health sciences education"*

Autores: Manuel Pardo Ríos, Carmen Amalia López López, Rafael Castro Delgado, Isabel Morales Moreno, Daniel Guillen Martínez, Pablo López Guardiola, Rafael Melendreras Ruiz, Miriam Mendoza López, María Belén López Ayuso, Robert Greif, Gabriel Gijon Noguerón, Ana Nicolás Carrillo.

Fecha de Publicación: Enero 2025

Revista: Teaching and Learning in Nursing

ISSN: 1557-3087

Ranking: Q2 (87/193)

Journal Impact Factor: 1.7

Categoría: Nursing

Base de datos: JCR (Journal Citation Report)

ARTÍCULO II.

Título: *"Impact of virtual reality on adolescents´risk perception while driving in extreme weather conditions"*.

Autores: Carmen Amalia López López, Antonio Hernández Fernández, Manuel Pardo Ríos, Claudia De Barros Camargo.

Fecha de Publicación: agosto 2025

Revista: Revista de Gestão Social e Ambiental

ISSN: 1981-982X

Ranking: Q4 (361/384)

Journal Impact Factor: 0.4

Categoría: Management, Monitoring, Policy and Law

Base de datos: Scopus

ARTÍCULO III.

Título: "Can immersive virtual reality assess hypothermia resuscitation decisionmaking? A cross-sectional study in a civil–military disaster management context".

Autores: Carmen Amalia Lopez Lopez, Robert Greif, Federico Semeraro, Ana Belen Ocampo Cervantes, Manuel Pons Claramonte, Sergio Nieto Caballero, Manuel Pardo Ríos, Daniel Martínez Guillen Martinez, Marina Sánchez Gómez, Martin Plamenov Georgiev, Martin Lyubomirov Ivanov, Lucia Lopez Ferrandiz.

Fecha de Publicación: marzo 2026

Revista: BMJ Open

ISSN: 2044-6055

Ranking: Q2 (84/232)

Journal Impact Factor: 2.3

Categoría: Medicine, General & Internal

Base de datos: JCR (Journal Citation Report)

ARTÍCULO IV.

Título: *"Impact of Virtual Reality on risk perception, stress and neurophysiological patterns in driving situations during floods: a quasi-experimental study".*

Autores: Carmen Amalia Lopez Lopez, Federico Semeraro, Antonio Hernández Férnández, Claudia de Baros Camargo, Pablo López Guardiola, Jose Joaquin Ceron Madrigal, María Botía González, Ana Belén Ocampo Cervantes, Manuel Pardo Rios, Daniel Guillén Martínez

Fecha de Publicación: abril 2026

Revista: Heliyon

ISSN: 2405-8440

Ranking: Q1 (29/136)

Journal Impact Factor: 3.6

Categoría: Multidisciplinary Sciences.

Base de datos: JCR (Journal Citation Report)

ARTÍCULO V.

Título: *"Immersive Virtual Reality for Assessing Decision-Making in Mass Casualty Incident and Tactical Combat Casualty Care Scenarios Among Military Personnel as First Responders".*

Autores: Carmen Amalia López López, Federico Semeraro, Manuel Pardo Ríos, Ana Belén Ocampo Cervantes, Daniel Guillén Martínez, Marina Sánchez Gómez, Nereo Venero Sánchez, Miriam Mendoza López, Martin Ivanov, José Cerón Madrigal, María Botia González, Mireia Alcazar Artero.

Fecha de Publicación: abril 2026

Revista: BMJ Military Health

ISSN: 2633-3767

Ranking: Q2 (118/332)

Journal Impact Factor: 1.7

Categoría: Military Medicine

Base de datos: JCR (Journal Citation Report).

I – INTRODUCCIÓN

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1.1 EVOLUCIÓN DEL PARADIGMA FORMATIVO EN CIENCIAS DE LA SALUD

La formación en ciencias de la salud y en el ámbito de las emergencias está experimentando una transformación profunda, evolucionando desde modelos tradicionales centrados en la transmisión de contenidos y en la simulación convencional hacia enfoques más activos, inmersivos, experienciales y orientados al desempeño (1,2). La enseñanza ya no se concibe únicamente como un proceso de adquisición teórica, sino como un itinerario de aprendizaje contextualizado y progresivo, capaz de reproducir situaciones complejas, inciertas y de alta exigencia. Esta evolución responde tanto a los cambios pedagógicos del siglo XXI como a la necesidad de adaptar la educación sanitaria a contextos clínicos y operativos cada vez más dinámicos, interprofesionales y tecnológicamente mediados (1-3).

1.1.1 El paradigma formativo en el siglo XXI

En ciencias de la salud, el paradigma formativo ha evolucionado desde modelos centrados en la transmisión unidireccional de contenidos hacia enfoques participativos, competenciales y centrados en el estudiante. La literatura reciente describe esta transición como un desplazamiento desde formatos estáticos y bidimensionales hacia ecosistemas de aprendizaje interactivos, colaborativos y orientados a la aplicación práctica del conocimiento (1). Aprender ya no supone solo recibir información, sino construir conocimiento a través de la experiencia, la toma de decisiones, la reflexión y la resolución de problemas en contextos próximos a la práctica profesional (1,2,4).

La educación sanitaria del siglo XXI debe preparar a los profesionales para actuar con seguridad, rapidez y criterio en escenarios clínicos complejos (4). La adquisición de competencias no puede centrarse exclusivamente en el saber teórico, sino también en el desarrollo del razonamiento clínico, la capacidad de adaptación, la gestión emocional, el trabajo en equipo y la toma de decisiones bajo presión, de modo que la innovación educativa se convierte en una necesidad estructural de la formación en salud (5).

1.1.2 Limitaciones de los modelos tradicionales de formación

Aunque los modelos tradicionales han sido la base de la formación sanitaria, presentan limitaciones importantes cuando se trata de entrenar competencias complejas en escenarios de alta exigencia. La enseñanza expositiva y la simulación convencional no siempre permiten reproducir con suficiente fidelidad la incertidumbre, la presión temporal, la carga cognitiva y la complejidad contextual propias de muchas situaciones reales de emergencia, catástrofe o atención crítica (6-8). A ello se suman dificultades logísticas, alto consumo de recursos, menor escalabilidad y escasa posibilidad de repetir escenarios infrecuentes, costosos o peligrosos. Estas carencias resultan especialmente visibles en la preparación para incidentes con múltiples víctimas y desastres, donde la exposición real es limitada pero la necesidad de entrenamiento eficaz es máxima (6-8).

1.1.3 Necesidad de innovación educativa en contextos complejos

La creciente complejidad de los entornos sanitarios, las emergencias y los desastres exige incorporar estrategias educativas más flexibles, seguras, repetibles y orientadas al entrenamiento de competencias. La innovación educativa no responde solo a la incorporación de nuevas tecnologías, sino a una exigencia pedagógica: preparar a los profesionales para actuar con eficacia en situaciones cambiantes y de alto impacto clínico u operativo (1,2,6). En este marco, la simulación avanzada, la evaluación del desempeño y las tecnologías inmersivas ocupan un lugar cada vez más relevante. La realidad virtual y, más recientemente, el metaverso educativo no debe entenderse como meros recursos tecnológicos, sino como expresiones de una transformación pedagógica más amplia que reconfigura el acceso al conocimiento, el entrenamiento y la evaluación de competencias en entornos complejos (1-5,9,10).

1.2 TECNOLOGÍAS INMERSIVAS Y REALIDAD VIRTUAL EN EDUCACIÓN

1.2.1 Concepto de realidad extendida, virtual, aumentada y mixta.

El desarrollo de las tecnologías inmersivas ha generado una terminología amplia que conviene delimitar. El término realidad extendida o XR (extended reality) se emplea como concepto paraguas para agrupar las tecnologías digitales capaces de modificar, ampliar o sustituir la percepción del entorno físico, principalmente la realidad virtual (RV), la realidad aumentada (RA) y la realidad mixta (RM) (10,11).

La RV genera un entorno completamente digital mediante visores o head-mounted displays, que sustituyen la percepción del mundo físico por una experiencia tridimensional simulada y, en su modalidad inmersiva, combina estimulación visual, auditiva y háptica favoreciendo la sensación de presencia, entendida como la percepción subjetiva de “estar allí” (11). En educación sanitaria, esta tecnología ha adquirido especial relevancia porque permite entrenar competencias en contextos difíciles de reproducir con métodos convencionales, ya sea por limitaciones físicas, logísticas o éticas (5, 11).

La RA no sustituye el entorno real, sino que superpone sobre él información digital (imágenes, modelos anatómicos, indicadores), aplicándose en educación médica al aprendizaje anatómico, la orientación procedural y la adquisición de destrezas (11). La RM ocupa una posición intermedia entre la RA y la RV: integra objetos virtuales en el entorno real de modo que ambos coexistan e interactúen en tiempo real, lo que la hace prometedora para tareas de manipulación, navegación espacial y entrenamiento basado en la interacción contextual (11).

Las revisiones actuales muestran que la RV ha predominado en formación inmersiva de alta complejidad, mientras que la RA y la RM se han vinculado a tareas de visualización, guía procedimental y entrenamiento técnico, dependiendo su valor educativo del tipo de tarea, contexto y diseño pedagógico (5,11). Dentro de este ecosistema aparece el metaverso, entendido como evolución hacia espacios virtuales persistentes, compartidos e interactivos, que amplía las posibilidades de las tecnologías XR hacia experiencias multiusuario y simulación socialmente distribuida (10).Adoptar XR como término global y diferenciar dentro de él RV, RA y RM resulta útil tanto conceptual como metodológicamente, pues cada tecnología implica distintos grados de inmersión, presencia, interacción, realismo y potencial pedagógico (4, 5,11,12).

1.2.2 Inmersión, presencia e interacción

Inmersión, presencia e interacción son tres dimensiones relacionadas, pero no equivalentes. La inmersión se refiere a las características objetivas del sistema tecnológico: el grado en que un entorno digital envuelve al usuario mediante estímulos sensoriales, tridimensionalidad, seguimiento del movimiento y retroalimentación en tiempo real, especialmente relevante en RV con head-mounted displays (5,11). La presencia, en cambio, es la respuesta subjetiva del usuario, la sensación psicológica de "estar allí". Es considerada el correlato subjetivo de la inmersión y no depende únicamente de la tecnología, sino que es dependiente de factores individuales, diseño del escenario y realismo percibido (4,13).

Interactuar no significa únicamente observar un escenario, sino poder actuar sobre él, modificar elementos, explorar el espacio, tomar decisiones y recibir consecuencias o retroalimentación derivadas de la propia conductalo que convierte al aprendiz en agente activo y favorece el entrenamiento contextualizado de habilidades clínicas, procedimentales y decisionales (5,11,14).

En educación sanitaria el potencial formativo de la tecnología no reside solo en su novedad, sino en su capacidad para generar experiencias de aprendizaje activas, contextualizadas y psicológicamente significativas. Por ello, estos tres conceptos deben considerarse dimensiones nucleares para comprender el valor pedagógico de la realidad virtual y de las tecnologías inmersivas en la formación sanitaria contemporánea (5,14,15).

1.2.3 Potencial de la realidad virtual en formación y evaluación

La RV ha adquirido un papel relevante en educación por su capacidad para generar experiencias de aprendizaje activas, seguras, repetibles y contextualizadas (4).En ciencias de la salud permite enfrentarse a situaciones difíciles de reproducir por motivos éticos, logísticos o de seguridad, mejorando determinados resultados de aprendizaje y la implicación del alumnado (4,5).Las revisiones más recientes muestran que contribuye a la adquisición de conocimientos, al desarrollo de habilidades clínicas y al aumento de la autoconfianza (5); un metaanálisis en enfermería concluyó que la RV mejoró el conocimiento interprofesional, el rendimiento en habilidades clínicas y la autoconfianza, aunque el tamaño del efecto depende del diseño y de la competencia evaluada (5,16).

La RV presenta también un potencial creciente como herramienta de evaluación. La revisión de Neher y colaboradores señala su utilidad en la evaluación de grado en medicina y enfermería, especialmente en tareas basadas en el desempeño en escenarios de urgencias y en competencias relacionadas con la atención al paciente, la comunicación y el conocimiento médico, ya sea como instrumento automatizado o complementario al evaluador humano (5,15). Otro valor central es su capacidad para integrar formación y evaluación en un mismo entorno, registrando decisiones, tiempos de respuesta, errores y patrones de interacción de forma automática y en tiempo real, lo que favorece evaluaciones más objetivas y feedback más preciso (4,15).

Su valor es particularmente alto en contextos de alta complejidad. Una revisión sobre realidad extendida en primeros intervinientes concluyó que estas tecnologías mejoraron la exactitud del triaje, el tiempo de respuesta, la corrección del tratamiento y el conocimiento adquirido (6); otra revisión sobre RV de alta fidelidad para incidentes con múltiples víctimas señaló aportaciones de realismo, seguridad y repetibilidad, recomendando entenderla como complemento y no sustituto de la simulación en vivo (7). No obstante, la RV no es eficaz por sí misma: la heterogeneidad de diseños, dispositivos e instrumentos dificulta la comparación de estudios y obliga a integrarla siguiendo criterios de constructive alignment, considerando además los costes, el desarrollo de software, el mantenimiento y la formación del profesorado (4,5,15).Así, la RV combina inmersión, repetibilidad, seguridad, objetivación del desempeño y feedback inmediato, pero su incorporación debe estar guiada por criterios pedagógicos y de validez educativa (5,6,15,16).

1.2.4 Usabilidad, aceptación tecnológica y experiencia del usuario

La incorporación de tecnologías inmersivas en educación sanitaria no depende únicamente de su potencial pedagógico, sino también de cómo son percibidas y vividas por el usuario. En este sentido, la usabilidad, la aceptación tecnológica y la experiencia del usuario constituyen dimensiones decisivas para que la realidad virtual, la realidad mixta o los entornos metaversales puedan integrarse de forma estable en los procesos de enseñanza y evaluación. La literatura reciente en educación médica señala que muchas intervenciones muestran resultados prometedores en aprendizaje, pero subraya igualmente que su adopción real exige atender a factores organizativos, técnicos y didácticos, entre ellos la facilidad de uso, la percepción de utilidad, la comodidad durante la experiencia y la integración curricular (17,18).

La usabilidad es el grado en que una herramienta inmersiva permite realizar una tarea de manera clara, eficiente y satisfactoria, e incluye la estabilidad del sistema, la calidad del audio y vídeo, la intuitividad de la navegación y la adecuación a los objetivos docentes. En un estudio de 2024 sobre RM en un hospital universitario, los estudiantes puntuaron 71,4 en la System Usability Scale (SUS), valor indicativo de buena usabilidad. Sin embargo, percibir beneficio educativo no implicaba considerar la experiencia tan valiosa como un encuentro clínico presencial (19).

La aceptación tecnológica alude a la disposición de estudiantes y docentes a utilizar de forma continuada una tecnología educativa (18). La aceptación tecnológica, analizada con frecuencia mediante el Technology Acceptance Model, se vincula a variables como la utilidad percibida, facilidad de uso, intención de uso y actitud del usuario hacia la tecnología. Esto explica que herramientas técnicamente avanzadas puedan fracasar si se perciben como complejas o poco relevantes (18).

La experiencia del usuario es un constructo más amplio que incorpora dimensiones afectivas, motivacionales y perceptivas como la satisfacción, la sesnsión de presencia, implicación emocional, confort y posible malestar asociado al uso. En general, los estudiantes informan de alta presencia y bajos niveles de cybersickness, aunque la evidencia disponible sigue siendo limitada y heterogénea (20,21).Estudios con enfermeras y estudiantes sobre plataformas metaversales muestran que la efectividad depende de la preparación del usuario, las propiedades de la plataforma y el diseño de programas estructurados y fáciles de usar (22), y la usabilidad en grado en ciencias de la salud destaca el valor de los escenarios realistas y del debriefing grupal como parte esencial del proceso de aprendizaje (23).En conclusión, una tecnología inmersiva será más valiosa cuanto más usable resulte, mayor aceptación genere y mejor experiencia ofrezca, siempre articulada con objetivos docentes claros (17,19-24).

Por ello, la usabilidad, la aceptación tecnológica y la experiencia del usuario deben considerarse no como variables accesorias, sino como componentes estructurales para comprender la viabilidad real de las tecnologías inmersivas en la educación en ciencias de la salud (17,19-24).

1.2.5 Oportunidades y limitaciones de la formación inmersiva

La formación inmersiva ofrece oportunidades especialmente valiosas en ciencias de la salud porque permite recrear entornos complejos, poco frecuentes o de alto riesgo en condiciones seguras, controladas y repetibles. Las revisiones recientes coinciden en que la RV favorece la práctica deliberada y la integración de conocimientos, habilidades y toma de decisiones, con beneficios en aprendizaje, retención y valoración del alumnado en anatomía, entrenamiento clínico, cirugía, enfermería y urgencias (4,5,6,24).

Asimismo, estas tecnologías facilitan la integración entre formación y evaluación ya que los entornos inmersivos permiten registrar variables de desempeño como tiempos de respuesta, trayectorias de actuación, decisiones y errores, favoreciendo evaluaciones más objetivas de las competencias clínicas (5,15). Además, aporta ventajas organizativas relevantes. La posibilidad de repetir escenarios, modular su dificultad, menor dependencia de pacientes reales o de simulaciones físicamente costosas y facilitar entrenamiento distribuido o remoto incrementa su atractivo para las instituciones formativas (6, 14,24,25).

En educación clínica y en preparación para desastres, estas características favorecen la escalabilidad, la flexibilidad espaciotemporal y la práctica en contextos donde la exposición real es limitada, pero la necesidad de preparación es alta (6,14,24,25).

No obstante, la literatura advierte que estas ventajas deben interpretarse con cautela. La elevada heterogeneidad metodológica de los estudios, en cuanto a dispositivos, niveles de inmersión, diseños, escenarios, poblaciones e instrumentos de medida, dificulta la comparación de resultados y limita la existencia de evidencia longitudinal sólida sobre transferencia del aprendizaje, mantenimiento de competencias y coste-efectividad (5,14,24). A ello se suman limitaciones técnicas, económicas y humanas, relacionadas con la inversión en hardware y software, el mantenimiento, la capacitación docente, la adaptabilidad de los usuarios, la privacidad y el cumplimiento normativo. En este sentido, se subraya la necesidad de alinear la tecnología con objetivos pedagógicos claramente definidos, evitando que la innovación quede reducida a un mero efecto de novedad (5,25).

Por otra parte, la experiencia inmersiva puede asociarse a efectos adversos como náuseas, mareo, desorientación, fatiga visual o malestar. Aunque los estudios suelen describir altos niveles de presencia y baja incidencia de cybersickness entre los estudiantes, la evidencia disponible continúa siendo limitada (4,26).

Por todo ello, la evidencia permite considerar la formación inmersiva como una oportunidad significativa para la renovación de la educación en ciencias de la salud, especialmente en el entrenamiento de competencias procedimentales, decisionales y contextuales. Sin embargo, su efectividad depende no solo de la tecnología empleada, sino también de la calidad del diseño educativo, del contexto institucional y de la experiencia formativa ofrecida al estudiante (6,14,25).

1.3 PROCESOS COGNITIVOS Y NEUROFISIOLOGICOS EN ENTORNOS INMERSIVOS.

1.3.1 Atención, carga cognitiva y rendimiento

En los entornos inmersivos, la atención constituye uno de los procesos cognitivos más relevantes, ya que condiciona qué estímulos son seleccionados, procesados y convertidos en aprendizaje significativo. La realidad virtual posee una notable capacidad para captar y sostener la atención del usuario gracias a la combinación de inmersión sensorial, presencia y agencia, lo que favorece una mayor implicación con la tarea. Modelos como el Cognitive Affective Model of

Immersive Learning establecen que presencia y agencia actúan como affordances psicológicas centrales del aprendizaje inmersivo, e influyen sobre variables cognitivas y afectivas como la carga cognitiva, la autorregulación, la motivación y, en último término, los resultados de aprendizaje (13). En contextos aplicados de alta complejidad, esta implicación atencional puede contribuir además a mejorar el rendimiento en tareas inmersivas orientadas al triaje, la toma de decisiones y la respuesta operativa (6).

Sin embargo, esa mayor captación atencional no implica automáticamente una mejora del aprendizaje. Los entornos inmersivos también pueden incrementar la demanda cognitiva del estudiante, especialmente cuando incorporan múltiples estímulos, navegación compleja o elementos de interacción poco alineados con el objetivo docente, generando una "cara oscura" vinculada al estrés tecnológico y al aumento innecesario de la carga mental cuando el diseño no está bien guiado pedagógicamente. Por ello, la cuestión no es únicamente si la realidad virtual atrae más la atención, sino si lo hace de manera funcional y compatible con la capacidad cognitiva disponible (5,13).

En este contexto, la carga cognitiva se convierte en una variable clave para comprender la eficacia de la formación inmersiva. La evidencia reciente sugiere que la realidad virtual favorece el aprendizaje cuando reduce la carga extrínseca, facilita la organización de la información relevante y estimula una carga orientada a la construcción de esquemas. Un estudio de 2025 con estudiantes de medicina sobre aprendizaje de neuroanatomía mostró que la realidad virtual mejoró el rendimiento respecto a la instrucción tradicional, al tiempo que redujo la carga cognitiva extrínseca (27). De forma complementaria, un estudio de 2024 en laboratorios de realidad virtual observó que la incorporación de mecanismos de guía atencional reducía la carga cognitiva y mejoraba el rendimiento académico, lo que refuerza la idea de que el diseño instruccional modula directamente la relación entre inmersión y aprendizaje (28).

La relación entre atención, carga cognitiva y rendimiento debe entenderse, por tanto, del resultado del equilibrio entre exigencia cognitiva y soporte pedagógico. Cuando el entorno inmersivo guía adecuadamente la atención hacia lo relevante, estructura la interacción y evita distracciones superfluas, el estudiante dedica más recursos al procesamiento profundo de la tarea. Por el contrario, cuando la inmersión introduce complejidad innecesaria, la sobrecarga cognitiva compromete el aprendizaje y el desempeño. En este sentido, la realidad virtual es especialmente útil cuando se diseña para canalizar la atención, facilitar la comprensión espacial o procedimental y sostener la implicación sin saturar al usuario (28).

En cuanto al rendimiento, la revisión sistemática de 2025 sobre realidad virtual inmersiva en educación médica concluye que la mayoría de los estudios reportan mejores resultados de aprendizaje y percepciones subjetivas favorables (5), y los entornos inmersivos resultan prometedores para evaluar tareas basadas en desempeño(15).En RCP (reanimación cardiopulmonar), una revisión y metaanálisis de 2024 encontró que la formación basada en realidad virtual o aumentada fue tan efectiva como la presencial tradicional (29). Además, los resultados también señalan que la realidad virtual no solo modifica los resultados finales sino también, procesos intermedios relacionados con la atención y el esfuerzo cognitivo. En simulación clínica de emergencias los estudios muestran mayores niveles de implicación y focalización atencional que con la simulación de escritorio lo que sugiere un mayor compromiso con la tarea durante la experiencia (30).Por otra parte, la medición dinámica de carga cognitiva en simulaciones de reanimación con EEG (electroencefalograma) y ECG (electrocardiograma) mostró que es factible registrarla en tiempo real, con mayor carga en noveles que en expertos pese a un rendimiento similar (31). Estos hallazgos resultan especialmente relevantes porque sugieren que el rendimiento en entornos inmersivos no depende solo del resultado observable, sino también del coste cognitivo con el que ese resultado se alcanza, y la realidad virtual mejora cuando alinea inmersión, foco atencional, exigencia cognitiva y objetivos formativos (5,13,28).

1.3.2 Estrés y respuesta fisiológica

El estrés en entornos inmersivos puede entenderse como una respuesta psicofisiológica de adaptación ante demandas percibidas como relevantes, inciertas o amenazantes. En el contexto educativo, especialmente en ciencias de la salud, esta respuesta adquiere un interés particular porque muchos escenarios formativos buscan recrear condiciones de presión, urgencia o complejidad semejantes a las de la práctica real. La literatura reciente indica que la realidad virtual permite inducir reactividad de estrés de manera controlada, reproducible y relativamente segura, lo que la convierte en una herramienta útil tanto para el entrenamiento como para el estudio de los procesos fisiológicos asociados al rendimiento bajo presión. Un metaanálisis sobre tareas estresoras en realidad virtual concluyó que estos entornos son eficaces para evocar respuesta de estrés en múltiples biomarcadores, con efectos especialmente consistentes en marcadores simpáticos y con evidencia también en cortisol (32).De forma complementaria, una revisión sistemática sobre estrés, aprendizaje y rendimiento en simulación sanitaria subraya que la activación emocional inducida por escenarios simulados puede influir de manera relevante sobre el desempeño, lo que refuerza el interés de estudiar estos procesos en entornos inmersivos aplicados a la formación en salud (33).

Desde una perspectiva fisiológica, la respuesta al estrés en realidad virtual se ha estudiado mediante distintos sistemas de medida. La revisión sistemática sobre marcadores neurobiológicos en investigación educativa en ciencias de la salud identifica entre los indicadores más utilizados la frecuencia cardiaca, la variabilidad de la frecuencia cardiaca, el cortisol, la alfa-amilasa salival, la presión arterial, la saturación de oxígeno y la frecuencia respiratoria. Estos marcadores permiten objetivar procesos que los autoinformes no siempre captan con precisión, especialmente cuando el objetivo es analizar la activación emocional, la carga mental o la autorregulación fisiológica durante tareas de aprendizaje exigentes (34,35).

En los entornos inmersivos, la activación fisiológica no debe interpretarse de forma simplista como un resultado negativo. La evidencia reciente sugiere que un determinado grado de activación puede contribuir a incrementar el realismo percibido, la implicación con la tarea y la movilización atencional, mientras que una activación excesiva puede comprometer la toma de decisiones, aumentar la carga cognitiva o dificultar el aprendizaje. Por ello, la cuestión relevante no es únicamente si la realidad virtual induce estrés, sino con qué intensidad, en qué momento y con qué efecto sobre el desempeño. La literatura reciente subraya, precisamente, que las respuestas fisiológicas varían según el tipo de experiencia, el objetivo del entorno virtual y el marcador utilizado, lo que obliga a interpretar los datos dentro de un marco contextual y no como respuestas uniformes (32,33).

Un aspecto especialmente valioso de la realidad virtual es que permite registrar la respuesta fisiológica de forma sincronizada con la tarea, lo que abre la posibilidad de analizar no solo niveles globales de activación, sino también fluctuaciones momento a momento. La revisión sobre biosensores portables en experiencias inmersivas muestra que los dispositivos más utilizados en realidad virtual incluyen sensores de frecuencia cardiaca, conductancia cutánea, electroencefalografía y monitorización respiratoria, precisamente porque permiten seguir el estado fisiológico del usuario durante la interacción con el entorno (35). Este enfoque resulta especialmente útil en educación sanitaria, donde interesa conocer cómo cambian la activación autonómica y la carga emocional durante fases críticas de una simulación, en lugar de limitarse a medidas pre y postintervención (34,35).

No obstante, la literatura también advierte que la respuesta fisiológica en realidad virtual puede verse influida por factores que no siempre equivalen a un estrés formativo relevante. Entre ellos destacan la novedad tecnológica, la familiaridad previa con dispositivos inmersivos, la susceptibilidad individual a la simulación y la aparición de cybersickness, que puede generar síntomas físicos y alterar variables fisiológicas como la frecuencia cardiaca o la actividad electrodérmica. En consecuencia, la interpretación de los datos fisiológicos en entornos inmersivos exige distinguir entre la activación asociada al aprendizaje o a la presión de la tarea y la activación derivada del malestar tecnológico o de efectos secundarios del dispositivo (36,37).

Su principal fortaleza radica en que permite inducir, registrar y analizar la respuesta fisiológica en condiciones controladas, integrando indicadores objetivos con medidas cognitivas y conductuales. Desde el punto de vista del marco teórico, esto resulta especialmente relevante porque sitúa la respuesta fisiológica no como un elemento accesorio, sino como una dimensión central para comprender cómo los entornos inmersivos modulan la experiencia del usuario, la carga mental y el rendimiento en tareas complejas (33-35).

La realidad virtual pues, constituye un entorno especialmente adecuado para estudiar la relación entre estrés, activación fisiológica y aprendizaje en contextos de alta exigencia, integrando indicadores objetivos con medidas cognitivas y conductuales. Desde el punto de vista del marco teórico, esto resulta especialmente relevante porque sitúa la respuesta fisiológica como dimensión central para comprender cómo los entornos inmersivos modulan la experiencia del usuario, la carga mental y el rendimiento en tareas complejas (33-35).

1.3.3 Emociones y toma de decisiones

Las emociones constituyen un componente esencial del aprendizaje y del desempeño en entornos inmersivos, ya que influyen en la manera en que el usuario interpreta la situación, distribuye sus recursos atencionales y selecciona una respuesta. La literatura reciente sobre realidad virtual subraya que los entornos interactivos inmersivos no solo transmiten información, sino que generan estados afectivos capaces de modular la conducta y el compromiso con la tarea. Las emociones no deben entenderse como un elemento accesorio de la experiencia virtual, sino como una dimensión central de cómo el usuario percibe el escenario, evalúa su significado y actúa dentro de él (38,39,40).

Desde una perspectiva teórica, esta relación entre emoción y aprendizaje ha sido recogida por modelos como el Cognitive Affective Model of Immersive Learning (CAMIL), que plantea que la inmersión influye sobre factores cognitivos y afectivos a través de la presencia y la agencia, y que dichos factores terminan repercutiendo en los resultados de aprendizaje. Entre estos procesos afectivos se incluyen el interés, la motivación, la autoeficacia y la carga cognitiva, todos ellos estrechamente vinculados a la manera en que el aprendiz toma decisiones en escenarios dinámicos. Así, la realidad virtual puede favorecer decisiones más implicadas y contextualizadas cuando la activación emocional resulta funcional para la tarea, pero también puede dificultarlas si la intensidad afectiva excede la capacidad de regulación del usuario (13,41).

En educación sanitaria, esta interacción es especialmente relevante porque muchas decisiones deben adoptarse en condiciones de incertidumbre, presión temporal y complejidad contextual. La revisión reciente sobre integración de realidad virtual en educación médica destaca que estos entornos se están utilizando cada vez más para el entrenamiento de habilidades no técnicas, incluida la toma de decisiones clínicas, precisamente porque permiten recrear situaciones complejas en las que intervienen no solo conocimientos declarativos, sino también procesos emocionales, juicios rápidos y priorización de acciones. La realidad virtual ofrece un marco particularmente útil para entrenar decisiones en las que emoción y cognición no operan por separado, sino de manera integrada (17).

La evidencia más reciente indica, además, que la realidad virtual puede diseñarse para generar respuestas emocionales diferenciadas y analizar su impacto sobre la conducta.Un estudio sobre simulaciones con pacientes virtuales capaces de expresar y modificar sus respuestas emocionales según la interacción con el estudiante mostró que la incorporación de estas respuestas afectivas aumenta el realismo interpersonal y mejora el potencial formativo de la simulación (42).En paralelo, investigaciones con primeros intervinientes han mostrado que variables emocionales y psicopatológicas, como los síntomas postraumáticos, se relacionan con el rendimiento y con la forma de decidir dentro de tareas inmersivas (43,44). Esto refuerza, que las decisiones en realidad virtual no dependen solo de la información disponible, sino también del estado emocional y de la capacidad de regulación afectiva del usuario.

Por ello, en los entornos inmersivos la toma de decisiones debe entenderse como un proceso en el que convergen percepción, emoción, cognición y acción. Las emociones pueden facilitar el aprendizaje cuando incrementan la relevancia subjetiva del escenario, favorecen la implicación y ayudan a consolidar experiencias significativas; sin embargo, también pueden sesgar la valoración del riesgo, estrechar el foco atencional o favorecer respuestas impulsivas o evitativas cuando la activación es excesiva. En consciencia, el interés de la realidad virtual para la formación no radica únicamente en su capacidad para presentar información de forma más atractiva, sino en su potencial para estudiar y entrenar cómo las personas deciden bajo condiciones emocionalmente significativas, especialmente pertinente en ciencias de la salud, las emergencias y otros contextos de alta complejidad (13, 38).

1.3.4 Neurofisiología aplicada al aprendizaje inmersivo

La incorporación de medidas neurofisiológicas ha permitido ampliar el análisis del aprendizaje inmersivo más allá de los cuestionarios de satisfacción y de las pruebas de rendimiento, permitiendo observar, en tiempo real, cómo se articulan los procesos cognitivos, emocionales y fisiológicos durante la experiencia de aprendizaje (45). En este marco, la neurofisiología aplicada al aprendizaje inmersivo no pretende sustituir a las medidas educativas tradicionales, sino complementarlas con indicadores objetivos que permitan comprender mejor la activación atencional, la carga mental, la regulación emocional y la respuesta al estrés mientras el estudiante interactúa con el entorno virtual (45).

Entre las herramientas más utilizadas destaca la electroencefalografía, por su capacidad para registrar la actividad eléctrica cerebral de forma no invasiva y con buena resolución temporal. La literatura sobre EEG en educación muestra su uso para estudiar atención, memoria de trabajo, carga cognitiva, compromiso y estados emocionales, aunque también subraya una notable heterogeneidad metodológica en dispositivos, protocolos y estrategias analíticas, lo que obliga a interpretar los resultados con cautela y confirma el creciente interés por integrar la señal cerebral en el estudio de experiencias educativas complejas (46). En entornos inmersivos, ciertas variaciones en bandas alfa, beta o theta pueden relacionarse con estados de concentración, carga mental o fatiga, pero estas asociaciones no deben interpretarse de forma simplista: el EEG permite observar patrones neurocognitivos del procesamiento de la tarea siempre que se analice en combinación con el contexto instruccional y con otras medidas conductuales y fisiológicas (46).

Junto al EEG, otros marcadores fisiológicos resultan importantes: la frecuencia cardiaca, la variabilidad de la frecuencia cardiaca, la conductancia cutánea, la respiración y biomarcadores salivales. La revisión sistemática sobre marcadores neurobiológicos en formación sanitaria concluye que la frecuencia cardiaca y su variabilidad son sensibles a estresores educativos, mientras que cortisol y alfa-amilasa muestran resultados más variables, sin que ninguno sea indicador directo del éxito educativo (45). En realidad virtual, el uso de biosensores portables permiten un análisis multimodal simultáneo (EEG, HR/HRV, conductancia cutánea, respiración) útil para distinguir entre fenómenos que pueden parecer similares desde el exterior, por ejemplo, esfuerzo cognitivo, implicación emocional, estrés o fatiga, pero que responden a dinámicas fisiológicas diferentes (35,45).

Pedagógicamente, este enfoque permite comprender cómo aprende el estudiante dentro del entorno inmersivo y no solo si alcanza un buen resultado, identificar momentos críticos de sobrecarga o pérdida de atención y avanzar hacia evaluaciones más ricas que contemplen el coste cognitivo y fisiológico que ha supuesto alcanzar los resultados. La evidencia insiste en la prudencia metodológica: las señales neurofisiológicas no son autoexplicativas y requieren protocolos rigurosos para evitar interpretaciones reduccionistas (45,46). En conjunto, la neurofisiología aplicada al aprendizaje inmersivo aporta un marco prometedor para estudiar la interacción entre cerebro, cuerpo y conducta en contextos educativos complejos, enriqueciendo la evaluación pedagógica clásica mediante indicadores objetivos que permitan comprender con mayor profundidad qué ocurre durante la experiencia formativa, cómo responde el aprendiz y en qué condiciones la inmersión favorece o dificulta el aprendizaje (35, 45,46).

1.3.5 Evaluación multimodal del aprendizaje y experiencia de usuario

La evaluación del aprendizaje en entornos inmersivos tiende hacia enfoques multimodales que combinan indicadores de distinta naturaleza para comprender no solo el resultado final de una tarea, sino también el proceso por el que el estudiante llega a él. En RV, una valoración basada exclusivamente en pruebas de conocimiento o autoinformes resulta insuficiente, por lo que se incorporan progresivamente medidas de rendimiento, analíticas de interacción, percepción del usuario y registros fisiológicos o neurofisiológicos (48-51). En educación sanitaria esta aproximación es especialmente pertinente porque las tareas integran dimensiones cognitivas, técnicas, emocionales y decisionales al mismo tiempo. La revisión sistemática de Neher y colaboradores muestra que la realidad virtual se utiliza sobre todo en escenarios de emergencia y en competencias relacionadas con atención al paciente, comunicación y conocimiento médico, ofreciendo oportunidades para automatizar parte de la evaluación y reducir la carga del examinador, aunque su implementación debe alinearse con los objetivos de aprendizaje (15).

Desde esta perspectiva, la evaluación multimodal articula varios planos: indicadores de rendimiento (exactitud, tiempos de respuesta, secuencia de acciones, calidad del desempeño) (15,50); analíticas de interacción y aprendizaje, que reconstruyen trayectorias, patrones de conducta y participación (49).Una revisión sistemática de 2025 sobre learning analytics en entornos virtuales inmersivos concluye, precisamente, que este campo se encuentra en expansión, pero con escasa integración teórica y notable diversidad metodológica (49).A estos planos se añade la evaluación de la experiencia del usuario (presencia, satisfacción, facilidad e intención de uso, implicación, confort, malestar) (53,48). Los estudios sobre cybersickness y presencia en educación sanitaria pone de relieve que los estudiantes suelen referir niveles altos de presencia y bajos de cybersickness, aunque la evidencia sigue siendo limitada (54).

Finalmente, los enfoques multimodales incorporan medidas fisiológicas y neurofisiológicas: la combinación de EEG, frecuencia cardiaca, conductancia cutánea o respiración se está extendiendo para analizar estados del usuario durante la interacción virtual (51),enriqueciendo la interpretación con información sobre activación, carga mental, estrés y compromiso atencional (50, 51, 55).Por tanto, la evaluación multimodal integra lo que el estudiante hace, cómo lo hace, cómo vive la experiencia y cómo responde su organismo, ofreciendo una comprensión más completa y ecológica del aprendizaje en realidad virtual, aunque exige protocolos rigurosos y marcos interpretativos sólidos, entendiéndose como estrategia metodológica orientada a captar la complejidad del aprendizaje en entornos inmersivos (49, 50, 51, 56).

1.4 TOMA DE DECISIONES EN SITUACIONES DE ALTA COMPLEJIDAD SANITARIA, EMERGENCIAS Y CATÁSTROFES

Los entornos de emergencia, desastre y alta complejidad sanitaria exigen procesos de decisión rápidos, adaptativos y contextualizados, condicionados por la incertidumbre, la presión temporal, la información incompleta y la necesidad de priorizar acciones críticas (57).La toma de decisiones en estos contextos no responde a un único modelo lineal, sino a la combinación de estrategias intuitivas, analíticas y basadas en reglas, moduladas por experiencia, entrenamiento, estrés y naturaleza de la situación (58).En el ámbito sanitario y prehospitalario influyen además factores organizativos, humanos y contextuales como la coordinación interprofesional, la disponibilidad de recursos y las exigencias del escenario operativo (59).

1.4.1 Factor humano y modelos de toma de decisiones en emergencias

El factor humano ocupa un lugar central en la toma de decisiones en emergencias, ya que las decisiones no dependen únicamente del conocimiento técnico o de los algoritmos disponibles, sino también de cómo los profesionales perciben la situación, interpretan las señales del entorno, manejan la incertidumbre y regulan su actuación bajo presión (58). En los servicios de emergencias extrahospitalarias, la toma de decisiones se describe como un proceso dinámico y continuo, en el que los clínicos deben construir sentido de la situación, formular hipótesis, reevaluarlas sobre la marcha y adaptar su actuación en función de nueva información o del cambio de contexto. La evidencia reciente señala que, incluso cuando existen protocolos, su aplicación real está mediada por la experiencia, por la percepción de control y por la necesidad de ajustar la respuesta a la singularidad de cada caso (58,59).

Desde un punto de vista teórico, la investigación sobre decisiones en eventos de alto riesgo ha identificado varios modelos explicativos. Entre ellos, uno de los más citados en contextos de emergencia es el Recognition-Primed Decision Making (RPD), propio del marco de la naturalistic decision-making, según el cual los profesionales expertos no comparan siempre múltiples opciones de forma analítica, sino que reconocen patrones familiares en la situación y generan con rapidez una respuesta plausible basada en la experiencia previa (57). La revisión sistemática sobre toma de decisiones en eventos de alto riesgo confirma que las estrategias de tipo recognition-primed aparecen de forma consistente en profesiones como sanitarios, bomberos, ámbito militar o en profesionales de rescate, especialmente cuando existe una elevada presión temporal y la situación exige actuar con rapidez. Aun así, la misma revisión muestra que las estrategias analíticas siguen siendo relevantes en contextos con menor urgencia o cuando la incertidumbre obliga a contrastar hipótesis de manera más deliberada (57).

Esta coexistencia entre decisiones rápidas e intuitivas y decisiones más lentas y analíticas conecta también con los modelos de doble proceso, que distinguen entre un procesamiento inmediato, automático y basado en reconocimiento de patrones, y otro más reflexivo, deliberado y secuencial (60). Un estudio ergonómico reciente sobre la toma de decisiones del incident commander en simulaciones de incidentes con múltiples víctimas mostró precisamente una transición desde decisiones más instantáneas al inicio del evento hacia decisiones más consideradas conforme evolucionaba el ejercicio, apoyando la utilidad de este marco dual para comprender la dinámica decisional en emergencias complejas. La toma de decisiones en emergencias no puede reducirse a "intuición" o "análisis", sino que implica la movilización flexible de ambos tipos de procesamiento según el momento y la estructura del problema (61).

El factor humano incluye también variables como la experiencia profesional, la tolerancia a la ambigüedad, la carga mental, la comunicación y la interacción con el equipo, la experiencia facilita un uso más eficiente de las señales del entorno y permite anticipar escenarios, pero no elimina por completo la vulnerabilidad a sesgos, errores o sobrecarga, especialmente cuando la información inicial es escasa, ambigua o contradictoria (58,59). La agenda de investigación EMS **(**Emergency Medical Services) 2021-2026 en los Países Bajos identifica como prioridades la toma de decisiones compartida, la calidad de la información proporcionada por el despacho y otros factores humanos y organizativos que afectan a la respuesta prehospitalaria (62), lo que subraya que la decisión en emergencias no es solo un acto cognitivo individual, sino también un proceso situado dentro de un sistema sociotécnico más amplio (63). Así, los modelos de toma de decisiones en emergencias deben contemplar simultáneamente el peso de la experiencia, los procesos intuitivos basados en reconocimiento, la deliberación analítica cuando el contexto lo permite y la influencia del sistema en el que actúa el profesional, con el fin de diseñar mejores estrategias de formación, simulación, apoyo cognitivo y entrenamiento en competencias no técnicas (57,59,60,62).

1.4.2 Actuación del primer interviniente en contextos civiles y militares

La actuación del primer interviniente constituye una fase crítica en la cadena de respuesta ante emergencias y desastres: las primeras decisiones condicionan la seguridad de la escena, la priorización asistencial, la movilización de recursos y, en muchos casos, el pronóstico de las víctimas (68). En contextos civiles esta figura, incluye profesionales de emergencias sanitarias, bomberos, policía, voluntarios entrenados o sistemas organizados de first responders; en contextos militares, la actuación inicial se desarrolla con frecuencia en escenarios de amenaza activa, condiciones ambientales hostiles, limitaciones logísticas y necesidad de coordinación táctica (65,66). Pese a sus diferencias operativas, comparten un mismo núcleo competencial: valoración rápida, decisión bajo presión, manejo inicial de la víctima y coordinación efectiva con el sistema de respuesta (66,67).

En el ámbito civil, su valor depende no solo de la rapidez de llegada, sino también de su integración dentro del sistema prehospitalario y de la calidad de su preparación para intervenciones tiempo-dependientes. Un estudio descriptivo realizado en Noruega subraya que estos sistemas mejoran la preparación para los cuidados prehospitalarios críticos cuando existe una estructura clara de activación, formación y coordinación con los servicios de emergencias (68). Esto sugiere que la actuación no debe entenderse como una respuesta aislada, sino parte de una arquitectura asistencial más amplia donde la eficacia depende del individuo y del sistema en el que actúa (69).

En contextos militares se añaden exigencias del entorno táctico: amenaza, autoprotección, priorización inmediata y, a menudo, recursos limitados (70, 71). La literatura sobre entrenamiento en incidentes con múltiples víctimas y escenarios tácticos destaca competencias específicas en triaje, control de hemorragias, evacuación, coordinación operativa y toma de decisiones con fuerte presión temporal (6,72). El primer interviniente militar se sitúa en la intersección entre atención sanitaria, seguridad táctica y gestión del entorno, lo que incrementa notablemente la complejidad de la respuesta inicial (71,72).

La literatura reciente sobre entrenamiento de primeros intervinientes en incidentes con múltiples víctimas y escenarios tácticos destaca que estas situaciones exigen competencias específicas en triaje, control de hemorragias, evacuación, coordinación operativa y toma de decisiones con fuerte presión temporal (6,72). Por ello, en el ámbito militar la actuación del primer interviniente se sitúa en la intersección entre atención sanitaria, seguridad táctica y gestión del entorno, lo que incrementa notablemente la complejidad de la respuesta inicial (71,72).

La bibliografía más reciente insiste en la creciente necesidad de interoperabilidad civil-militar en la preparación y respuesta ante desastres, ya que los incidentes con múltiples víctimas y las catástrofes de gran magnitud exigen con frecuencia cooperación entre estructuras sanitarias, protección civil y fuerzas armadas (73-75). Los marcos de entrenamiento inmersivo y de simulación avanzada se están consolidando como recursos útiles para aproximar ambos mundos, ensayar escenarios compartidos, entrenar la coordinación y reducir la distancia entre doctrinas y procesos de decisión (76). Las revisiones recientes sobre realidad extendida en primeros intervinientes concluyen que estas tecnologías son prometedoras para mejorar preparación, exactitud del triaje, tiempos de respuesta y experiencia de usuario en escenarios de alta complejidad (7,77,78).

Desde el punto de vista de este marco teórico, la actuación del primer interviniente debe analizarse desde la técnica asistencial pero también desde el factor humano, la presión del contexto, la coordinación interprofesional y la adaptación al entorno operativo, justificando el uso de metodologías inmersivas que permitan entrenar no solo procedimientos, sino también juicio, flexibilidad y respuesta bajo presión (7,77,79).

1.4.3 Triage y atención en incidentes con múltiples víctimas

El triaje constituye uno de los procesos más críticos en los incidentes con múltiples víctimas (IMV), ya que permite priorizar la asistencia cuando la demanda supera temporalmente los recursos disponibles. Su objetivo no es ofrecer de inmediato el tratamiento más completo a cada paciente, sino maximizar el beneficio colectivo mediante una clasificación rápida, funcional y orientada a la supervivencia. La literatura reciente insiste en que el triaje en IMV debe entenderse como una herramienta dinámica de priorización dentro de un sistema más amplio de respuesta, y no como un acto aislado o puramente técnico (80,81,82).

Desde el punto de vista operativo, el triaje en IMV se caracteriza por realizarse en escenarios de elevada incertidumbre, presión temporal, información incompleta y frecuente desorganización inicial (80). Estas condiciones incrementan la probabilidad de sobretriaje y subtriaje, dos errores con consecuencias importantes: el primero consume recursos escasos en pacientes menos prioritarios, mientras que el segundo retrasa la atención de víctimas críticas. La actualización de guía clínica de 2025 sobre manejo de IMV subraya que la calidad del triaje depende no solo del algoritmo empleado, sino también de la estructura del sistema, la coordinación de la escena, la comunicación y la reevaluación continua de las víctimas (81,84).

La evidencia reciente muestra, además, que no existe un sistema universal de triaje válido para todos los contextos. Los algoritmos más utilizados presentan rendimientos variables según el tipo de incidente, el perfil de los intervinientes, la experiencia del equipo y el entorno asistencial (80,81). El estudio Delphi internacional sobre respuesta a IMV de inicio súbito identificó consenso en aspectos nucleares del triaje y del soporte vital prehospitalario, pero también puso de manifiesto la necesidad de adaptar procesos y prioridades al contexto real del desastre (85).Una revisión sistemática sobre entrenamiento en realidad extendida para IMV concluyó que la mejora del triaje depende no solo del método de entrenamiento, sino también de cómo se estructura la experiencia formativa y de la fidelidad con la que se reproduce la complejidad de la escena (77,86).

La atención sanitaria en los IMV no puede separarse del proceso de triaje, ya que ambas dimensiones forman parte de una misma lógica de priorización. Tras la clasificación inicial, la atención se orienta hacia intervenciones de alto impacto vital, control de hemorragias, manejo de la vía aérea, movilización segura, distribución de pacientes y coordinación con la evacuación. Las guías actuales sobre manejo de IMV insisten en que el triaje no debe concebirse únicamente como una etiqueta de color o categoría, sino como el inicio de una secuencia asistencial que conecta priorización, tratamiento inicial y destino del paciente dentro del sistema de respuesta (80,84,87).

Otro aspecto clave es la relación entre triaje y entrenamiento. La revisión sistemática de 2024 sobre realidad extendida en primeros intervinientes mostró que estas tecnologías pueden mejorar la exactitud del triaje, el tiempo de respuesta, la corrección de las actuaciones y la experiencia percibida en escenarios de IMV (77). Además, se confirma que estos entornos aportan realismo, seguridad, repetibilidad y confianza, aunque se recomienda su uso como complemento, y no como sustituto pleno, de otras formas de simulación en vivo (7). Estos hallazgos resultan especialmente relevantes para este marco teórico pues refuerza que el triaje en IMV no depende solo del conocimiento declarativo del algoritmo, sino de la capacidad de aplicarlo con rapidez, criterio y adaptación en entornos complejos y cambiantes (7,77,86) donde convergen juicio clínico, organización de la escena, priorización ética y respuesta operativa (80,84,85), representando uno de los escenarios paradigmáticos en los que la toma de decisiones bajo presión adquiere mayor relevancia, en condiciones de incertidumbre, carga cognitiva, necesidad de coordinación y reevaluación continua (57,66,86).

1.4.4 Atención sanitaria en medicina táctica

La medicina táctica se sitúa en la intersección entre la atención sanitaria urgente y la operación en entornos hostiles, donde la asistencia debe prestarse bajo amenaza, con recursos limitados y en escenarios marcados por la inseguridad, la presión temporal y la necesidad de compatibilizar la supervivencia de la víctima con la seguridad del interviniente y del equipo (88). A diferencia de la asistencia prehospitalaria convencional, la atención sanitaria en medicina táctica no se desarrolla en un entorno clínicamente neutro, sino en contextos donde el peligro activo, la movilidad forzada, la dificultad de evacuación y la incertidumbre operativa condicionan de forma decisiva la secuencia asistencial (88,70). La literatura reciente la describe como un campo donde la toma de decisiones clínicas está inseparablemente ligada a la evaluación táctica del entorno (89,90).

En este marco, el modelo doctrinal más influyente es Tactical Combat Casualty Care, desarrollado para adaptar la atención al herido en combate a las condiciones reales del campo táctico. Las actualizaciones recientes del Committee on Tactical Combat Casualty Care mantienen la organización de la asistencia en fases, con prioridades distintas según el nivel de amenaza y la posibilidad de intervenir con seguridad, lo que refuerza la lógica de una atención progresiva y dependiente del contexto (70,91). Este enfoque implica que la asistencia no sigue únicamente una lógica clínica, sino también una lógica secuencial condicionada por el entorno: en fases iniciales, el control de una hemorragia masiva o el desplazamiento de la víctima hacia una zona más segura puede tener prioridad sobre otras maniobras que, en un escenario civil convencional, se ejecutarían antes (70,91,92).

Uno de los rasgos distintivos de la medicina táctica es la priorización de intervenciones críticas de alto impacto vital. La evidencia reciente y las guías más recientes sitúan entre las prioridades iniciales el control de hemorragias potencialmente exanguinantes, el manejo de la vía aérea cuando es posible, la identificación y tratamiento del compromiso respiratorio grave, la prevención de la hipotermia y la preparación para la evacuación (79,91,93). Estas prioridades han sido operacionalizadas en secuencias como MARCH (massive hemorrhage, airway, respirations, circulation, head injury/hypothermia), ampliamente utilizadas en entrenamiento y asistencia táctica, y especialmente útiles cuando el entorno impide aplicar de forma íntegra y simultánea todos los procedimientos habituales de la atención avanzada (89,94).La relevancia de este modelo reside en que convierte la atención en una cadena de decisiones jerarquizadas, adaptadas al riesgo, al tiempo disponible y a la viabilidad real de intervenir en cada momento (70,91).

La literatura reciente subraya también que la medicina táctica no se limita al ámbito militar, sino que ha ampliado su influencia a contextos civiles de amenaza activa, incidentes con tirador, rescates complejos y respuesta integrada entre cuerpos de seguridad y servicios sanitarios. Las revisiones recientes sobre Tactical Combat Casualty Care y Tactical Emergency Casualty Care describen una transferencia progresiva de principios originalmente militares hacia escenarios civiles de alto riesgo, adaptados a contextos donde la amenaza persiste y la entrada de los equipos asistenciales depende de la seguridad de la escena, la zonificación operativa y la coordinación interagencial (89,92,95). Esto refuerza la idea de que la medicina táctica debe entenderse como una competencia transversal para determinados escenarios de alta complejidad, más allá del combate estrictamente militar (70,90).

Desde el punto de vista del factor humano, la atención sanitaria en medicina táctica exige un elevado nivel de entrenamiento técnico y, al mismo tiempo, de juicio situacional (57). El interviniente debe decidir no solo qué intervención es clínicamente indicada, sino cuándo es factible, segura y compatible con la situación táctica, en entornos de amenaza, presión temporal e información incompleta (70,88). Esta presión puede favorecer errores de priorización, omisiones o retrasos cuando el entrenamiento no reproduce con suficiente fidelidad la carga emocional, sensorial y cognitiva del entorno (57,88). Por ello, la simulación, los serious games y la realidad virtual pueden ser especialmente útiles para medicina táctica y para la preparación de primeros intervinientes, al permitir entrenar algoritmos como MARCH, juicio operativo, triage y coordinación bajo condiciones más próximas a la realidad que la enseñanza expositiva convencional (77,96).

Así, la atención sanitaria en medicina táctica representa un paradigma de decisión clínica bajo amenaza, en el que la asistencia se integra de forma inseparable con la seguridad, la movilidad y la misión operativa (70,89,90). Su inclusión en el marco teórico resulta especialmente pertinente porque ejemplifica con claridad cómo los procesos cognitivos, emocionales y fisiológicos implicados en la toma de decisiones bajo presión se activan en una situación de máxima exigencia, marcada por la incertidumbre, la urgencia, la amenaza persistente y la necesidad de coordinación táctica (57,88). Es por ello, que los entornos inmersivos constituyen una herramienta especialmente valiosa para estudiar y entrenar este tipo de respuesta, ya que permiten reproducir escenarios complejos, practicar algoritmos y prioridades asistenciales, y observar el desempeño en condiciones más próximas a la realidad operativa que la enseñanza convencional (7,77,96).

1.4.5 Reanimación en hipotermia accidental

La hipotermia accidental constituye una emergencia tiempo-dependiente de elevada complejidad, tanto por la gravedad fisiopatológica que puede alcanzar como por las particularidades diagnósticas y terapéuticas que introduce en la reanimación (97). A diferencia de otros contextos de parada cardiorrespiratoria, en la hipotermia profunda la disminución del metabolismo puede prolongar la viabilidad tisular y hacer posible la supervivencia con buen pronóstico neurológico incluso tras periodos prolongados de colapso circulatorio, lo que obliga a adaptar la estrategia asistencial y a evitar decisiones precipitadas de limitación terapéutica (97,98). La literatura reciente insiste en que la reanimación en hipotermia accidental debe entenderse como un proceso específico, condicionado por la temperatura central, el mecanismo de enfriamiento, la estabilidad hemodinámica y la disponibilidad de recursos avanzados de recalentamiento (97,99).

Desde el punto de vista clínico, la atención inicial se basa en el reconocimiento precoz del cuadro, la prevención de mayor pérdida de calor y la priorización de medidas de soporte vital adaptadas al paciente hipotérmico. En el entorno prehospitalario, los trabajos más recientes subrayan la importancia de combinar aislamiento pasivo, manejo cuidadoso del paciente y, cuando esté indicado y disponible, calentamiento activo externo, todo ello junto con una medición fiable de la temperatura central (97,100). Un estudio nacional noruego publicado en 2024 mostró variabilidad en los recursos y métodos disponibles para el manejo prehospitalario de la hipotermia accidental, lo que refuerza la idea de que la calidad de la atención depende en gran medida de la preparación del sistema y no solo del conocimiento individual del interviniente (101).

La reanimación cardiopulmonar en la hipotermia accidental presenta características diferenciales. En los pacientes con parada cardiaca por hipotermia severa, las recomendaciones contemporáneas mantienen la necesidad de iniciar y sostener maniobras de soporte vital, al tiempo que identifican de forma temprana si el paciente puede beneficiarse de recalentamiento extracorpóreo mediante ECLS (Extracorporeal Life Support)/ECMO (Extracorporeal Membrane Oxygenation) o bypass cardiopulmonar (97,98,99). La evidencia reciente sobre soporte extracorpóreo en hipotermia sugiere que este abordaje sigue siendo una de las estrategias con mayor potencial de supervivencia neurológicamente favorable en casos seleccionados, especialmente cuando la selección se integra con criterios pronósticos específicos y con la disponibilidad real de centros expertos (98,102). Los análisis publicados en 2024 han reactivado la discusión sobre los puntos de corte y los criterios de selección para recalentamiento extracorpóreo, en relación con la actualización de recomendaciones y con la forma de equilibrar el riesgo de futilidad terapéutica frente a la posibilidad de supervivencia recuperable (102,103).

En este proceso de selección, la literatura ha dado especial relevancia a herramientas pronósticas como el HOPE score, diseñado para estimar la probabilidad de supervivencia en pacientes con parada cardiaca hipotérmica candidatos a soporte extracorpóreo (103,104).Aunque no sustituye al juicio clínico, el HOPE (Hypothermia Outcome Prediction after Extracorporeal Life Support) score se ha consolidado como apoyo para la toma de decisiones en centros con capacidad ECLS, al integrar variables como edad, sexo, mecanismo de enfriamiento, temperatura central, potasio sérico y duración de la reanimación (103, 104).Su uso refleja bien la especificidad de la hipotermia accidental: frente a otros tipos de parada, variables como la asfixia asociada, el mecanismo de enfriamiento o la bioquímica inicial adquieren aquí un peso pronóstico especialmente relevante (97,104,105).

La decisión clínica en este escenario resulta particularmente compleja porque combina elementos de medicina de emergencias, cuidados críticos, rescate y logística de evacuación. La evidencia reciente sobre terapias de recalentamiento muestra que los resultados no dependen únicamente de una técnica aislada, sino también de la rapidez en el reconocimiento, la prevención del deterioro durante la extricación y el transporte, la correcta categorización del paciente y la derivación a centros capaces de ofrecer soporte avanzado de recalentamiento y ECLS cuando esté indicado (97,98). Los estudios recientes sobre manejo prehospitalario muestran además una variabilidad importante en monitorización, equipos de calentamiento, protocolos y entrenamiento, lo que refuerza la idea de que el pronóstico depende en gran medida de la preparación del sistema, de la coordinación entre niveles asistenciales y de la estandarización de procedimientos (101,106). Por ello, la reanimación en hipotermia accidental constituye un ejemplo más en el que la coordinación del sistema, la estandarización de procedimientos y el entrenamiento específico tienen un impacto decisivo sobre el resultado clínico (97,106).

Podemos confirmar pues, que la reanimación en hipotermia accidental representa uno de los escenarios más singulares de la medicina de emergencias, porque obliga a adaptar los algoritmos habituales a una fisiopatología distinta y a una ventana terapéutica potencialmente más amplia (97,98). Su inclusión en este marco teórico es especialmente pertinente porque ejemplifica cómo la toma de decisiones en contextos de alta complejidad depende simultáneamente del conocimiento clínico, del juicio pronóstico, de la respuesta fisiológica del paciente y de la capacidad del sistema para proporcionar una atención escalonada y especializada (99,103,104). Decidir bien no depende solo de aplicar maniobras correctas, sino de reconocer qué paciente puede beneficiarse de estrategias avanzadas, cuándo activar recursos extraordinarios y cómo sostener la continuidad asistencial desde el entorno prehospitalario hasta el centro especializado (97,104,105).

1.4.6 Conducción en condiciones extremas como modelo de riesgo

La conducción en condiciones extremas constituye un escenario más útil para estudiar la percepción del riesgo y la toma de decisiones en contextos de incertidumbre, presión ambiental y amenaza potencial. La literatura reciente muestra que fenómenos como la lluvia intensa, la niebla, la nieve, las inundaciones y la baja visibilidad modifican de forma significativa la conducta del conductor, incrementan la complejidad perceptiva del entorno y elevan el riesgo de siniestro (107,108). En este sentido, la conducción bajo condiciones meteorológicas adversas puede entenderse como un escenario válido para analizar cómo los individuos valoran el peligro, ajusta su comportamiento y responden ante señales cambiantes del medio (109,110). La evidencia sugiere, además, que esta adaptación conductual no siempre compensa por completo el aumento objetivo del riesgo, lo que refuerza el interés de este contexto para estudiar la relación entre percepción, decisión y acción en situaciones dinámicas y amenazantes (107,108).

Desde el punto de vista cognitivo, estos escenarios exigen una integración rápida de información visual, espacial y situacional, así como una actualización constante de la decisión de continuar, reducir la velocidad, detenerse o modificar la ruta (112). La evidencia reciente indica que el empeoramiento de las condiciones meteorológicas tiende a aumentar el riesgo percibido, pero que esta relación no siempre es lineal, ya que en situaciones de visibilidad extremadamente reducida algunos conductores pueden infraestimar el peligro o mostrar respuestas poco adaptativas (107,111). Esta complejidad convierte la conducción extrema en un marco especialmente interesante para estudiar la interacción entre percepción, carga cognitiva y conducta, porque obliga al conductor a reajustar continuamente su evaluación del entorno y su respuesta motora ante señales cambiantes del medio (112).

En el caso específico de las inundaciones, el riesgo adquiere una dimensión singular, ya que la decisión de atravesar una vía inundada suele producirse en condiciones de información incompleta y con una percepción frecuentemente errónea de la profundidad, la fuerza del agua o la capacidad del vehículo para mantener la tracción (113). Un estudio de simulación publicado en 2024 mostró que proporcionar información más detallada sobre la profundidad del agua ayudaba a los conductores a estimar mejor el riesgo y a tomar decisiones más informadas ante carreteras potencialmente inundadas (114). Estos hallazgos son relevantes porque sugieren que la respuesta del conductor no depende solo de la presencia del peligro, sino también de cómo se comunica y representa ese peligro en el momento de la decisión (113,114).

La literatura reciente también ha subrayado el papel de la edad y la experiencia en la percepción del riesgo durante la conducción (107). En población joven, varios trabajos de los últimos años muestran que los conductores noveles identifican peor determinados peligros relacionados con visibilidad reducida, condiciones nocturnas o entornos complejos, y que sus juicios de riesgo pueden diferir de los de conductores con mayor experiencia. Esta evidencia refuerza la idea de que la conducción en condiciones extremas es un modelo adecuado para explorar diferencias individuales en la valoración del riesgo, la anticipación del peligro y la elección de conductas seguras o inseguras (107,115).

Además, el interés de este modelo no se limita a la seguridad vial, sino que se extiende al campo de la educación preventiva. Las situaciones de conducción extrema permiten trabajar con escenarios realistas en los que el sujeto debe interpretar señales ambientales, regular la activación emocional y decidir bajo presión, elementos muy próximos a otros contextos de emergencia y alta complejidad (113,116). La evidencia sobre entrenamiento inmersivo en reconocimiento y prevención de peligros también respalda el valor de escenarios realistas para desarrollar habilidades cognitivas, mejorar el rendimiento y favorecer el aprendizaje aplicado (117). Por todo esto, la conducción bajo condiciones meteorológicas adversas y, de forma particular, en escenarios de inundación, constituye un modelo de riesgo pertinente para el estudio de la toma de decisiones en entornos dinámicos (107,108,114). Su relevancia para este marco teórico reside pues, en que el escenario integra variables perceptivas, cognitivas, emocionales y conductuales en una misma situación, haciéndolo especialmente útil para investigar y entrenar competencias relacionadas con la valoración del peligro, la autorregulación y la respuesta adaptativa ante amenazas ambientales (109,114,116).

II – JUSTIFICACIÓN

II - JUSTIFICACIÓN

La formación en ciencias de la salud y en el ámbito de las emergencias constituye un reto prioritario en contextos donde la toma de decisiones debe realizarse con rapidez, bajo presión y en escenarios caracterizados por la incertidumbre, la complejidad y, en ocasiones, el riesgo vital. En estos entornos, la preparación de los profesionales y de los primeros intervinientes no puede limitarse a la adquisición de conocimientos teóricos, sino que debe incluir el entrenamiento de competencias prácticas, cognitivas y emocionales necesarias para actuar de forma eficaz y segura ante situaciones críticas.

A pesar de esta necesidad, persiste una brecha importante entre las demandas reales de los contextos asistenciales y operativos y las posibilidades que ofrecen los modelos tradicionales de formación. La enseñanza convencional, basada de forma predominante en sesiones expositivas, simulación no inmersiva o entrenamiento puntual, presenta limitaciones para reproducir con fidelidad la presión temporal, la carga cognitiva, la activación emocional y la complejidad ambiental propias de escenarios como los incidentes con múltiples víctimas, la medicina táctica, la reanimación en hipotermia accidental o la toma de decisiones ante situaciones de riesgo. Estas limitaciones dificultan no solo el aprendizaje contextualizado, sino también la evaluación objetiva del desempeño en condiciones próximas a la realidad.

En paralelo, la transformación digital de la educación sanitaria ha favorecido la incorporación de metodologías más activas, flexibles e inmersivas. En este marco, la realidad virtual y otras tecnologías inmersivas ofrecen una oportunidad especialmente relevante, al permitir la recreación de escenarios complejos en entornos seguros, controlados y repetibles. Además de facilitar el entrenamiento técnico, estas herramientas permiten abordar dimensiones menos accesibles en los modelos clásicos, como la percepción del riesgo, la respuesta fisiológica al estrés, la atención, la carga cognitiva, la experiencia del usuario y la toma de decisiones bajo presión.

No obstante, el valor educativo de estas tecnologías no debe asumirse de forma acrítica. Su integración en ciencias de la salud requiere evidencia que permita comprender no solo su viabilidad o aceptación, sino también su utilidad real en la formación, en la evaluación del desempeño y en el estudio de los procesos cognitivos, emocionales y neurofisiológicos implicados en la actuación ante situaciones complejas. Asimismo, resulta necesario analizar su aplicabilidad en distintos contextos, desde la educación superior en ciencias de la salud hasta escenarios de emergencias, desastres, medicina táctica y seguridad vial, con el fin de determinar en qué medida estas herramientas pueden contribuir a mejorar la preparación de los usuarios y la calidad de la respuesta.

La presente tesis doctoral se justifica, por tanto, en la necesidad de generar evidencia aplicada sobre el potencial de la realidad virtual y de las tecnologías inmersivas en la educación en ciencias de la salud y en la preparación ante contextos críticos. A través de un compendio de cinco artículos, esta investigación aborda de forma complementaria la viabilidad del metaverso y de la realidad virtual en educación sanitaria, su impacto sobre la percepción del riesgo en escenarios de conducción extrema, su influencia sobre el estrés y los patrones neurofisiológicos, y su utilidad para el entrenamiento y la evaluación de la toma de decisiones en incidentes con múltiples víctimas, medicina táctica y reanimación en hipotermia accidental.

Esta tesis pretende aportar conocimiento útil para el diseño de estrategias formativas más innovadoras, seguras, evaluables y adaptadas a la complejidad de los entornos sanitarios y de emergencia contemporáneos. Su finalidad no es únicamente explorar nuevas herramientas tecnológicas, sino contribuir a comprender cómo estas pueden mejorar la formación, la evaluación y la preparación de quienes deben actuar ante situaciones donde el tiempo, la incertidumbre y la calidad de la decisión resultan determinantes.

III – OBJETIVOS

III - OBJETIVOS

3.1. OBJETIVO GENERAL

Analizar el potencial de la realidad virtual en contextos de emergencias, desastres y alta complejidad, considerando su utilidad para la formación, el entrenamiento y la evaluación de los usuarios, así como su influencia en la percepción del riesgo y en la respuesta cognitiva, emocional y neurofisiológica implicada en la toma de decisiones.

3.2. OBJETIVO ESTUDIO I

Evaluar la viabilidad, los desafíos y las oportunidades de integrar el metaverso y las tecnologías de realidad virtual (RV) en la educación en ciencias de la salud.

3.3. OBJETIVO ESTUDIO II

Analizar el impacto de una experiencia inmersiva de realidad virtual (RV) en la percepción del riesgo de los adolescentes durante una tarea de conducción simulada bajo condiciones de lluvia extrema, evaluada mediante medidas conductuales y registros de neuroimagen.

3.4. OBJETIVO ESTUDIO III

Evaluar el impacto de la realidad virtual (RV), en comparación con métodos audiovisuales no inmersivos, sobre la percepción del riesgo, los niveles de estrés y los patrones neurofisiológicos durante un escenario de conducción simulado en condiciones de inundación.

3.5. OBJETIVO ESTUDIO IV

Analizar la toma de decisiones en dos escenarios de RV: 1) incidente con múltiples víctimas (IMV) y 2) un escenario de Tactical Combat Casualty Care (TCCC). La finalidad es explorar la respuesta de los participantes ante situaciones de alta exigencia operativa mediante indicadores objetivos, subjetivos, fisiológicos y neurocognitivos

3.6. OBJETIVO ESTUDIO V

Evaluar un escenario de hipotermia accidental desarrollado con realidad virtual inmersiva durante el ejercicio OTAN Emergency Management Exercise Bulgaria 2025. Se analizaron: 1) la exactitud de las decisiones clínicas frente a un estándar de referencia consensuado y 2) la experiencia del usuario. El propósito final fue valorar la aplicabilidad de este enfoque para la formación y evaluación de primeros intervinientes en contextos civil–militares.

IV – ESTUDIO I

Meta-health: a national swot analysis for the development of a metaverse and virtual reality in health sciences education.

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Teaching and Learning in Nursing 20 (2025) e579–e586

Contents lists available at ScienceDirect

Teaching and Learning in Nursing

journal homepage: www.journals.elsevier.com/teaching-and-learning-in-nursing

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Research

Meta-health: a national swot analysis for the development of a metaverse and virtual reality in health sciences education

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ARTICLE INFO

Article History:
Accepted 16 January 2025

Keywords:
Metaverse
Virtual Reality
Health Sciences Education
Immersive Learning
Ethical Challenges
Clinical Simulations
Meta-Health

ABSTRACT

Background: The integration of virtual reality (VR) and the metaverse into health sciences education (HSE) offers immersive, interactive learning environments that simulate clinical scenarios. However, their adoption faces technological, pedagogical, and ethical challenges.
Aim: To assess the feasibility, opportunities, and barriers to integrating VR and the metaverse into HSE through a national, multidisciplinary project.
Methods: A multicenter qualitative study was conducted with 37 professionals from nine universities. Data were collected through discussion groups and analyzed using thematic and SWOT analyses. Themes such as technological barriers, educational benefits, and ethical concerns were identified.
Results: Key strengths include interdisciplinary expertise and institutional commitment to innovation. Weaknesses involve high costs and steep learning curves. Opportunities lie in enhancing skill acquisition, global collaboration, and virtual assessments. Threats include rapid technological changes and ethical considerations.
Conclusions: The metaverse and VR have transformative potential for HSE, but challenges such as cost, training, and ethical standards must be addressed. Strategic investment and robust ethical frameworks are essential for their successful implementation.

Introduction

The integration of virtual reality (VR) into health sciences education (HSE) presents a unique opportunity to enhance experiential learning (Junga et al., 2024). VR enables immersive, interactive environments that simulate real-life clinical experiences (SIMZINE Redazione, 2024). The concept of the metaverse, a virtual space where multiple users can engage simultaneously, further expands the potential for collaborative and realistic simulations in health sciences (Radianti et al., 2020).

METAHEALTH is a national project funded by the Ministry of Science and Innovation of Spain, aimed at integrating cutting-edge technologies like the metaverse and VR into HSE. The project focuses on creating immersive virtual environments that simulate real clinical scenarios, allowing health disciplines students to practice skills in a risk-free setting.

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[#] **Meta-health research group:** Information about the Meta-Health Research Group in Supplementary File 1.

https://doi.org/10.1016/j.teln.2025.01.009
1557-3087/

Background

The educational paradigm is evolving, with metaverse applications transforming medical education through real-time, immersive, and interactive learning experiences. (Junga et al., 2024). The exponential revolution, marked by the expansive growth of virtual learning resources across various scientific fields, was almost unimaginable during the days when knowledge was controlled by instructors and limited to paper-based and in-person teaching methods. Students now have the flexibility to choose their sources of information and, with the advent of asynchronous learning, the time for their education. Today, we continue to teach three-dimensional and dynamic concepts in flat, static formats. The emergence of extended reality (XR) has surpassed its role in the educational revolution and is leading to a true social transformation (Popov et al., 2024; SIMZINE Redazione, 2024).

XR is an abstract concept that encompasses a range of technologies, such as VR, augmented reality (AR), and immersive reality (IR) (Piromchai et al., 2015). XR, still in the process of full implementation, allows for the creation of virtual spaces where people can interact, even when they are not physically together. This immersive experience, results in significant improvements in procedural memory, speed, accuracy, and the transfer of knowledge to real-life scenarios compared to instructor-led training.

VR has proven effective in improving student engagement and knowledge retention. For health sciences, this technology facilitates the simulation of clinical scenarios (Makransky & Lilleholt, 2018). A metaverse expands on these capabilities by enabling multiple users to collaborate in the same simulation, while also shaping the future of post-pandemic medical education through emerging technologies and tailored recommendations for institutions to embrace revolutionary changes. (Lewis, Popov, & Fatima, 2024).

Health Sciences Education

The use of VR in health sciences is growing, especially in medical and nursing education, where it is used to simulate anatomy, patient care, and procedural training (Kyaw et al., 2019). Studies show that students who use VR simulations develop superior spatial and procedural skills compared to those using traditional learning methods (Chen et al., 2021; Junga et al., 2024; Radianti et al., 2020).

Studies have highlighted how VR provides nursing students with an immersive and engaging platform to practice clinical skills in a safe controlled environment (Saab et al., 2021; Ferrandini Price et al., 2018). The technology has been praised for its ability to simulate complex scenarios, allowing students to make decisions and witness the consequences in real-time, thus enhancing their clinical reasoning and confidence (Sun et al., 2020). In the study conducted by Ferrandini Price et al. (2018) compared traditional clinical simulation with immersive VR for training nursing students in handling incidents involving multiple victims. The findings indicated that VR was as effective as traditional simulation for basic triage, while reducing students.

Designing the Metaverse for HSE

An effective health sciences metaverse should provide realistic and immersive simulations. The immersive virtual environments help students better understand complex medical procedures by allowing them to perform tasks that replicate real-life scenarios (Ghaempanah, Moasses Ghafari, Hesami, et al., 2024). One of the key strengths of the metaverse is its capacity for fostering collaboration. Health sciences students can use the metaverse to practice teamwork and interprofessional collaboration in complex clinical scenarios (Johnston et al., 2018). By simulating real-life healthcare team interactions, the metaverse allows students from various disciplines to work together and improve communication and decision-making skills.

Objective

The aim of this study is to assess the feasibility, challenges, and opportunities of integrating metaverse and virtual reality (VR) technologies into health sciences education (HSE).

Methodology

The methodological approach of this project is based on a qualitative framework, using both discussion groups and the SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) to assess the feasibility, challenges, and opportunities for implementing the metaverse and VR in HSE. To ensure a structured approach to data collection, a series of guiding questions were developed specifically for the SWOT analysis. These questions are provided in the Supplementary File 1. The qualitative data were analyzed through Thematic Analysis (Braun & Clarke, 2006), ensuring a structured identification of patterns and their alignment with the SWOT framework. This combination provides a robust foundation for interpreting multidisciplinary perspectives on the integration of virtual reality (VR) and the metaverse into health sciences education.

Discussion Groups

To gather qualitative data and gain a broad, multidisciplinary perspective, we organized discussion groups with experts in HSE, educational technology, and VR research. These groups included professionals from different universities and specialties who are on the project team (Supplementary File 2).

This is a multicenter study, involving 37 professionals from 9 universities: 8 in Spain and one expert from a university in Switzerland. The sample consisted primarily of healthcare professionals (about 70%) from health fields such as medicine, nursing, dentists, physiotherapists and podiatrist. The remaining 30% of participants included engineers, teachers, and pedagogical experts. This diverse composition allowed for a holistic view of the challenges and opportunities in integrating immersive technologies into health sciences education, as both the technical and educational aspects were thoroughly discussed.

Data Collection

Three discussion group sessions were conducted, each lasting 90 to 120 min. Each participant attended only one session. Prior to the start of each meeting, participants were asked to provide demographic and professional information, including age, gender, professional role, and years of experience. Throughout the sessions, they were encouraged to freely express their opinions while remaining aligned with the key areas of interest. All sessions were audio-recorded with the participants' consent, and facilitators took detailed notes to ensure comprehensive data collection. This approach allowed us to link participant characteristics with the qualitative insights obtained, thereby facilitating a more nuanced interpretation of the results.

Data Processing

After the discussion, the recordings were transcribed verbatim. These transcriptions were then systematically coded using qualitative data analysis software (MAXQDA®), allowing for the identification of recurring themes, concepts, and patterns. The coding process involved both inductive and deductive approaches. Initially, an open coding technique was applied to identify emerging themes from the data, followed by axial coding to connect these themes to the broader research questions. Categories were then formed, including themes such as "technological barriers," "pedagogical benefits," and "ethical

Table 1
Sociodemographic and Professional Characteristics of the Expert Discussion Group Participants.

Characteristic	Participants	Percentage

Table 2
Summary of SWOT Analysis Results with Testimonies.

Aspect	Result	Testimonies
Strengths	- Interdisciplinary collaboration across institutions and fields.	"The strength of our team is the diversity of expertise, from medicine to technology, which allows for a holistic approach."
	- Strong institutional commitment to educational innovation.	*"Our institution has always been a pioneer in adopting new educational technologies, and this project is a natural fit."*
Weaknesses	- High initial costs for equipment and infrastructure.	*"The cost of acquiring and maintaining VR headsets and software is a big hurdle, especially for smaller institutions."*
	- Steep learning curve for educators and students.	*"Many educators are not familiar with these technologies, and it will take significant time and resources to train them."*
Opportunities	- Potential to revolutionize HSE with immersive learning.	*"The metaverse offers a level of interactivity and realism that we've never been able to achieve in traditional settings."*
	- Ability to collaborate internationally and reach underserved regions.	*"We can use this platform to provide quality education to students in remote areas who lack access to physical facilities."*
Threats	- Rapid evolution of VR technologies may require frequent updates.	*"With technology changing so fast, what we implement today could become obsolete in just a few years."*
	- Ethical concerns around data privacy and the use of virtual patients.	*"We need to be very careful with how we handle personal data in virtual environments, especially when simulating patients."*

1. **Strengths**

- **Interdisciplinary Expertise**. The project benefits from a highly qualified and interdisciplinary team. This diversity allows for a comprehensive approach to designing and implementing the metaverse.
- **Commitment to Innovation**. All participating institutions demonstrated a strong commitment to innovation in education, making them well-positioned to pioneer the use of VR in their curricula.

2. **Weaknesses**

- **Technological Barriers**. A key weakness identified was the potential difficulty for some institutions to invest in the necessary infrastructure. High costs associated with VR headsets, software, and continuous updates were noted as significant challenges.
- **Initial Resistance**. The learning curve associated with adopting VR and metaverse technologies was another area of concern. Educators and students may be resistant to change, particularly if they are unfamiliar with the tools.

3. **Opportunities**

- **Revolutionizing HSE**. The metaverse offers a unique opportunity to transform how health sciences are taught. From clinical simulations to virtual anatomy lessons, the metaverse can provide immersive, hands-on experiences that would otherwise be impossible in traditional classrooms.
- **Global Reach and Collaboration**. The use of virtual environments allows for greater collaboration across borders. Institutions in underserved regions could access high-quality training and resources through the metaverse, overcoming geographical barriers to education.

4. **Threats**

- **Rapid Technological Changes**. The rapid pace of VR technological advancement could result in obsolescence, requiring frequent updates and additional investments in hardware and software.
- **Ethical and Legal Considerations**. Data privacy, informed consent, and the ethical treatment of virtual avatars and patients were identified as ongoing concerns that need to be addressed before full-scale implementation can take place.

Quantitative Findings

Although the project was primarily qualitative in nature, the analysis also yielded some quantitative insights from participant feedback:

- 80% of the participants believed that VR would significantly improve students' practical skills in clinical environments.
- 75% expressed concerns about the initial cost of implementation, though they acknowledged long-term benefits for student learning.
- 90% emphasized the importance of addressing ethical concerns, particularly in relation to data privacy and the representation of virtual patients.

Discussion

The results of this study highlight both the immense potential and the significant challenges of integrating the metaverse and VR into HSE. These findings not only confirm the viability of the metaverse as a revolutionary educational tool but also point to areas that require careful consideration and further research.

Main Challenges of Virtual Reality

The implementation of VR and the metaverse in HSE faces several technological hurdles. The high cost of VR hardware and software can be a barrier to widespread adoption (Boyles, 2017). Additionally, technical limitations like motion sickness and restricted fields of view can affect the user experience, limiting the amount of time students can spend in virtual environments (Rebenitsch & Owen, 2016).

Ethical issues such as data privacy and informed consent are critical in the design of health education metaverses. The use of virtual patients and simulations may expose sensitive data if proper security measures are not taken (Christman et al., 2022). Moreover, the ethical treatment of virtual patient avatars and the need for realistic yet respectful representations must be carefully managed.

VR simulations must be closely aligned with health sciences curricula to ensure that they effectively support learning outcomes (Cook et al., 2019). Educational designers need to integrate VR into the broader curriculum, balancing theoretical knowledge with practical simulation-based learning experiences. Failure to do so could result in simulations that are engaging but lack educational value.

The Fig. 1 represent the main challenges of VR. Developing a VR metaverse for health sciences presents several challenges. One major

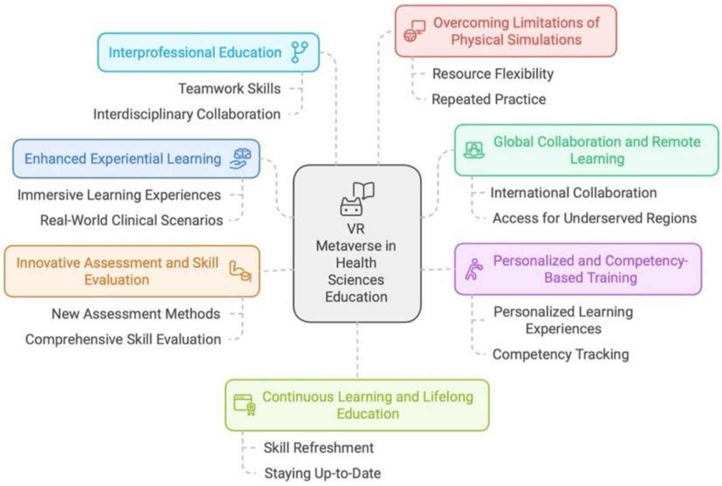

Fig. 2. Summary of the main opportunities.

international talent, promote mobility, and provide high-quality, accessible education that meets the demands of a rapidly evolving global society. Most importantly, it determines a conceptual change in teaching and learning, not without risks (Gorshkov, 2024).

Virtual Nurse Education

In healthcare, particularly in nursing, clinical simulation has become one of the most prominent learning methodologies in both university teaching and clinical practice (Cant & Cooper, 2017). United States (US) guidelines, such as those established by the American Heart Association (AHA) and American Red Cross, emphasize the importance of evidence-based methods in CPR training to ensure high-quality resuscitation practices and improved patient outcomes. The 2024 guidelines highlight the need for innovative, accessible, and scalable training solutions to increase bystander intervention rates and enhance skill retention, particularly in geographically diverse populations like those in the US (Hewett Brumberg et al., 2024). It is proposed to combine Problem-Based Learning (PBL) or Case-Based Learning (CBL) with the pedagogical foundations of Clinical Simulation (Briefing-Simulation-Debriefing framework) to develop Virtual Clinical Simulation (VCS). Through VCS, a metaverse could be created, serving as a resource hub—a common repository where educators can share their simulation sessions.

Conclusion and Future Directions

The integration of the metaverse and VR into HSE presents a transformative opportunity to enhance learning outcomes, particularly in terms of practical skill acquisition, knowledge retention, and interprofessional collaboration. Moreover, the metaverse promotes teamwork among diverse healthcare students, aligning with the increasing emphasis on multidisciplinary approaches.

However, the challenges identified—particularly the technological barriers and ethical concerns—must be carefully addressed to ensure the successful implementation of these technologies. This is particularly interesting for large countries such as the US, where geographical barriers can limit access to high-quality training resources. By leveraging VR, nurse educators can provide consistent and engaging training experiences to students and laypersons in remote or underserved areas, aligning with efforts to improve nationwide accessibility to healthcare education. The high initial cost of VR equipment and the steep learning curve, while significant, can be mitigated with appropriate investment and training. More importantly, ensuring that data privacy and ethical standards are maintained within virtual environments.

In conclusion, while the metaverse holds great promise for revolutionizing HSE, its full potential will only be realized through a careful balancing of technological innovation with ethical considerations. Future research should focus on refining the usability of VR tools, making them more accessible, and addressing the legal and ethical frameworks necessary for their responsible use in educational settings.

Dimension 1: Research team and reflexivity

Personal characteristics

1. **Interviewer/facilitator**:

Author 1 and Author 4 led the interviews and focus groups.

2. **Credentials**:

The main researchers hold PhD and MD degrees, representing health and educational sciences expertise.

3. **Occupation**:

At the time of the study, the researchers were university professors, health professionals, and engineers.

4. **Gender**:

Male: 4, Female: 5.

5. **Experience and training**:

The researchers have extensive experience in qualitative research, virtual reality, and health sciences education.

Relationship with participants

6. **Relationship established**:

Yes, prior contact with participants was established to explain the purpose of the study.

7. **Participant knowledge of the interviewer**:

Participants were aware of the research objectives and the roles of the investigators, particularly related to educational innovation and technology integration.

8. **Interviewer characteristics**:

26. **Derivation of themes**:

Themes were derived inductively from the data collected during the discussion groups.

27. **Software**:

MAXQDA® software was used to manage and analyze the data.

Acknowledgments

The authors acknowledge the staff of the VR LAB at the UCAM (Catholic University of Murcia), whose members are Manuel Pardo, Pau Guardiola, Alberto Lanchares, Andrés Pedreño, and Javier Alonso.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.teln.2025.01.009.

References

Ballarini, M., & Delestage, C.-A. (2024). Economic and artistic implications of the technical standardization of virtual reality. *Post-Print*. hal-04649644, HAL https://hal.archives-ouvertes.fr/hal-04649644.

Bonde, M. T., Makransky, G., Wandall, J., Larsen, M. V., Morsing, M., Jarmer, H., et al. (2014). Improving biotech education through gamified laboratory simulations. *Nature Biotechnology*, *32*(7), 694–697. doi:10.1038/nbt.2955.

Boyles, R. (2017). Virtual reality and augmented reality in education. *United States Military Academy*. West Point, NY. Recuperado de https://www.westpoint.edu/sites/default/files/inline-images/centers_research/center_for_teching_excellence/PDFs/mtp_project_papers/Boyles_17.pdf.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. doi:10.1191/1478088706qp063oa.

Brown, T. L., & Green, M. (2020). Virtual reality for assessment in HSE. *Journal of Medical Education*, *35*(1), 45–58. doi:10.1097/ACM.0000000000000005.

Cant, R. P., & Cooper, S. J. (2017). Use of simulation-based learning in undergraduate nurse education: An umbrella systematic review. *Nurse Education Today*, *49*, 63–71. doi:10.1016/j.nedt.2016.11.015.

Chen, X., Chen, X., & Wang, X. (2021). Collaboration in virtual reality: A new approach for health sciences. *Medical Simulation*, *29*(3), 167–176. doi:10.1097/SIH.0000000000000547.

Christman, M. P., Crespi, C. M., & Saraf, A. (2022). Ethical considerations in virtual health training. *Ethics in Healthcare*, *45*(2), 203–214. doi:10.1016/j.jethics.2022.01.001.

Cook, D. A., & Hatala, R. (2019). Incorporating virtual simulations into HSE. *Medical Education Review*, *54*(4), 288–298. doi:10.1111/medu.13882.

Ferrandini Price, M., Escribano Tortosa, D., Nieto Fernandez-Pacheco, A., Pérez Alonso, N., Cerón Madrigal, J. J., Melendreras-Ruiz, R., García-Collado, Á. J., Pardo Ríos, M., & Juguera Rodriguez, L. (2018). Comparative study of a simulated incident with multiple victims and immersive virtual reality. *Nurse Education Today*, *71*, 48–53. doi:10.1016/j.nedt.2018.09.006.

Freina, M., & Ott, M. (2015). A literature review on immersive virtual reality in education: State of the art and perspectives. *eLearning Papers*, *45*, 1–24. doi:10.7238/elc.v45i0.25730.

Gavish, N., Gutierrez, T., Webel, S., & Rodríguez, J. (2015). Advanced virtual training for health sciences students. *Healthcare Technology Research*, *22*(2), 201–215. doi:10.1016/j.healtech.2015.05.002.

Ghaempanah, F., Moasses Ghafari, B., Hesami, D., et al. (2024). Metaverse and its impact on medical education and health care system: A narrative review. *Health Science Reports*, *7*, e70100. doi:10.1002/hsr2.70100.

Gorshkov, M. (2024). *To err is human, to teach VR: virtual reality and artificial intelligence in medical education*. EuroMedSim.

Johnston, S., Martin, J., & Cohen, A. (2018). Enhancing communication skills through virtual simulation. *Nurse Educator*, *43*(2), 74–79. doi:10.1097/NNE.0000000000000520.

Junga, A., Schulze, H., Scherzer, S., et al. (2024). Aprendizaje inmersivo en educación médica: análisis de conocimientos de comportamiento para dar forma al futuro de los cursos basados en realidad virtual. *BMC Medical Education*, (1413), 24. doi:10.1186/s12909-024-06337.

Kyaw, B. M., Saxena, N., & Posadzki, P. (2019). Virtual reality for health professions education: systematic review and meta-analysis by the digital health education collaboration. *Journal of Medical Internet Research*, *21*(1), e12959. doi:10.2196/12959.

Hewett Brumberg, E. K., Douma, M. J., Alibertis, K., Charlton, N. P., Goldman, M. P., Harper-Kirksey, K., Hawkins, S. C., Hoover, A. V., Kule, A., Leichtle, S., McClure, S. F., Wang, G. S., Whelchel, M., White, L., & Lavonas, E. J. (2024). American Heart Association and American Red Cross. 2024 American Heart Association and American Red Cross Guidelines for First Aid *Circulation*, *150*(24), e519–e579. doi:10.1161/CIR.0000000000001281.

Lewis, K. O., Popov, V., & Fatima, S. S. (2024). From static web to metaverse: reinventing medical education in the post-pandemic era. *Annals of Medicine*, *56*(1). doi:10.1080/07853890.2024.2305694.

Makransky, G., & Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of virtual reality in education. *Computers & Education*, *125*, 14–26. doi:10.1016/j.compedu.2018.05.014.

Piromchai, P., Avery, A., Laopaiboon, M., Kennedy, G., & O'Leary, S. (2015). Virtual reality training for improving the skills needed for performing surgery of the ear, nose, or throat. *Cochrane Database of Systematic Reviews*, *2015*(9), CD010198. doi:10.1002/14651858.CD010198.pub2.

Popov, V., Mateju, N., Jeske, C., & Lewis, K. O. (2024). Simulación basada en Metaverse: una revisión del alcance de la educación médica en las últimas dos décadas en la lente de la "maravillosa máquina de educación médica". *Annals of Medicine*, *56*(1), 2424450. doi:10.1080/07853890.2024.2424450.

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778. doi:10.1016/j.compedu.2019.103778.

Rebenitsch, L., & Owen, C. (2016). Review on cybersickness in applications and visual displays. *Virtual Reality*, *20*(2), 101–125. doi:10.1007/s10055-016-0285-9.

Saab, M. M., Hegarty, J., Murphy, D., & Landers, M. (2021). Incorporating virtual reality in nurse education: A qualitative study of nursing students' perspectives. *Nurse Education Today*, *104*, 104556. doi:10.1016/j.nedt.2021.105045.

SIMZINE Redazione. (2024). To err is human, to teach VR. *SIMZINE*, (14). doi:10.69079/simzine.H24.n14.00015.

Singhaphandu, R., & Pannakkong, W. (2024). A review on enabling technologies of industrial virtual training systems. *International Journal of Knowledge and Systems Science (IJKSS*, *15*(1), 1–33. doi:10.4018/IJKSS.352515.

Sun, Z.-L., et al. (2020). Effectiveness of virtual reality in nursing education: A meta-analysis. *Journal of Medical Internet Research*, *22*(9), e18290. doi:10.2196/18290.

Zhao, J., Xu, X., Jiang, H., & Ding, Y. (2020). The effectiveness of virtual reality-based technology on anatomy teaching: A meta-analysis of randomized controlled studies. *BMC Medical Education*, *20*(1), 127. doi:10.1186/s12909-020-1994-z.

V – ESTUDIO II

Impact of virtual reality on adolescent´s risk perception while in extreme weather conditions.

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RGSA REVISTA DE GESTÃO SOCIAL E AMBIENTAL

RGSA – Revista de Gestão Social e Ambiental
ISSN: 1981-982X
Submission date: 6/13/2025
Acceptance date: 8/15/2025
DOI: https://doi.org/10.24857/rgsa.v19n9-067
Organization: Interinstitutional Scientific Committee
Chief Editor: Ana Carolina Messias de Souza Ferreira da Costa
Assessment: Double Blind Review pelo SEER/OJS

IMPACT OF VIRTUAL REALITY ON ADOLESCENTS' RISK PERCEPTION WHILE DRIVING IN EXTREME WEATHER CONDITIONS

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ABSTRACT

Objective: The aim of this study is to analyze the impact of an immersive virtual reality (VR) experience on adolescents' risk perception during a simulated driving task under extreme rainfall conditions, assessed through behavioral measures and neuroimaging records.

Theoretical Framework: The research is based on contributions from neuroeducation and risk psychology, which highlight the role of immersive experiences in emotional activation and behavioral change.

Method: A quasi-experimental design was conducted with 78 high school students (47 females, 31 males; mean age = 18.7 years; SD = 1.52). The experience was implemented using Quest 3 VR headsets, while a subsample of 10 participants used the Emotiv EPOC+14 system to record brain activity at three critical moments: flood onset, peak danger, and rescue. Questionnaires and focus groups were applied.

Results and Discussion: Findings show a significant increase in risk perception after the immersive experience, with gender differences in willingness to modify behaviors (p=0.004) and in reflection on safe decision-making (p=0.042). Neuroimaging data revealed predominant right-hemisphere activation in females and left-hemisphere activation in males, with a "freezing" pattern in males during peak danger.

Implications of the Research: These results suggest that VR can be an effective tool for road safety education, provided that gender-based neurobiological differences are considered.

Originality/Value: This study provides innovative evidence by integrating neuroimaging and immersive VR experiences in road safety, proposing personalized educational interventions based on neural processing patterns.

Keywords: Virtual Reality, Risk Perception, Neuroimaging, Road Safety, Driving.

IMPACTO DA REALIDADE VIRTUAL NA PERCEPÇÃO DE RISCO DOS ADOLESCENTES AO DIRIGIR EM CONDIÇÕES CLIMÁTICAS EXTREMAS

RESUMO

Objetivo: O objetivo deste estudo é analisar o impacto de uma experiência imersiva de realidade virtual (RV) na percepção de risco de adolescentes durante uma simulação de direção em condições de chuva extrema, avaliada por meio de medidas comportamentais e registros de neuroimagem.

Marco Teórico: A pesquisa fundamenta-se em contribuições da neuroeducação e da psicologia do risco, que ressaltam o papel das experiências imersivas na ativação emocional e na modificação de condutas.

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Método: Foi adotado um delineamento quase-experimental com 78 estudantes do ensino médio (47 mulheres, 31 homens; idade média = 18,7 anos; DP = 1,52). A experiência foi realizada com óculos Quest 3 de RV, enquanto uma subamostra de 10 participantes utilizou o sistema Emotiv EPOC+14 para registrar a atividade cerebral em três momentos críticos: início da inundação, pico de perigo e resgate. Foram aplicados questionários e grupos focais.

Resultados e Discussão: Os resultados mostram um aumento significativo na percepção de risco após a experiência imersiva, com diferenças de gênero na disposição para modificar condutas (p=0,004) e na reflexão sobre decisões seguras (p=0,042). Os dados de neuroimagem revelaram ativação predominante do hemisfério direito em mulheres e do hemisfério esquerdo em homens, com um padrão de "congelamento" em homens durante o pico de perigo.

Implicações da Pesquisa: Os achados sugerem que a RV pode ser uma ferramenta eficaz na educação para o trânsito, desde que sejam consideradas as diferenças neurobiológicas de gênero.

Originalidade/Valor: Este estudo traz evidências inovadoras ao integrar neuroimagem e experiências imersivas de RV na segurança viária, propondo intervenções educacionais personalizadas com base em padrões neurais de processamento.

Palavras-chave: Realidade Virtual, Percepção de Risco, Neuroimagem, Segurança Viária, Direção.

IMPACTO DE LA REALIDAD VIRTUAL EN LA PERCEPCIÓN DEL RIESGO EN ADOLESCENTES AL CONDUCIR EN CLIMA EXTREMO

RESUMEN

Objetivo: El objetivo de este estudio es analizar el impacto de una experiencia inmersiva de realidad virtual (RV) en la percepción del riesgo en adolescentes, sometidos a una simulación de conducción en condiciones de lluvia extrema, evaluada mediante medidas conductuales y registros de neuroimagen.

Marco Teórico: La investigación se sustenta en aportes de la neuroeducación y la psicología del riesgo, que destacan el papel de las experiencias inmersivas en la activación emocional y en la modificación de conductas.

Método: Se empleó un diseño cuasi-experimental con 78 estudiantes de secundaria (47 mujeres, 31 hombres; edad media = 18.7 años; DE = 1.52). La experiencia se desarrolló mediante gafas Quest 3 de RV, mientras que una submuestra de 10 participantes utilizó el sistema Emotiv EPOC+14 para registrar la actividad cerebral en tres momentos críticos: inicio de inundación, máximo peligro y rescate. Se aplicaron cuestionarios y grupos de discusión.

Resultados y Discusión: Los hallazgos muestran un aumento significativo en la percepción del riesgo tras la experiencia inmersiva, con diferencias de género en la disposición a modificar conductas (p=0.004) y en la reflexión sobre decisiones seguras (p=0.042). Los datos de neuroimagen evidencian activación predominante del hemisferio derecho en mujeres y del izquierdo en hombres, con un patrón de "congelación" en varones durante el máximo peligro.

Implicaciones de la investigación: Estos resultados sugieren que la RV puede ser una herramienta eficaz en la educación vial, siempre que se consideren diferencias neurobiológicas de género.

Originalidad/Valor: Este estudio aporta evidencia innovadora al integrar neuroimagen y experiencias inmersivas de RV en seguridad vial, proponiendo intervenciones educativas personalizadas basadas en patrones de procesamiento neural.

Palabras clave: Realidad Virtual, Percepción del Riesgo, Neuroimagen, Seguridad Vial, Conducción.

1 INTRODUCTION

The perception of risk in driving under adverse weather conditions, such as extreme rain or floods, is a priority challenge for road education and accident prevention. Adolescents and young people are highly vulnerable due to a combination of inexperience, overconfidence and impulsivity, factors that reduce their ability to anticipate dangerous situations (McCartt et al., 2009). This deficit in risk perception increases the probability of serious incidents in driving scenarios under environmental stress (Carrasco González, Barriga Jiménez, & León Rubio, 2006).

The literature also shows gender differences in risk perception, highlighting that women tend to adopt more conservative strategies and show greater responsiveness to educational interventions, while men tend to overestimate their abilities (Scott-Parker et al., 2013). These findings suggest the importance of including the gender variable in the analysis of road safety programs, considering possible differentiated neurobiological bases.

In this context, virtual reality (VR) has emerged as an innovative tool in education. Its ability to generate immersive and realistic scenarios allows exposing adolescents to high-risk conditions in controlled environments, encouraging safe decision-making without exposing them to real dangers (Pérez Rubio et al., 2023; Iwaasa, 2024). VR applied to road safety offers significant potential to reinforce experiential learning and promote sustainable behavioral changes (González-Ortega et al., 2018).

In order to broaden the understanding of the impact of these immersive experiences, it is necessary to integrate neuroimaging techniques that allow real-time analysis of brain activation linked to risk perception and decision-making. Previous research has shown that electroencephalography (EEG) records with devices such as Emotiv+COPD 14 provide relevant data on hemispheric patterns and emotional responses in educational contexts (Badcock et al., 2013; Duvinage et al., 2013; Hernández & De Barros, 2022).

Research question: How does an immersive VR driving experience in extreme rain influence adolescent risk perception, considering gender differences and brain activation patterns?

General objective: To evaluate the impact of an immersive VR experience on the perception of the risk of adolescents when driving in extreme rain conditions, integrating behavioral and neurophysiological measures.

Specific objectives:

a) Analyze changes in risk perception before and after immersive simulation.

b) Identify gender differences in the willingness to modify driving behaviors.

c) To examine the patterns of brain activation associated with critical moments of the experience.

d) To assess the effectiveness of VR as an educational tool in road safety.

2 THEORETICAL FRAMEWORK

The perception of risk in the field of driving has been widely studied from the psychology of behavior and road safety, constituting a key predictor of preventive behaviors (Santos, Santos, Santana, & Nunes, 2020). It is recognized that adolescents and young people have a more limited perception of danger, which increases the likelihood of road accidents (Alvia Párraga & Linares Giler, 2024). This phenomenon is explained by factors such as lack of experience, tendency to impulsivity and propensity to underestimate the consequences of their decisions (McCartt et al., 2009). In contexts of adverse climatic conditions, the reduced capacity for anticipation and emotional regulation significantly increases the vulnerability of this group (Carrasco González, Barriga Jiménez, & León Rubio, 2006).

Research has also shown gender differences in risk perception. Young women tend to be more conservative and more responsive to road safety education messages, while men tend to overestimate their responsiveness, engaging in riskier behaviors (Scott-Parker et al., 2013). These differences not only respond to social or cultural factors, but also seem to be related to differentiated neurobiological patterns in risk processing, which justifies their analysis using neuroimaging techniques.

In recent decades, virtual reality (VR) has emerged as an innovative educational strategy, allowing immersive experiences that generate meaningful learning by simulating high-risk situations in controlled environments (Pérez Rubio et al., 2023). VR has been shown to be effective in enhancing attention, empathy and emotional memory, fundamental aspects in the internalization of safe behaviors (Makransky & Lilleholt, 2018). Its use in road education is especially promising, since it allows adolescents to experience driving scenarios in extreme conditions without risking their integrity (González-Ortega et al., 2018). In addition, recent studies show that VR contributes to changing attitudes and behaviors through perceptual realism and emotional activation (Iwaasa, 2024), aspects that are little achieved by traditional road prevention programs.

On the other hand, neuroimaging applied to education is an emerging field that provides information on how the brain processes risk perception and decision-making under pressure.

The use of technologies such as the Emotiv EPOC+14 system, validated in cognitive neuroscience studies by Badcock et al. (2013) and Duvinage et al. (2013), provides real-time records of brain activity in complex scenarios. Recent research has shown that hemispheric differences in neural activation may be associated with different ways of processing risk: the right hemisphere is associated with more emotional and intuitive processing, while the left hemisphere is associated with a more analytical and rational approach (Hernández & De Barros, 2022, 2024).

The integration of VR and neuroimaging offers a double advantage: on the one hand, it increases the effectiveness of the educational experience by simultaneously activating the emotional and cognitive dimension of learning; and on the other hand, it allows to objectively evaluate how adolescents process critical situations in real time. This approach responds to gaps in the literature, where although there are studies on risk perception and educational programs, there are few investigations that integrate immersive technologies with neurophysiological data to analyze the effectiveness of road safety interventions (Slobounov et al., 2015).

In conclusion, the theoretical framework of this research is based on three pillars:

a) the vulnerability of adolescents in the perception of road risk;

b) gender differences as a critical variable in decision-making; and

c) the methodological innovation that involves the combination of virtual reality and neuroimaging for the analysis and design of more personalized and effective educational programs.

3 METHODOLOGY

Quasi-experimental design with a single group of adolescent participants. The experimental procedure was developed in three phases: immersive experience with neuroimaging, post-exposure survey and discussion group. This approach has been chosen based on previous literature, which indicates that pre-test evaluations can introduce response biases in educational studies (Holmos-Flores et al, 2023).

The intervention phase was conducted in a conditioned laboratory where participants were simultaneously equipped with Quest 3 virtual reality glasses and the Emotiv EPOC+ 14 neuroimaging system. After the calibration of the devices, a synchronized driving simulation was projected in extreme rain and flood conditions. The neurophysiological record focused on three key moments of the scenario: the start of the flood, the critical point of maximum perceived danger, and the final rescue sequence. These moments were selected for their relevance to assess changes in brain activation associated with risk perception.

After the immersive experience, a discussion group was generated among the participants. The discussion was moderated by a facilitator with experience in qualitative research techniques. A semi-structured guide was used that addressed the key issues defined according to the objectives of the study. The session was recorded with the prior consent of the participants to facilitate further analysis.

This work has been approved by the Research Ethics Committee of the UCAM (Universidad Católica de Murcia) with code CE112309, including specifically the neurophysiological registration protocols and the handling of sensitive data derived from neuroimaging.

3.1 PARTICIPANTS

The sample was composed of 78 high school students, selected in a non-probabilistic way from a school environment. The inclusion criteria were students between 15 and 18 years of age with basic knowledge about road education. Those with medical conditions or vision problems that prevented them from wearing VR goggles safely were excluded. The participants and their legal guardians received a detailed explanation of the study and informed consent was obtained.

For the neuroimaging experience, the sample, selected for convenience, was composed of 10 students (5 men and 5 women) of secondary education, aged between 15 and 18 years (M = 16.4, SD = 0.82). The sample size is based on previous neuroimaging studies on risk perception (Hernández and De Barros, 2022) that show that a sample of 10 participants allows detecting significant effects on neural activation paradigms during immersive experiences. The sample was chosen for convenience considering that the participants did not present contraindications for the use of virtual reality devices.

3.2 PROCEDURE

The study procedure was developed in several phases:

1. Recruitment and consent: Participants were contacted and informed consent was obtained.

2. Intervention: Participants experienced a 15-minute simulation (Figure 1A) of driving in adverse weather conditions using Quest 3 glasses.
3. Post-test survey: After the immersive experience, they completed a questionnaire (Figure 1B) designed to assess risk perception and induced reflection.
4. Discussion group: Groups moderated by a facilitator with experience in qualitative research were formed to explore the perceptions of the participants.

3.3 MEASURING INSTRUMENTS

The measurement instruments used in this study are:

1. Qualitative analysis. The transcripts of the discussion groups were made with TurboScribe® and revised by two authors to ensure the accuracy and fidelity of the data. Subsequently, MAXQDA 2022.8® (with the AI Assist extension) was used to carry out the qualitative analysis, coding and organizing the responses, which allowed identifying patterns and developing emerging categories. This process facilitated the structured understanding of participants' perceptions and learning after virtual reality and on-screen simulations.
2. Quantitative analysis. An ad hoc designed risk perception questionnaire including open questions and a 5-point Likert scale was conducted to assess post-experience reflection.
3. Neuroimaging analysis. The measurement of brain activity was performed using the Emotiv EPOC+14 system, a wireless and non-invasive electroencephalography device. The equipment incorporates 14 strategically positioned electrodes (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) following the International System 10-20, with references in the mastoids (CMS/DRL). This device was selected for its real-time recording capability at 128 Hz, allowing to accurately capture the rapid changes in neural activity associated with the perception of risky situations during the immersive experience.

Figure 1

Images taken during the sample collection phase where participants perform a simulation of 15 minutes driving in adverse weather conditions using Quest 3 glasses.

Own source.

3.4 NEUROIMAGING

The data analysis implemented in this study was structured in three fundamental phases to examine the patterns of neuronal activation during the immersive experience with virtual reality, following the standardized protocols PRONIN© and SIEN©.

In the initial phase, a pre-processing of the electroencephalographic signals obtained by Emotiv EPOC+ 14 was performed, applying the Neuroimaging Operative Protocol (PRONIN©). This protocol included the verification of environmental conditions (illumination: 500-750 lux; temperature: 20-22 °C), the evaluation of the state of the participants, and the control of electromagnetic interference. Digital filtering (0.5-45 Hz) and baseline correction techniques were applied, ensuring a minimum quality threshold of 95%. The PRONIN© protocol also established standardized periods of basal registration with open and closed eyes (3 minutes each) before the immersive experience.

The second phase consisted of the spectral analysis of EEG signals by fast Fourier transform (FFT), identifying four main frequency bands: theta (4-8 Hz) related to emotional response to danger, alpha (8-13 Hz) for attentional control during simulated driving, beta (13-30 Hz) for concentration in critical situations, and gamma (30-100 Hz) for high-level cognitive processing during decision-making. Power and coherence measurements between electrodes were calculated to assess brain functional connectivity during the three key moments of the scenario: flood onset, maximum danger hotspot, and rescue sequence.

The final phase incorporated the Standardized Neuroimaging Interpretation System (SIEN©), which integrates three dimensions of analysis: structural (patterns of hemispheric activation and brain connectivity), functional (analysis of frequency bands and temporal patterns), and contextual (environmental variables and state of the participant). This system allowed to evaluate the specific lobes and brain waves for risk perception: level of alertness, emotional commitment, stress response, sustained attention and decision-making under pressure

3.5 STATISTICAL ANALYSIS

Statistical analysis was performed using standard tools for the evaluation of data from Likert scales, continuous and categorical variables. All analyses were performed with Python (version 3.8) using pandas, scipy and sklearn libraries. The p-values were interpreted with a significance level set at $\alpha = 0.05$. Correlation coefficients and factor loads were analyzed to assess the magnitude of latent patterns and associations, respectively.

- Descriptive analysis: For categorical variables, such as gender, the absolute (n) and relative frequencies (%) were calculated. For continuous variables, such as age and years of driving experience, the mean and standard deviation (SD) were calculated. Responses to Likert scale items were analyzed using median and interquartile range (IQR).
- Tests for differences between groups: A comparison of responses according to gender was made using the Student t-test for independent samples. The assumptions of normality and homogeneity of variances were previously verified.
- Correlation analysis: The relationship between the continuous variables (age, years of driving experience) and the answers to the items of the questionnaire was evaluated by Pearson correlation coefficients.

- Factor analysis: An exploratory factor analysis was performed using a factor analysis model with extraction of two components. This allowed to identify underlying patterns in the responses to Likert scale items.

The study was approved by the Research Ethics Committee of the UCAM. Informed consent of participants and guardians, confidentiality of data, and safe use of immersive and neurophysiological technologies were ensured.

4 RESULTS AND DISCUSSIONS

This section describes the main findings obtained after the application of the Virtual Reality experience and the subsequent evaluation using a questionnaire based on a Likert scale. The descriptive results of the demographic characteristics and the responses provided by the participants are also presented.

4.1 DEMOGRAPHIC CHARACTERISTICS AND DRIVING EXPERIENCE

A total of 78 subjects participated in the study, of which 60.26% (n = 47) were female and 39.74% (n = 31) male. The mean age of the participants was 18.7 years (SD = 1.52), while the mean years of driving was 0.49 years (SD = 0.88). These figures reflect that the sample was composed predominantly of young drivers with limited experience, in line with the objectives of the study, focused on assessing the perception of risk in a potentially vulnerable group.

4.2 DESCRIPTIVE RESULTS OF LIKERT SCALE ITEMS

The items evaluated the perception of risk and the impact of the Virtual Reality experience on the participants. Results are presented in Table 1. In general terms, the responses showed a positive trend towards recognizing the risks associated with driving in adverse conditions and the educational impact of simulation.

Table 1

Descriptive results of Likert Scale items.

Item	Median	RIC
1. Driving in extreme rain is significantly more dangerous than I thought.	5.0	1.0
2. I am now more aware of the risks associated with driving on flooded roads.	5.0	0.75
3. The simulation has helped me better understand the potential consequences of driving in adverse weather conditions.	5.0	1.0
4. Experience with VR has made me reflect on the need to make safer driving decisions.	5.0	1.0
5. I am more willing to change my driving habits after knowing the risks.	5.0	1.0
6. The simulation has been effective in showing me how unpredictable and dangerous driving can be in emergency situations.	5.0	0.0
7. I better understand the importance of maintaining a reduced speed and controlling the safe distance in rainy conditions.	5.0	0.75
8. The VR experience helped me better understand other drivers facing dangerous conditions.	5.0	1.0
9. I feel better prepared to face difficult driving situations in the future.	4.0	1.0
10. I am now more determined to avoid unnecessary risks when climatic conditions are adverse.	5.0	1.0

The median for all items was 5 (maximum score on the scale), with an interquartile range (IQR) ranging from 0.75 to 1.00. This indicates that the majority of participants agreed or fully agreed with the statements raised in the questionnaire. Highlights include:

1. Increased risk perception: The item 'Driving in extreme rain conditions is significantly more dangerous than I thought' obtained a median of 5.0 and a RIC of 1.00, reflecting that participants effectively internalized the risk associated with this situation.
2. Awareness of risks on flooded roads: The item 'I am now more aware of the risks associated with driving on flooded roads' also obtained a median of 5.0 with a narrower RIC of 0.75, highlighting a slightly greater consensus on this aspect.
3. Educational impact of the simulation: The item 'The simulation has been effective in showing me how unpredictable and dangerous driving can be in emergency situations' reflected high levels of agreement (median = 5.0; RIC = 1.00), suggesting that Virtual Reality was perceived as an effective tool to convey these ideas.

In general, all the items presented similar values, which reinforces the idea that the Virtual Reality experience had a uniform and positive impact on the participants' perception. It should be noted that the item related to preparing for difficult driving situations in the future ('I feel better prepared to face difficult driving situations in the future') showed a RIC of 1.00, suggesting some dispersion in opinions regarding this aspect.

4.3 COMPARATIVE RESULTS BY GENDER

The results presented in Table 2 highlight two items with statistically significant differences between men and women. Item 4 (*"The virtual reality experience has made me think about the need to make safer driving decisions")*. This item showed significant differences with a p = 0.042. Women recorded a lower dispersion in their responses (IQR = 0.5) compared to men (IQR = 1.0), indicating a stronger consensus in this group. Item 5 (*"I am more willing to change my driving habits after knowing the risks")*. This item showed significant differences with a p = 0.004. Women scored consistently higher (median = 5.0, ICR = 0.0), while men showed greater variability in their responses (median = 4.0, ICR = 1.0). This finding suggests that women internalized more uniformly the educational message of the experience.

Table 2

Comparative results by gender.

Item	Median	RIC(H)	Median (M)	RIC(M)	Statistic	P-value
ITEM1	5.0	1.0	5.0	0.0	678.0	0.511
ITEM2	5.0	1.0	5.0	0.0	615.0	0,129
ITEM3	5.0	1.0	5.0	0.5	612.0	0.148
ITEM4	5.0	1.0	5.0	0.5	562.5	0.042
ITEM5	4.0	1.0	5.0	0.0	489.0	0.004
ITEM6	5.0	0.0	5.0	0.5	747.5	0,800
ITEM7	5.0	1.0	5.0	0.0	601.0	0,089
ITEM8	5.0	1.0	5.0	1.0	574.5	0.064
ITEM9	4.0	1.5.	4.0	1.0	612.0	0,200
ITEM10	5.0	0.5	5.0	1.0	733.0	0,958

On the other hand, for most of the items, how ITEM 1 (*"Driving in extreme rainy conditions is significantly more dangerous than I thought"*) and ITEM 10 (*"I am now more determined to avoid unnecessary risks when weather conditions are adverse"*), no statistically significant differences were found, with values of p = 0.511 and p = 0.958, respectively. This indicates similar perceptions between men and women in these specific aspects.

The results indicate that, although men and women shared similar perceptions in most of the items, there are important differences in aspects related to reflection and willingness to modify behaviors behind the wheel after the Virtual Reality experience. In particular, women showed a greater willingness to change their driving habits and a more consistent reflection on the need to make safe decisions.

This result indicates that women more consistently internalized the risks associated with driving in adverse conditions, which could be key to the design of personalized interventions

VI – ESTUDIO III

Can immersive virtual reality assess hypothermia resuscitation decision-making? A cross-sectional study in a civil–military disaster management context

VI - ESTUDIO III

Can immersive virtual reality assess hypothermia resuscitation decision-making? A cross-sectional study in a civil–military disaster management context

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Can immersive virtual reality assess hypothermia resuscitation decision-making? A cross-sectional study in a civil–military disaster management context

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To cite: Lopez Lopez CA, Greif R, Semeraro F, *et al.* Can immersive virtual reality assess hypothermia resuscitation decision-making? A cross-sectional study in a civil–military disaster management context. *BMJ Open* 2026;**16**:e113246. doi:10.1136/bmjopen-2025-113246

► Prepublication history and additional supplemental material for this paper are available online. To view these files, please visit the journal online (https://doi.org/10.1136/bmjopen-2025-113246).

Received 01 November 2025
Accepted 10 March 2026

Check for updates

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ABSTRACT

Objectives To evaluate the feasibility and acceptability of an immersive virtual reality (VR) scenario for assessing decision-making in accidental hypothermia resuscitation within a civil–military disaster-management exercise, and to explore neurophysiological signals as hypothesis-generating correlates of decision-making.

Design Cross-sectional observational study.

Setting A multinational civil–military disaster-management exercise in Bulgaria (September 2025).

Participants Convenience sample of first responders who completed the VR scenario and post-experience questionnaire (n=62; mean age 30.6 years (SD 7.8); 59/62 male (95.2%) and 3/62 female (4.8%); 43/62 civilian (69.4%) and 19/62 military (30.6%)).

Interventions Participants completed an interactive 360° immersive VR scenario with multiple-choice decision points covering key steps in accidental hypothermia management. A subsample underwent exploratory neurophysiological monitoring (electroencephalogram (EEG)/ECG) during the scenario.

Primary and secondary outcome measures Primary outcome was decision accuracy across scenario decision points. Secondary outcomes included perceived usefulness, ease of use, presence and physical discomfort. Exploratory outcomes (subsample) included EEG-derived engagement index and frontal alpha asymmetry.

Results Sixty-two participants completed the simulation. Perceived usefulness and ease of use reached the highest median score (7.0 (IQR 6–7.0)), with >95% agreement across items. Decision accuracy across decision points ranged from 37.5% to 85.7%, with lower accuracy in hypothermia-specific algorithm steps compared with general resuscitation actions. In a very small exploratory EEG/ECG subsample, illustrative case-level, event-locked individual traces suggested possible differences preceding incorrect responses (hypothesis-generating only).

Conclusions Immersive VR was feasible and well accepted for assessing hypothermia resuscitation decision-making in a civil–military exercise. Observed performance highlighted hypothermia-specific decision gaps. Controlled and longitudinal studies are needed to evaluate learning gain and training effectiveness.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ The study used a cross-sectional observational design embedded within a live multinational civil–military exercise, with a standardised single-exposure immersive virtual reality (VR) scenario.

⇒ Clinical decision-making was captured via automated platform-generated decision logs, providing objective item-level decision records without reliance on recall.

⇒ User experience was assessed using established validated instruments (Unified Theory of Acceptance and Use of Technology and Igroup presence questionnaire), with internal consistency evaluated in the study sample.

⇒ Recruitment was opportunistic among exercise participants who reached the VR station, and enrolment required sufficient proficiency in the study language.

⇒ The absence of a control group and longitudinal follow-up limited inferences about training effectiveness, learning gain and skill retention.

INTRODUCTION

The management of crises and disasters requires high level of preparedness including full-scale joint exercises to review the coordination between civil protection institutions and the armed forces.[1] The North Atlantic Treaty Organization (NATO) organises these deployments under the framework of the Euro-Atlantic Disaster Response Coordination Centre (EADRCC).[2] In parallel, it conducts LIVEX (*Live Exercises*) such as the *Vigorous Warrior* series to test procedures in realistic conditions, to identify gaps and to create an evidence base to help unify prehospital care among allied countries.[3] Along this line, NATO initiatives have proposed standardisation recommendations (Tägerwilen II consensus)[4] and interoperable surveillance systems NATO epidemiological/deployment health surveillance system, version 2 (EpiNATO-2) to improve healthcare preparedness and coordination.[5]

In this context, training using virtual reality (VR) has gained relevance in civil–military settings, supporting remote training of teams who are deployed or geographically dispersed.[6] The evidence shows that operational performance greatly depends on the quality of the training rather than the technology used,[7] and studies on military skiing show specific risks of the environment that justify the preparation of realistic and assessable scenarios.[8] Recent reports show that training reduces prehospital and Medical Evacuation (MEDEVAC) categorisation errors, and supports the use of structured assessment through VR.[9] In-person training in cold or evacuation settings presents logistical, safety and reproducibility limitations, which makes its standardised practice difficult, and justifies the exploration of immersive solutions such as VR.

In recent years, VR has proven its usefulness in emergency and disaster management, facilitating planning, training and decision-making under simulated high-pressure conditions. In the healthcare field, multiple studies have confirmed its effectiveness in the acquisition of clinical competencies and in the evaluation of cognitive and emotional responses to critical situations. However, the application of these technologies in real response contexts or in civil–military exercises remains limited. Importantly, to our knowledge, immersive VR has not yet been used in a large-scale civil–military exercise to assess decision-making for accidental hypothermia resuscitation. This gap between operational practice and scientific evidence has been highlighted in recent studies on the integration of technological tools in real disasters, such as those conducted during the Turkey earthquake,[10] as well as in three-dimensional reconstructions of rescue operations that demonstrate the potential of immersive technologies for postintervention analysis and the improvement of operational safety.[11]

Therefore, within the NATO Emergency Management Exercise '"Bulgaria 2025', we evaluated an immersive VR accidental hypothermia scenario developed and deployed in a multinational civil–military setting. Specifically, we assessed: (1) the accuracy of clinical decisions against an agreed-upon reference standard, and (2) user experience and feedback, to determine the usefulness of this approach for assessing first responders' hypothermia decision-making.

MATERIALS AND METHODS

Study design

The descriptive cross-sectional study was conducted during a NATO Emergency Management Exercise 'Bulgaria 2025' in the period 8–11 September 2025. An immersive VR experience was assessed, centred on hypothermia resuscitation with making of clinical decisions, safety and MEDEVAC. Each participant completed the experience once.

Setting

The collection of data was performed at the Base of Operations of the exercise (Erden Airfield, Montana, Bulgaria), in a delimited space, during a continuous exercise, from Monday, 8 September to Thursday, 11 September 2025. A private Wi-Fi network connection was used to ensure the quality of the link of the goggles. The participants remained outside the area and entered in groups of five (figure 1); no parallel activities were conducted in the tent during the simulation.

Participants

The target group of participants was composed of military and civil first responders. Given the observational and opportunistic character of the study, a prior sample

Figure 1 (A) Volunteer group during the immersive simulation with virtual reality headsets and haptic vests. (B) Participant belonging to the subsample in which neurophysiological monitoring using electroencephalogram (EEG) was also performed.

calculation was not performed. All the available participants during the exercise were considered as the convenience sample. Inclusion/exclusion criteria of VR safety were applied (exclusions due to epilepsy, a history of severe cybersickness, pregnancy or other standard criteria). The selection was performed through convenience, through access to the VR area by assigned turns and/or open invitation. The language of the scenario and questions was communicated only in English. Written informed consent was obtained before participation. In line with the exercise organisers' data-protection guidance, we did not collect any directly identifying information (eg, names, ID numbers, contact details). We collected only limited, non-identifiable participant characteristics (age, sex, civil/military status, years of emergency experience and prior VR exposure). Information on professional role and prior Advanced Life Support (ALS)/hypothermia education was not collected under the exercise data-collection rules.

VR equipment and intervention

Meta Quest 3 (Meta Platforms, Inc., Menlo Park, CA, USA) goggles were used, as well as noise-cancelling on-ear headphones Woojer Vest 3 haptic vests (Woojer Ltd., Tel Aviv, Israel) with default settings to standardise visual, auditory and tactile simulation. The platform used for the experience was Wonda (Wonda VR, Paris, France), configured as a 360° interactive experience with multiple-choice questions throughout the scenario (temperature algorithm, minimal exposure, immobilisation, airway management and shock/drug considerations in hypothermia according to guidelines). The clinical scenario was developed by a multidisciplinary team from RINVEMER (*Red de Investigación en Emergencias*; Prehospital Emergency Research Network) of the Spanish Society of Emergency Medicine, in collaboration with the *Servei Andorrà d'Atenció Sanitària* and ERC (*European Resuscitation Council*) members. The recording was performed in the Pal-Arinsal sky station (Andorra) with four Insta360X4 cameras (8K, FlowState). The video of the simulation in 2D format for its methodological consultation is available at https://youtu.be/R5SVzCW-8uI. Before the VR experience, a standardised briefing (≈2 min) was performed on the use of the VR equipment and safety. After completing the VR scenario and questionnaire, all participants received a brief standardised debriefing summarising the key hypothermia-specific resuscitation decision points.

Operational variables and definitions

The primary result variables included objective performance (exactness of each clinical decision). The automated recordings were obtained from the Wonda VR platform, which provided the data for each participant (item, answer, correction/correct). Due to the exercise organisers guidance, the data were not associated with any personal identification code.

As secondary variables, a questionnaire was administered to assess sociodemographic variables, the experience of the user and the efficacy of the simulation with VR training (online supplemental material 1). The questionnaire was composed of validated scales from the literature.[12–16] Internal consistency of the multi-item scales in our sample was assessed using Cronbach's α.

- Performance expectancy: To measure the perceived usefulness of the VR simulation, the 4-item performance expectancy scale from the Unified Theory of Acceptance and Use of Technology (UTAUT)[12] was used. This scale assessed the degree to which a person believes that the use of a system will help improve their work performance. The scale has been shown to have a high reliability in many studies, with Cronbach's Alpha values (α) higher than 0.90.[13]
- Effort expectancy: To measure the perceived ease of use of the VR system, the 4-item effort expectancy (EE) scale from the UTAUT model[12] was adapted. This scale assesses the degree of ease of use of the system. As a fundamental construct of acceptance of the technology, the EE scale has been shown to have a high internal consistency in previous studies, with reported Cronbach's α values that tend to be higher than 0.85.[14]
- Presence: The subjective sense of 'being present' in the virtual environment was measured through the Igroup presence questionnaire (IPQ).[15] The IPQ is an instrument composed of 14 items that measure 3 key dimensions of presence: spatial presence, involvement and sense of realness experience, along with a general item for general presence. The IPQ is a widely known standard for research on presence, and has been demonstrated to have good psychometric properties, with reliability scores for its subscales generally higher than 0.75.[15 16] Electroencephalogram (EEG): EEG measurements were obtained from a subsample (link to the recording of one of the cases can be found at: https://youtu.be/Gju_TUwhs9o). The EEG signals were processed using a high-pass filter at 0.5 Hz and a low-pass filter at 40 Hz to remove low and high-frequency interference, respectively. The signals were segmented into epochs of 5 s around key events, with a baseline period of 10 s before each event to establish resting brain activity. Frontal alpha asymmetry (FAA) was calculated as: α(AF3)−α(AF4), with values<0 interpreted as caution/avoidance, and values>0 as approach/safety. Engagement, measured as sustained attention, was calculated using the beta (alpha+theta) ratio. If beta (alertness/effort) dominates and alpha/theta (relaxation/wandering) decrease, the engagement index increases, indicating greater attention. The values were aligned to each event, analysing the 5 s before and after the event. These changes were compared with a prior quiet period (baseline from 0 to 10 s) before the stimulus.

Statistical analysis

Descriptive techniques were applied to report sociodemographic characteristics and the previous experience with VR through absolute frequencies (n) and percentages (%). Age was described through the mean (M), SD and range (minimum–maximum). There were no missing data in the analysed sample (n=62); therefore, no imputation was required.

The mean exactness was estimated per participant (and type of decision) with a 95% CI. The measurements of the questionnaire were summarised as the mean±SD and/or median (IQR) according to the distribution. For the Likert scales (Usefulness, Ease of use, Immersion and Personal comfort), the median (Me) and IQR were calculated. Composite scores (mean of the items) were created for the main constructs: usefulness (items 1–4), ease of use (items 5–8) and immersion (IQR, items 1–14). The results from the 7-point Likert scales (see the Materials and methods section) were categorised to show the distribution of the answers into Disagreement (1–3), Neutral (4) and Agreement (5–7). In the EEG subsample, an exploratory and intrasubject analysis was performed. Starting from the CSV (Comma-Separated Values) file exported from EmotivPRO, the two metrics recorded by the system were extracted for each participant and for each predefined critical moment: FAA (F4–F3 differences in the alpha band according to the export from Emotiv) and engagement index. The noise reduction (filters and signal/contact quality control) was performed in EmotivPRO, and the reading, organisation and aggregation of the data was performed with Python.

Ethical considerations and data availability

All the participants signed a written informed consent. The study was approved by the Ethics Committee of UCAM (Catholic University of Murcia) with code CE112309. The anonymised datasets (logs and questionnaires without direct identifiers) will be available on reasonable request to the corresponding author, subject to authorisation from the exercise organiser. In line with the exercise data-protection rules and the ethics-approved protocol, no directly identifying information was collected. EEG/ECG files were labelled only with a numeric study code, and no linkage file enabling re-identification existed. Data were stored on password-protected, access-restricted devices.

Patient and public involvement

Patients and/or members of the public were not involved in the design, conduct or reporting of this study. The results will be disseminated through publication and can be shared with participating organisations on request.

RESULTS

Sociodemographic characteristics and experience of the users

During the NATO Emergency Management Exercise 'Bulgaria 2025', 465 personnel formed the operational teams. Exercise Control allocated teams to multiple activities and simulations; our VR station was one of these activities. Of the 105 personnel who reached our station during the study period, 43 were not enrolled due to insufficient proficiency in the study language. A total of 62 participants volunteered, provided written informed consent and completed the VR scenario and postexperience questionnaire; all 62 were included in the analyses. The mean age of participants was 30.6 years (SD 7.8; range 20–54). The sample was predominantly male (n=59; 95.2%). Most participants were from the civilian context (n=43; 69.4%), and 19 participants (30.6%) were from the military context. The median years of professional experience was 5.0 (IQR 2.0–10.0). Most participants reported prior VR exposure 'a few times' (n=55; 88.7%) (table 1). Professional role and prior ALS/hypothermia education were not collected due to exercise data-collection constraints.

Table 1 Sociodemographic characteristics and previous experience of the participants

Variable	Category	Frequency (n)/ statistics
Age (years)	Mean±SD (range: min–max)	30.6±7.8 (20–54)
Years of experience	Median (IQR)	5 (2–10)
Gender	Male	95.2% (59)
	Female	4.8% (3)
Service/context	Military	30.6% (19)
	Civil	69.4% (43)
Previous VR experience	None	6.5% (4)
	A few times	88.7% (55)
	Regularly	4.8% (3)

VR, virtual reality.

User perception: usefulness and ease of use

The perception of acceptance of the system was exceptionally high in both constructs (usefulness and ease of use). From the total, 90.3% or more participants were found in the category of agreement (scores from 5 to 7) in almost all of the declarations of usefulness. The composite score of 'Ease of use' (EE) was equally high. This reflects a virtually unanimous consensus, as at least 98% of the participants perceived the interaction as clear and the system as easy to use (table 2). The UTAUT Effort Expectancy scale showed good internal consistency (Cronbach's α=0.81).

Immersion and personal comfort

The composite score of presence/immersion (IPQ) (table 3) obtained a median of 6.71 (IQR: 5.86–7.0). The level of general physical discomfort was extremely low (figure 1). This high immersion score was based on the consensus of the participants, who strongly reported that they felt present in the virtual space, with key items of the IPQ consistently reaching median scores of 7. The high level of physical acceptance is confirmed, given that

Table 2 Assessment of the usefulness and ease of use of the VR system

Item	Median (IQR)	Disagreement	Neutral	Agreement
Performance expectancy				
Useful in my work.	7 (6–7)	1 (1.6%)	4 (6.5%)	56 (90.3%)
It helps me complete tasks faster.	7 (7–7)	1 (1.6%)	2 (3.2%)	59 (95.2%)
It increases my productivity in training.	7 (7–7)	1 (1.6%)	0 (0.0%)	61 (98.4%)
It improves my overall work performance.	7 (7–7)	1 (1.6%)	1 (1.6%)	60 (96.8%)
Effort expectancy				
Clear and understandable interaction.	7 (7–7)	0 (0.0%)	1 (1.6%)	61 (98.4%)
Easy to acquire skill.	7 (7–7)	0 (0.0%)	0 (0.0%)	62 (100.0%)
Easy to use.	7 (7–7)	0 (0.0%)	1 (1.6%)	61 (98.4%)
Learning was easy.	7 (7–7)	0 (0.0%)	1 (1.6%)	61 (98.4%)

Disagreement (1–3); neutral (4); agreement (5–7).
VR, virtual reality.

69.0% (n=29) of the participants indicated not experiencing any discomfort (score of 1).

Of the 62 participants, 53 scored the contribution of the haptic vest to the immersion. The general perception on the use of the haptic vest in the CPR (cardiopulmonary resuscitation) hypothermia scenario was highly positive, with a median of 7 (IQR: 6–7). The IPQ showed good internal consistency (Cronbach's α=0.84).

Assessment of theoretical knowledge

The theoretical/operational results are shown in table 4. The participants demonstrated a high level of precision on the fundamental levels of pharmacological management and life support. The question with the highest percentage of correct answers was Q7, related to the non-administration of epinephrine if the body temperature is <30°C, with a percentage of correct answers of 85.7%.

However, participants showed lower accuracy on hypothermia-specific algorithm steps and early environmental actions. The lowest accuracy was observed for Q2 (management of an unconscious person in a mountainous environment), with 37.5% correct responses. Accuracy was also low for Q4 (defibrillation strategy when core temperature is <30°C, that is, delaying further shocks until rewarming after the first shock), with 46.0% correct responses. This heterogeneity was particularly evident between core ALS actions (eg, chest compressions and defibrillation in VF) and hypothermia-specific/environmental decision points (eg, hypothermia-modified defibrillation strategy and prevention of heat loss) (table 4).

Table 3 Presence and immersion scores

Questionnaire (IPQ) item	Median (IQR)
Sense of 'being there'.	7 (6–7)
I felt like I was just perceiving pictures (inverted).	2 (1–3)
I was completely captivated by the virtual world.	7 (6–7)
Awareness of my real environment real (inverted).	2 (2–4)
I felt present in the virtual environment.	7 (6–7)
The virtual world seemed more realistic.	7 (6–7)
I paid attention to my real environment (inverted).	2 (1–4)
I was not aware of my real environment.	7 (5–7)
I felt part of the virtual world.	7 (6–7)
How real did the virtual world seemed to you?	7 (6–7)
I felt separated from the real environment.	6 (5–7)
I felt present in the world I saw.	7 (6–7)
I was more aware of the virtual world than the real world.	7 (6–7)
I felt like I was just an observer (inverted).	1 (1–3)
Composite score of presence/immersion	7 (6–7.0)

IPQ, Igroup presence questionnaire.

Neurophysiological assessment

In a very small convenience subsample (n=11), we present illustrative event-locked single-participant traces as descriptive, hypothesis-generating observations only; no generalisable patterns are inferred. In the ECG analysis (figure 2), it was observed that attention decreased in high-demand moments. For example, when the helicopter arrived, it decreased, as compared with the baseline (S1: 2.09→1.32, −36.9%; S2: 1.01→0.76, −24.2%) and the FAA was slightly negative (S1 ≈ −0.09; S2 ≈ −1.31). The incorrect answers also showed a convergent pattern before failing, indicating less attention and negative FAA S1–Q11: FAA −4.97; engagement 1.65, −21%; S2–Q1: FAA −3.79; 0.85, −16%; S2–Q9: FAA −2.28; 0.90, −10%). On the other hand, the 'bottleneck' questions (Q4/Q5/Q9, temperature algorithm and minimum exposure) were also the ones that during the simulation, showed decreases in engagement and FFA that were more negative than baseline, which is coherent with the greater

Table 4 Results of the knowledge assessment questionnaire

Question	Distribution of answers (n)	Correct answer	Correct (n)	95% CI	Precision (%)
What should the rescuer do upon arrival?	A: 44 B: 18 C: 0 D: 0	Protect, alert and assist	44	(60.5% to 82.4%)	71.4
In the event of a possible loss of consciousness in a mountainous environment, what should the rescuer do?	A: 23 B: 10 C: 20 D: 9	Open airway	23	(24.0% to 51.0%)	37.5
After confirming that the patient is unconscious and not breathing, what should the rescuer do?	A: 1 B: 1 C: 45 D: 15	Start chest compressions	47	(65.8% to 86.5%)	76.2
If a patient with a temperature<30°C is in cardiac arrest, what specific recommendation does the algorithm mention regarding defibrillation?	A: 24 B: 8 C: 29 D: 0	After administering the first shock, we waited for the patient to warm up before trying again.	29	(33.6% to 58.3%)	46.0
How should we proceed when treating a hypothermic patient to prevent further heat loss?	A: 7 B: 24 C: 31 D: 0	Keep the patient's clothing on to expose only what is necessary.	31	(37.0% to 61.5%)	49.2
Ventricular fibrillation is detected on the monitor, what is the most appropriate course of action?	A: 10 B: 3 C: 49 D: 0	Apply defibrillation	49	(69.5% to 89.4%)	79.4
Under what conditions should adrenaline not be administered to a hypothermic patient?	A: 53 B: 9 C: 0 D: 0	Body temperature<30°C	53	(77.0% to 94.4%)	85.7
If ventricular fibrillation continues after three defibrillations, what action should be taken?	A: 5 B: 39 C: 15 D: 3	Delay further attempts until body temperature is >30°C.	39	(51.8% to 75.3%)	63.5
What is the key intervention for hypothermic patients before transfer to a hospital?	A: 3 B: 49 C: 7 D: 3	CPR, immobilisation and thermal insulation	49	(69.5% to 89.4%)	79.4
Which device is recommended for prolonged transport or difficult terrain?	A: 3 B: 49 C: 0 D: 10	Cardiac compressor	49	(69.5% to 89.4%)	79.4

demand for decision-making. As an internal contrast, Q8 concentrated the peak of attention (with a different affective tone: positive S1 FAA, slightly negative S2), and a low Q10 in both.

DISCUSSION

The present study evaluated, within the NATO Emergency Management Exercise 'Bulgaria 2025', the precision of the clinical decisions and the experience of the user during an immersive simulation of resuscitation of accidental hypothermia. The results show a high acceptability of VR, with maximum scores in usefulness and ease of use. The results show high acceptability of VR, with very high scores for usefulness and ease of use. Presence/immersion was also high and discomfort was minimal. However, user-experience responses clustered near the upper bound of the scales (eg, medians at or near the maximum with narrow IQRs), which suggests potential ceiling effects and limits the ability of these measures to discriminate between participants or detect change over time. In addition, although most participants reported only limited prior exposure to VR, the novelty of completing an immersive clinical scenario within a large-scale exercise may have contributed to uniformly

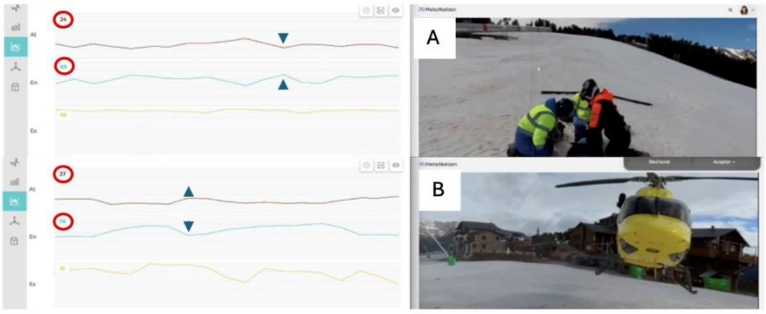

Figure 2 Neurophysiological variations during decision-making in the virtual reality experience. Comparison between two critical moments: (A) advanced life support decision phase with stable focus and high engagement; (B) helicopter arrival, showing increased focal attention but decreased situational awareness (tunnel vision).

favourable ratings. Similar findings have been reported in nursing education: Erbaş *et al* observed high presence with only mild cybersickness during an immersive postoperative VR scenario and emphasised that VR development should deliberately optimise presence while minimising cybersickness as a primary experiential outcome.[17] These levels of acceptance coincide with the previous literature on VR simulation applied to emergencies, which points out that a simple interface and a relevant clinical scenario are associated with a fast technological adaptation and a positive user experience.[18]

On the other hand, variability was observed in the precision among the different items of the theoretical questionnaire, with percentages of correct answers that oscillated between 37.5% and 85.57%. More specifically, a higher performance was measured in the life support decisions, and a lower performance in the management of hypothermia. This pattern is consistent with previously described challenges in adherence to hypothermia algorithms in special circumstances, particularly for temperature-dependent modifications and heat-loss prevention. Our findings may help identify specific decision steps that warrant targeted reinforcement in future training and assessment. The guidelines themselves indicate that the real adherence to these three steps is variable, and depend on the operational context and the availability of the equipment and training.[19 20] The recommendations of life support during a prehospital hypothermia point out some critical points (reliably measuring core temperature, adjusting the administration of drugs and shocks as a function of the temperature, and minimising loss of heat).[19] It was specifically in these points where the least precision was found, suggesting a low familiarity with the contents. Another possible cause of the lack of precision in some of the items is the deterioration of the resuscitation skills after 6–12 months.[20 21] Due to this, despite the consensus, there are gaps in knowledge that force the adaptation of procedures to each scenario, as recommended in the ERC 2021 (special situations section) and the most recent updates of the International Liaison Committee on Resuscitation (ILCOR).[21 22] Along the same line of operation, the Clinical Practice Guideline of the Joint Trauma System (2023) offers a standardised framework for the continuous training and assessment of prehospital procedures and results.[23] In our case, the lowest performance in temperature management and minimum exposure fits with the recommendations, which indicate where to concentrate the training efforts and assessment of performance to improve real-world practice.[19 20 23]

In contrast to most of the works centred on academic, hospital or prehospital settings, the present study integrates immersive VR in a civil–military exercise. To our knowledge, the decision-making during a hypothermia episode had not been previously assessed in this context. To help identify training needs, the evidence supports the use of simulation/VR with controlled variables and common rubrics; there are standardised hypothermia modules with checklists and debriefing that facilitate the objective assessment of performance and homogenisation of learning.[24] In addition, the scientific literature on emergencies shows that training with VR is not only not inferior, but it is advantageous in specific items as compared with conventional methods.[25 26] Within the NATO framework, VR allows assessing decisions under real operational conditions when the in-person simulation is limited by logistics or weather. Previous experiences in EADRCC/LIVEX already point out that virtual settings favour civil–military interoperability and the standardisation of training.[3]

Lastly, we explored the feasibility of collecting neurophysiological signals (EEG-derived engagement index and FAA, alongside ECG) during the VR scenario. In this small exploratory subsample, individual traces suggested that the engagement index tended to decrease and FAA shifted immediately before incorrect responses. These observations are hypothesis-generating only and should not be interpreted as objective measures of cognitive load or operational stress, nor as a basis for real-time intervention. Our EEG results show significant variability in attentional engagement during decision-making in hypothermia resuscitation, suggesting that cognitive distraction plays a crucial role in performance under high-stress conditions. The literature supports this interpretation due in other areas, it has been documented that the use of PPE (personal protective equipment) in emergency situations increases cognitive load and susceptibility to distraction, affecting the performance of healthcare professionals in critical contexts.[27] Complementarily, Nickerson *et al*[28] observed that distractions in high-cognitive-demand tasks, such as resuscitation, are reflected in changes in EEG patterns, particularly in FAA and the engagement index. These findings align with our observations, where fluctuations in these neurophysiological metrics appear to be associated with a decrease in performance, especially when external factors are present. Additionally, Udho *et al* noted that the physical limitations imposed by PPE reduces the ability to concentrate during critical procedures, contributing to cognitive distractions, an effect consistent with our evidence of attentional variability.[29] This approach is in line with the current trend of integrating biometric data and artificial algorithms in advanced training.[30] The pattern found in our results is consistent with studies that relate engagement with sustained attention and performance in demanding tasks[30] showing how modulation of frontal alpha activity improves attentional control in VR environments.[31 32] In addition, other authors have documented how the cognitive load in VR is reflected in measurable engagement metrics during learning.[33] In parallel, educational studies on VR confirm that presence/engagement is associated with better outcomes, and adjusting cognitive load is key to maintaining attention, exactly the type of adjustment that makes possible the 'cognitive telemetry' used in the present study.[33 34]

Strengths and limitations

The present study demonstrates the logistical feasibility and acceptability of deploying immersive VR to assess decision-making in accidental hypothermia within a live NATO civil–military exercise. Embedding the scenario in an operational training environment provided an ecologically relevant context for evaluating observed decision performance through automated decision logging. The addition of physiological and neurophysiological metrics (ECG and EEG) was exploratory and is presented as illustrative, hypothesis-generating observations that may inform future, adequately powered studies.

Several limitations should be acknowledged. First, participants were recruited opportunistically from volunteers who reached our VR station during the exercise; although we report the number who reached the station and were not enrolled due to language constraints, the total number of personnel scheduled/available to attend our station from the overall exercise population was not recorded, which may introduce selection bias and limits generalisability. Second, the study was cross-sectional and lacked a comparator group and longitudinal follow-up; therefore, it does not allow inferences about training effectiveness, learning gain or skill retention, and findings should be interpreted as feasibility/acceptability and observed decision performance during a single exposure. Third, performance was assessed through decision points within a scripted scenario and did not capture psychomotor skills or team performance. Fourth, we could not characterise participants' professional roles or prior ALS/hypothermia education due to exercise data-collection constraints, limiting interpretation of decision accuracy across backgrounds. Fifth, user-experience ratings were highly skewed towards the upper end of the scales, suggesting potential ceiling (and novelty) effects. Sixth, although time-to-decision was initially planned, it could not be collected reliably under the operational constraints of the exercise and was therefore removed from the reported outcomes. Cost and opportunity cost were not formally quantified in this feasibility study. Key resource drivers include hardware/software, scenario development, station setup and staff time; however, once developed, the scenario can be reused with standardised delivery and automated decision logging, potentially reducing marginal costs compared with repeated field simulations. Finally, the EEG/ECG component involved a very small subsample and is presented as illustrative, hypothesis-generating case-level observations only.

Implications and Future Lines

Our findings support the feasibility and acceptability of embedding immersive VR assessment within a live civil–military exercise, using automated decision logging to capture observed hypothermia decision-making under operational constraints. The heterogeneous accuracy across decision points, particularly for hypothermia-specific steps, suggests that VR decision logs may help identify concrete areas for targeted reinforcement during debriefing and future educational planning, without implying training effectiveness. Future studies should use prespecified controlled and/or longitudinal designs to evaluate learning gain, retention and transfer, and should prospectively capture participant background (eg, professional role and prior hypothermia/ALS education) and incorporate team-based and psychomotor outcomes. The neurophysiological component should be treated as hypothesis-generating: larger samples with prespecified EEG/ECG endpoints are needed to determine whether such measures add value beyond decision logs. Beyond hypothermia-related cardiac arrest, this approach could be extended to other complex, time-critical scenarios relevant to civil–military disaster operations, such as hypothermia triage and transport decisions, avalanche/mass-casualty triage, drowning and cold-water rescue pathways, crush injury and prolonged field care, hazardous materials exposure and multicasualty incident command-and-control decision-making. Future studies could compare VR with standard education (eg, guideline briefing/tabletop case) or conventional simulation using controlled allocations by teams/rotations, with prespecified outcomes and follow-up to assess learning gain, retention and implementation burden.

CONCLUSIONS

Immersive VR was feasible and well accepted for assessing accidental hypothermia resuscitation decision-making during a civil–military exercise. Automated decision logs identified protocol steps with lower accuracy, which may inform targeted debriefing and future training priorities. Controlled and longitudinal studies are needed to determine training effectiveness, learning gain and skill retention.

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Acknowledgements The authors would like to thank the professionals at the VR Lab at the UCAM: A. Lanchares, A. Pedreño, A. Fernández and J. Alonso. We would also like to thank the 'Servei Urgent Mèdic' of the 'Servei Andorrà d'Atenció Sanitaria' and 'Heliand' for their collaboration and assistance in creating the scenario used.

Contributors CALL and MPR led the work: they conceived the study, designed the study protocol and VR assessment approach, coordinated implementation during the civil–military exercise, oversaw data acquisition, curated the dataset and led interpretation of the findings. CALL and MPR also drafted the manuscript and coordinated revisions. MSG and DGM contributed substantially to study conduct, data collection/curation, statistical analysis and interpretation and critically revised the manuscript for important intellectual content. ABOC, SNC and MPC contributed substantially to methodology refinement, on-site study execution and/or data acquisition and interpretation of results and they critically revised the manuscript. RG and FS provided substantial expert input to the clinical content and decision standards, contributed to interpretation and critically revised the manuscript for important intellectual content. MPG and MLI contributed substantially to the civil–military/exercise context, supported operational coordination and/or data acquisition within the exercise environment, contributed to interpretation and critically revised the manuscript. LLF contributed substantially to study execution and data acquisition/management and critically revised the manuscript. All authors approved the final version of the manuscript, agreed to be accountable for all aspects of the work and confirmed that they meet the ICMJE authorship criteria (substantial contribution; drafting or critical revision; final approval and accountability). Guarantor: MPR. We used Data Analyst for the data.

Funding This work was funded by the Ministry of Science, Innovation and Universities in the research project entitled METAHEALTH: Design of a Metaverse for Higher Education in Health Sciences (PID2022-138884NA-I00), reference MCIN/AEI/10.13039/501100011033/FEDER, UE.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting or dissemination plans of this research.

Patient consent for publication Consent obtained directly from patient(s).

Ethics approval This study involves human participants and was approved by the Ethics Committee of UCAM (Catholic University of Murcia) with code CE112309. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. Not applicable.

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REFERENCES

1 North Atlantic Treaty Organization. NATO Press Release; Bulgaria 2025 Civil–Military Exercise: Strengthening multinational disaster response capacities, 2024. Available: https://www.nato.int
2 North Atlantic Treaty Organization (NATO). NATO Press Release; Euro-Atlantic Disaster Response Coordination Centre, 2025. Available: https://www.nato.int/cps/en/natohq/topics_52057.htm
3 Fazekas L, Mccown M, Taylor JB, *et al*. NATO Military Medical Exercise Vigorous Warrior 2017. *J Spec Oper Med* 2019;19:27.
4 Medby C, Forestier C, Ingram B, *et al*. The Tägerwilen II report: Recommendations from the NATO Prehospital Care Improvement Initiative Task Force. *Transfusion* 2024;64 Suppl 2:S58–61.
5 Hoysal N, Mccown ME, Fazekas L, *et al*. EpiNATO-2: Enhancing Situational Awareness and Overall Force Health Protection While Deployed in the Combined Joint NATO Environment: Describing the Identified 2016 Q Fever Outbreak in Kosovo Force (KFOR). *J Spec Oper Med* 2019;19:76–80.
6 Abadia de Barbara AH, Nicholas Iv TA, Del Real Colomo A, *et al*. Virtual simulation training using the Storz C-HUB to support distance airway training for the Spanish Medical Corps and NATO partners. *Stud Health Technol Inform* 2012;182:1–9.
7 Friedl KE, Hasselstrom H, Kingma BRM, *et al*. Introduction: Training is more important than technology (for performance in the cold). *Int J Circumpolar Health* 2023;82:2240572.
8 Pigman EC, Grice GP, Volcheck GW. Military nordic skiing injury profiles with two different types of NATO ski bindings. *Mil Med* 1990;155:354–6.
9 Pizzola JL. MEDEVAC miscategorization. *Mil Med* 2010;175:655–8.
10 Ivanov ML, Georgiev MP. Innovations, applications, and future perspectives in geospatial information visualization for disaster response: insights from the 2023 Kahramanmaras Earthquake urban search and rescue operations. *Nat Hazards* 2025;121:22787–816.
11 Pardo Ríos M, Morales Sánchez C, Parra Beneitez Y, *et al*. Urban search and rescue operations (USAR) in collapsed buildings after the 2023 earthquake in Türkiye. *Emergencias* 2023;35:288–96.
12 Venkatesh V, Morris MG, Davis GB, *et al*. User Acceptance of Information Technology: Toward A Unified View1. *MIS Q* 2003;27:425–78.
13 Ngusie HS, Kassie SY, Zemariam AB, *et al*. Understanding the predictors of health professionals' intention to use electronic health record system: extend and apply UTAUT3 model. *BMC Health Serv Res* 2024;24:889.
14 Mengying L, Dongquan F, Lin L, *et al*. Pathway analysis of clinical nurse educator's intention to use virtual reality technology based on the UTAUT model. *Front Public Health* 2024;12:1437699.
15 Tran TQ, Langlotz T, Young J, *et al*. Classifying Presence Scores: Insights and Analysis from Two Decades of the Igroup Presence Questionnaire (IPQ). *ACM Trans Comput-Hum Interact* 2024.
16 Bareišytė L, Slatman S, Austin J, *et al*. Questionnaires for evaluating virtual reality: A systematic scoping review. *Computers in Human Behavior Reports* 2024;16:100505.
17 Erbaş A, Akyüz E, Giustivi D, *et al*. Two important factors in virtual reality simulations: Nursing students' experiences of cybersickness and sense of presence. *Clin Simul Nurs* 2025;106:101787.

18 Zhang Z, Meybodi MM, Ingale A, *et al*. Extended reality technology for emergency medical service training: systematic review. *Front Disaster Emerg Med* 2025;3.
19 Lott C, Truhlář A, Alfonzo A, *et al*. European Resuscitation Council Guidelines 2021: Cardiac arrest in special circumstances. *Resuscitation* 2021;161:152–219.
20 Greif R, Morley PT, Bhanji F, *et al*. 2024 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations (CoSTR). *Circulation* 2024;150:e1236–310.
21 Al Jadidi H, Al Jufaili M. Effectiveness of a Short Refresher Course on the Retention of Cardiopulmonary Resuscitation-Related Psychomotor Skills (REF-CPR). *Oman Med J* 2023;38:e509.
22 Abuejheisheh AJ, Darawad MW. A national cross-sectional study on the retention of basic life support knowledge among nurses in Palestine. *BMC Nurs* 2024;23:828.
23 Joint Trauma System. DoD Center of Excellence for Trauma; Hypothermia: Prevention and Treatment (Clinical Practice Guideline, CPG ID: 23). DoD Center of Excellence for Trauma, 2023. Available: https://jts.health.mil/assets/docs/cpgs/Hypothermia_Prevention_Treatment_07_Jun_2023_ID23.pdf
24 Dikranian L, Levasseur K. Hypothermia and Arrhythmias: A Pediatric Trauma Simulation Case for Residents, Fellows, and Advanced Practice Providers. *MedEdPORTAL* 2025;21:11530.
25 Li Z, Wang W, Huang Z-Z. Virtual reality for emergency medicine training on traffic accident injury treatment: a randomized controlled trial. *Front Virtual Real* 2025;6:1518016.
26 Lindner M, Leutritz T, Backhaus J, *et al*. Knowledge Gain and the Impact of Stress in a Fully Immersive Virtual Reality–Based Medical Emergencies Training With Automated Feedback: Randomized Controlled Trial. *J Med Internet Res* 2025.:e67412.
27 Hanaki N, Miyata J, Yamada Y, *et al*. Choosing Wisely® in Japanese Emergency Medicine: Nine Recommendations to Improve The Value of Health Care. *J Emerg Med* 2023;64:371–9.
28 Nickerson TE, Lovett ME, O'Brien NF. Organ Dysfunction Among Children Meeting Brain Death Criteria: Implications for Organ Donation*. *Pediatr Crit Care Med* 2023;24:e156–61.
29 Udho S, Clow SE. Experiences, prevalence and drivers of disrespect and abuse of adolescents during facility-based childbirth in sub-Saharan Africa: a scoping review protocol. *BMJ Open* 2024;14:e078912.
30 Blackmore KL, Smith SP, Bailey JD, *et al*. Integrating Biofeedback and Artificial Intelligence into eXtended Reality Training Scenarios: A Systematic Literature Review. *Simulation & Gaming* 2024;55:445–78.
31 Berger AM, Davelaar EJ. Frontal Alpha Oscillations and Attentional Control: A Virtual Reality Neurofeedback Study. *Neuroscience* 2018;378:189–97.
32 Berger LM, Wood G, Kober SE. Effects of virtual reality-based feedback on neurofeedback training performance-A sham-controlled study. *Front Hum Neurosci* 2022;16:952261.
33 Makransky G, Terkildsen TS, Mayer RE. The effects of cognitive load on engagement in a virtual reality learning environment (ieee vr 2021). 2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR); 2021:120–9. 10.1109/VRW52623.2021.00025 Available: https://doi.org/10.1109/VRW52623.2021.00025
34 Feltman KA, *et al*. En aviación (simulación de vuelo), el aumento de carga se acompaña de cambios en alfa/θ frontales y del cociente β/(α+θ). In: *coherentes con mayor esfuerzo mental; convergen EEG y medidas subjetivas de workload. Frontiers in Neuroergonomics*. 2024. Available: https://doi.org/10.3389/fnrgo.2024.1397586

VII – ESTUDIO IV

Impact of Virtual Reality on risk perception, stress and neurophysiological patterns in driving situations during floods: a quasi-experimental study

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Contents lists available at ScienceDirect

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Research article

Impact of virtual reality on risk perception, stress and neurophysiological patterns in driving situations during floods: a quasi-experimental study☆

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ARTICLE INFO

Keywords:
Virtual reality
Risk perception
Stress
Neuroimaging
Driving simulation
Flood emergencies

ABSTRACT

Objective: This study aims to evaluate the impact of Virtual Reality (VR) compared to non-immersive audiovisual methods on risk perception, stress levels, and neurophysiological patterns during a simulated driving scenario under flood conditions.
Methods: A quasi-experimental study was conducted with two groups: the VR Group (VRG) and the Screen Group (SG). Sixty-six fourth-year undergraduate nursing students (33 per group) completed the study. Between-group differences in key risk perception items showed moderate effect sizes (Cohen's d = 0.6). The participants completed an ad hoc questionnaire on risk perception, and provided saliva samples to measure salivary alpha-amylase (SAA) levels before and after exposure to a simulated driving scenario that included flooding. During the simulation, a neuroimaging system was used to evaluate brain activation patterns.
Results: Both groups showed significant increases in SAA levels after the intervention, indicating stress induction: VRG 73.15% and SG 47.15%. The VRG showed greater changes in key items related to risk perception, such as knowledge of safety measures during floods ($p = 0.006$), and more complex neurophysiological activation patterns, particularly in areas associated with emotional integration and decision-making.
Conclusion: VR as a resource has a greater capacity to modify risk perception in simulated emergencies, providing a more immersive and effective experience as compared to traditional audiovisual methods.

☆ Given his role as Section Editor, Jose Ceron had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor.

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https://doi.org/10.1016/j.heliyon.2026.e44924
Received 4 February 2025; Received in revised form 12 March 2026; Accepted 9 April 2026

1. Introduction

The data from the World Health Organization (WHO) indicate that traffic accidents are some of the leading causes of deaths worldwide. Approximately 1.9 million people die every year due to traffic accidents, and between 20 and 50 million people suffer non-fatal accidents with sequelae of varying degrees [1]. In Spain, the General Directorate of Traffic (DGT) reported 1805 deaths in 2023 related with traffic accidents [2]. A specific area with an increasing risk involves deaths due to drowning or being trapped in vehicles during floods, which, although less frequent than other types of accidents, have a high death rate due to the speed with which the situation worsens [3].

Although often underestimated in public safety discourse, vehicle-related drowning during floods poses a serious risk with high fatality rates. A systematic review identified that attempting to drive through floodwaters accounts for up to 10% of all flood-related drowning deaths in high-income countries, highlighting the misjudgment of risk and behavioral errors under extreme conditions [3]. Supporting this, Ketenci et al. (2022) found that 0.57% of all autopsies performed over a seven-year period in Turkey were due to traffic accidents involving vehicle submersion in rivers, lakes, or the sea. In their study, 95% of the victims died from asphyxia by drowning, with many unable to exit the vehicle in time due to trauma or lack of seatbelt use [4]. These data emphasize the need for preventive strategies focused on behavior modification and risk perception, particularly in emergency situations such as flash floods.

Current disasters involving multiple casualties occur rarely, offering little opportunity for gaining experience and competence assessment. For these reasons, new trends in disaster training are focusing on the use of VR in order to mitigate the mortality and morbidity associated with disasters. [5]. Some studies have shown that a low perception of risk increases the probability of reckless decisions and deficient reactions before adverse conditions [6,7]. Psychological research on behavior highlights that emotional and cognitive factors affect perception, and therefore, the making of critical decisions [8]. In addition, recent studies have shown that the use of realistic simulations can have a positive influence on the perception of risk and the adaptive response of drivers, thus contributing to a better preparation in crisis scenarios [9,10].

Emergency training has evolved with the addition of immersive technologies such as virtual reality (VR). This technology allows for the simulation of risky situations in a safe environment, improving preparation and response without exposing the participants to a real risk [11]. A recent study showed that a VR simulations can be as effective as the traditional methods of clinical simulation, with the advantage of being more accessible and repeatable without physical risks [12]. Despite its numerous advantages, the use of virtual reality in education also presents certain limitations. These include high costs associated with equipment and content development, the need for adequate technical training for instructors and students, and accessibility barriers in low-resource settings. Additionally, some users may experience motion sickness or disorientation, known as cybersickness, which may limit the applicability of VR in certain populations [13]. In addition, another analysis showed that VR promotes the retention of knowledge when involving users in immersive and emotionally-significant experiences [14].

Given the above, the present study aims to analyze the impact of virtual reality on the change in the perception of risk and stress in situations of driving under intense rain and floods. The aim is to determine if the use of immersive simulations can contribute towards a better perception of risk, to avoid future dangerous responses during traffic emergencies due to flooding.

2. Materials and methods

A design with a quasi-experimental methodology was used in the present work to determine the change in the perception of risk, with groups who took part in the same intervention but with different resources for their posterior comparison (Fig. 1). The study was conducted at UCAM (Universidad Católica de Murcia), Faculty of Health Sciences, Murcia, Spain, between October and November 2024. Data collection and the intervention sessions took place at the UCAM Virtual Reality Center.

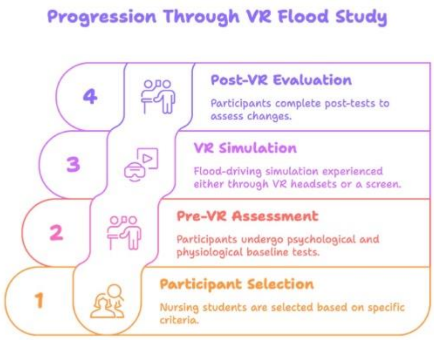

Fig. 1. Flowchart of the study design illustrating the four phases.

2.1. Sample selection

The selection of university students as participants was strategic, as they represent an accessible and relatively young population that can be trained in the prevention of risks when driving. Inclusion criteria were: (1) fourth-year undergraduate nursing students (Bachelor's Degree in Nursing) enrolled at UCAM (Universidad Católica de Murcia), (2) age ≥18 years, (3) valid driving license, (4) self-reported regular driving activity, and (5) no previous real-life experience of driving in flood conditions. The exclusion criteria were: (1) previous history of anxiety or panic disorders, (2) direct personal experience in emergency situations due to flooding in the last 5 years, (3) visual or vestibular problems that could interfere with the VR experience, and (4) taking medication that could affect the levels of salivary alpha-amylase. The randomization was performed with the use of a program that generates random numbers (Random Allocation Software 2.0), using permuted blocks of variable size to ensure balanced groups.

The calculation of the sample size was performed to be able to detect a moderate effect size (0.5) with a statistical power of 80%, and level of significance of 5%, with at least 30 participants needed in each of the groups. This calculation assumed a between-group comparison (VRG vs SG) using a two-tailed $\alpha = 0.05$; a total of 66 participants were finally included.

The sample selected was composed by volunteer university students who had not previously experienced a situation of driving in flood conditions. All participants held a valid driving license and reported regular driving activity, with a mean of 5 years of driving experience (SD = 1,22 años). This inclusion criterion ensured that participants were familiar with driving tasks, which increases the ecological validity of the simulated scenario. The participants signed their informed consent indicating their free and voluntary participation. The students were randomly assigned (1:1) to each of the study groups. These study groups were (Fig. 2).

- Virtual Reality Group (VRG): The participants will take part in the simulation experience in an immersive environments with virtual reality goggles.
- Screen Group (SG): The participants will view the same experience in a non-immersive device, such as a computer.

A total of 66 participants completed the study, with 33 randomly assigned to each group. Between-group comparisons of key

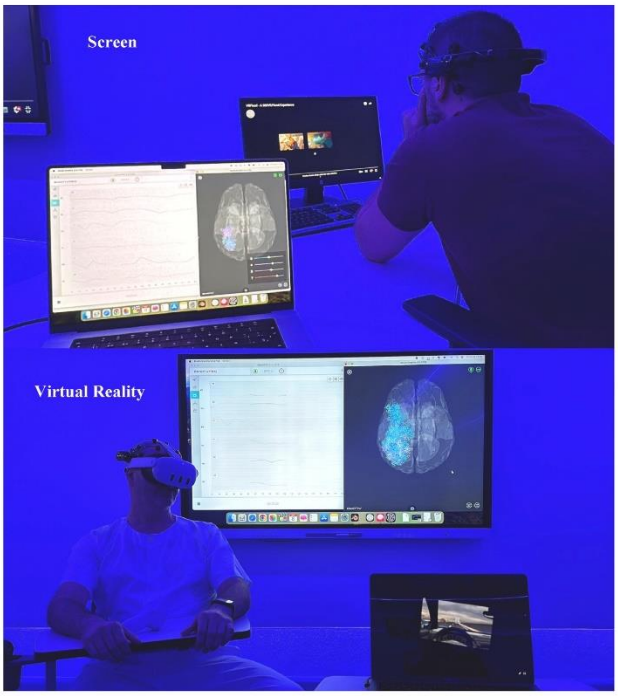

Fig. 2. Images of volunteers during the experiment where brain waves and brain activation map are assessed.

variables, such as risk perception, yielded moderate effect sizes (e.g., Cohen's d = 0.6 for Question 2 and Question 7 of the post-test).

2.2. Study procedure

The study procedure was divided into various study phases, which are detailed below.

1. Recruitment of Participants: Potential participants were informed about the possibility of participating in a study through ads in social networks and the virtual campus.
2. Assignment to Groups: The participants who met the inclusion criteria were randomly assigned to one of the study groups, thus ensuring the comparability between the VRG and the SG.
3. Stages of the experiment
   - Pre-exposure stage: Before the experience, the participants were asked to complete a risk perception questionnaire, and a sample of their saliva was collected to measure the baseline levels of Salivary Alpha-Amylase (SAA).
   - Exposure to the Simulation: The participants watched a simulation which showed a virtual scenario of intense rain, where a flooding situation occurs while they are in a vehicle. This scenario was made possible with the collaboration from the *Regional Flood Control District of Clark County* in the state of Nevada (USA). The link to the simulation is: https://youtu.be/TZYAKJ0Isiw?si=aF1utIcP_zyrdCYR
   - Post-exposure stage: Once the experience ended, the participants answered the risk perception survey once again and provided a second sample of saliva to measure the post-exposure SAA.

2.3. Measurement instruments

1. Perception of Risk Questionnaire: An ad hoc questionnaire was developed by the research team through expert consensus to specifically assess risk perception in the context of flood-related driving scenarios (Supplementary Material 1). The tool included 10 items rated on a 5-point Likert scale, covering aspects such as perceived severity, vulnerability, control, and emotional impact. In addition, basic sociodemographic information was collected. No existing validated questionnaires were found that fully addressed the specific objectives and context of this study.
2. Measurement of Stress with Salivary Alpha-Amylase (SAA): The saliva was obtained through a system of passive diffusion into a tube, with an extraction time of 1 min. Samples were collected at a fixed time of day, with participants in a seated, resting state and having refrained from eating, drinking, or exercising for at least 30 min prior to collection, to control for external influences on enzyme activity. The processing and analysis of the sample was performed following the same procedure as in previous studies [15, 16]. The method obtained an inter-assay coefficient of variation lower than 3%, and a linear regression coefficient of 0.992.
3. Neuronal Analysis: To acquire the neurophysiological data (Fig. 2), the electroencephalography device (EEG) EPOC X 14 Channel (EMOTIV Inc., San Francisco, United States) was used. The electrodes were distributed according to the international system 10-20 (AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2), with a sampling frequency of 256Hz. The device allows for the recording of brain activity in real time, with special attention given to the frontal and temporal regions, key areas in the processing of emotions and the response to stress. The EEG signal was processed and analyzed with the EmotivPRO and BrainViz programs, focusing on the frequency bands theta (4-8 Hz) alpha (8-13 Hz), and beta (13-30 Hz), related with states of alert, stress, and processing of emotions.

The neurophysiological analysis was carried out following the PRONIN protocol (Operational Protocol for Neuroimaging in Neuropedagogical Research, Property Reg. No. 04/2025/665), which structures the process into six critical phases, from pre-registration to validation. Data acquisition was performed using the EPOC X 14-channel device, with electrode placement according to the international 10-20 system and quality standards established in the protocol (impedance <5kΩ, stable signal, and an environment free from electromagnetic interference). The recording phase included both baseline conditions (eyes open and closed) and the immersive experience, under control of contextual variables (lighting, temperature, and classroom layout).

The EEG signals were processed using band-pass filters to isolate theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz) frequencies, which are respectively linked to sustained emotional attention, cortical inhibition, and alertness and decision-making states. No machine learning algorithms were applied at this stage; instead, descriptive and comparative analyses were conducted based on the SIEN framework (Standardized Interpretation System for Neuroimaging, Intellectual Property Reg. No. 04/2025/666). This system enabled data interpretation through three integrated dimensions.

- Structural dimension: Predominant activation patterns were identified in the frontal and temporal lobes, including documentation of lateralization and intra/interhemispheric connectivity.
- Functional dimension: Neuroeducational biomarkers such as focus, excitement, stress, and engagement were evaluated using EmotivPro's internal algorithms and exported to SIEN interpretation templates.
- Contextual dimension: Systematic observations were collected on the participant's state and environmental variables, allowing for an integrated and validated interpretation.

The correlation between these data and changes in risk perception was established according to the SIEN model, enabling the association of increased frontal beta activity and engagement biomarker values with cognitive processes related to situational evaluation and decision-making in critical contexts. This integrative matrix supported a coherent interpretation between neurophysiological indicators and the behavioral outcomes observed.

2.4. Statistical analysis

The medians and interquartile ranges (IQR) were reported for the ordinal variables, and the means ± standard deviations (SD) for the continuous variables, as appropriate. A statistical analysis was performed to compare the Pre and Post-Test results. The Wilcoxon test for related samples was used within each group. The levels of SAA, as they are continuous data, were analyzed with Student's *t*-test for related samples, as long as they met the assumptions of normality; otherwise, the Wilcoxon signed-rank test was used. In all the analyses, the level of statistical significance of $p < 0.05$ was utilized.

3. Results

3.1. Stress results measured with salivary alpha amylase

The analysis of the levels of salivary alpha amylase (SAA) provided significant findings, as shown in Fig. 3. In Fig. 3a, the total results showed SAA levels of 80.16 ± 62.70 μU/mL before the exposure, which increased to 128.89 ± 79.09 μU/mL after the intervention. The mean difference was 48.74 μU/mL (95%CI: 32.20 to 65.27; $p < 0.001$). The mean percentage of increase from the baseline mean to the end was approximately 60.80%.

The intra-group comparison (Pre-vs Post-Exposure) for the SG showed that the levels of SAA before the exposure were 76.17 ± 49.91 μU/mL, increasing to 112.09 ± 72.55 μU/mL after the exposure (Fig. 3b). The mean difference was 35.92 μU/mL (95% CI: 21.15 to 50.68; $p < 0.001$), with a mean increase of 47.15%. On the other hand, the results for the levels of SAA for the VRG (Fig. 3c). were 84.15 ± 73.94 μU/mL before the exposure, increasing to 145.70 ± 82.86 μU/mL, after the exposure. The mean difference was 61.55 μU/mL (95% CI: 31.64 to 91.47; $p < 0.001$), with a mean increase of 73.15%. Although the final values of the VRG seem larger than the SG, the difference was not statistically significant ($p = 0.089$).

3.2. Results of the pre and post-test analysis

The results of the pre and post-test analysis show that many questions obtained statistically significant changes, while the other items (specifically 4, 5, and 6) did not show relevant variations. The questions that did not show a significance included aspects such as the ability to react when facing a flood, and the general worry when driving under intense rain.

However, significant changes were observed in many key areas. Question 1 showed a highly significant change ($p = 0.000$), indicating a higher perception of risk when driving in adverse conditions. In question 2, the analysis showed a relevant change ($p = 0.032$), related with a more attention to safety-specific factors in these conditions. Question 3 also showed a notable change ($p = 0.001$), suggesting an increase in the awareness of associated risks.

On the other hand, question 7 showed a more marked change ($p < 0.001$), underlining a greater awareness about the risks of driving under intense rain conditions. Question 9 was also notable due to its significance ($p = 0.000$), indicating an increase in the perception of the danger of accidents under intense rain. Lastly, although question 10 showed a significant result ($p = 0.006$), the changes observed were more subtle as compared to the previous ones.

The comparative analysis between the groups revealed significant differences in certain key areas of the post-test questionnaire (Table 1). The question that assessed the safety of driving under intense rain conditions (Question 2) showed a significant difference between the groups ($p = 0.023$), with the VRG showing a higher median, which suggests an adjustment in the perception of confidence after the virtual reality intervention.

Similarly, the question on the perception of becoming trapped in a flood (Question 7) also revealed a significant change ($p = 0.007$), indicating that the VRG perceived themselves as being more aware of this possibility, as compared to the SG. The last question related to stress when driving under intense rain (Question 10) showed a notable difference ($p = 0.002$), indicating that the experience

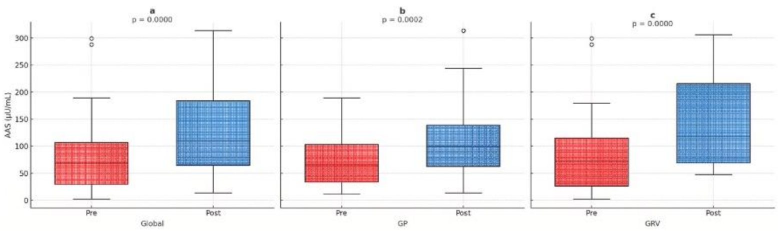

Fig. 3. Distribution of salivary alpha-amylase (SAA) levels before and after the intervention, for the Screen Group and the Virtual Reality Group.

Table 1
Comparison of the Median and the Interquartile Range (IQR) of the Post-Test results.

Question	SG (median ± IQR)	VRG (median ± IQR)	p-value
Perceived risk of driving in heavy rain	5.0 ± 1.0	5.0 ± 1.0	0.823
Safety when driving in heavy rain	1.0 ± 1.0	2.0 ± 1.25	0.022*
Probability of accident in heavy rain	5.0 ± 1.0	5.0 ± 1.0	0.869
Reaction to a vehicle flood	2.0 ± 2.25	2.0 ± 1.0	0.537
Concern about driving in heavy rain	4.5 ± 1.0	4.0 ± 1.0	0.519
Flood risk awareness	5.0 ± 1.0	5.0 ± 1.0	0.950
Knowledge of flood safety measures	2.5 ± 2.0	4.0 ± 1.0	0.006*
Probability of getting caught in a flood	4.0 ± 1.0	5.0 ± 1.0	0.3973
Insecurity due to the possibility of an accident in a flood	5.0 ± 1.0	4.5 ± 1.0	0.3380
Stress when driving in heavy rain	4.0 ± 1.0	5.0 ± 1.0	0.0015*

Mann-Whitney *U* Test; SG: Screen Group; VRG: Virtual Reality Group * if $p < 0.05$ and ** if < 0.001.

of virtual reality had a more pronounced effect on the perception of stress by the participants. In contrast, the other questions did not show significant differences between groups, suggesting that both intervention methods were equally effective in these specific areas.

3.3. Results of the neurophysiological analysis

The global results from the neurophysiological analysis of the VRG, as shown in Table 2, reflect the change in the emotional and cognitive metrics throughout the three phases. These results are based on a representative sample of the group to illustrate the trends observed. During Phase 1, the participants presented a high involvement and emotional loss of control, with a low attention and moderate stress. In Phase 2, an increase in attention and a reduction in the loss of control was observed, suggesting an adaptation to the critical scenario, while the levels of relaxation and stress were constant. Phase 3 showed a return to emotional control and an improvement in interest, along with a lower commitment, which suggests a cognitive closure of the emergency situation.

In the initial phase, a moderate attention was observed, which decreased in the critical phase and showed a slight recovery in the final phase. The commitment with the task followed a fluctuating pattern, increasing in the critical phase and decreasing at the end. The emotional loss of control showed a peak during the critical phase, as compared to the initial and final levels. The interest was maintained relatively stable in the first two phases, with an increase in the final phase. The notable change in relaxation was notable, as it started with low levels and significantly increased in the final phase, while stress showed a moderate variation throughout the phases.

The neurophysiological comparisons between the GRV and SV groups revealed different patterns. Fig. 4, which shows representative frames of each phase, together with the indicators of brain waves and neuroimages, support these findings, when showing that brain activation and processing adapted to the context of each stage. No statistically significant differences were observed between the VRG and SG groups when comparing each individual phase of the experiment (pre-exposure, critical, and post-exposure), suggesting that both conditions induced a comparable physiological response pattern over time. As similarities, both groups showed stable levels of stress during the experience, and a certain progressive adaptation to the critical situation. However, the differences were notable: the VRG group showed a more complete and complex hemispheric activation, with a greater sensory-emotional integration, while the SG showed a more localized activation and more analytical processing. The VRG experienced significantly higher levels of commitment, emotional response, and relaxation, along with a deeper immersion in the experience.

These findings suggest that virtual reality provides an experience that is closer to a real-world experience of emergency, activating neurological and emotional responses that were more intense and complex. On the other hand, the experience with the screen, although less immersive, could be useful as a training complement for the analysis and theoretical understanding of emergency situations.

Table 2
Summary of Emotional and Cognitive Metrics by phase for each of the study groups.

Metric	Phase 1		Phase 2		Phase 3	
	VRG	SG	VRG	SG	VRG	SG
Attention	22%	41%	26%	31%	26%	34%
Commitment	80%	49%	77%	53%	71%	46%
Loss of control	90%	41%	80%	53%	69%	40%
Interest	51%	30%	44%	29%	46%	37%
Relaxation	70%	8%	70%	6%	70%	30%
Stress	27%	27%	27%	21%	26%	30%

VRG: Virtual Reality Group; SG: Screen Group; Phase 1: represents the beginning of the intervention with a situation of observing rising water; Phase 2: corresponds to the critical moment with the water rising to the maximum level; Phase 3 is associated with the resolution of the emergency by being rescued by a helicopter. The analysis of attention, commitment, emotional loss of control, interest, relaxation and stress is included.

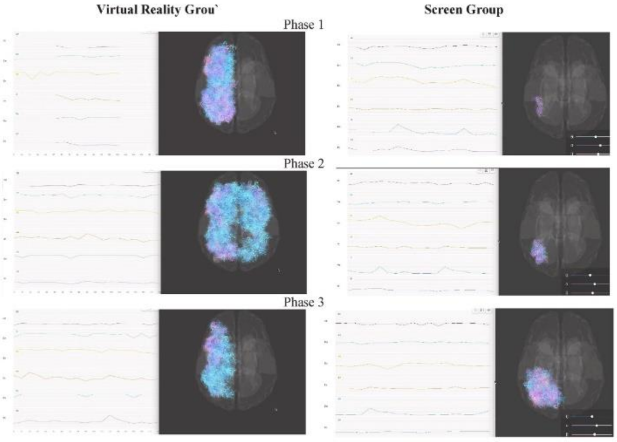

Fig. 4. Representative frames of each of the groups for each of the phases with brain waves and neuroimaging.

4. Discussion

Our results show that audiovisual resources increase the perception of risk and the emotional and cognitive responses in situations of emergency, especially when this experience is immersive. These results are in agreement with previous research studies that showed that academic stress, especially in moderate levels, can act as a positive stimulus for adolescents and university students, favoring their learning and coping skills, and promoting motivation [17,18].

In our study, the value of VR was confirmed as an educational tool in the prevention of situations of risk, highlighting its ability to induce significant changes in the perception of risk, and activating complex physiological and emotional responses [3]. In the same sense, Yomiuri Shimbun recently stated that digital technologies such as augmented reality (AR) and virtual reality (VR) can help in the visualization of risks during natural disasters such as floods or earthquakes [19].

4.1. Analysis of stress

The SSA marker data suggest that both groups experienced a significant increase in stress after the intervention, with better figures obtained by the VRG (73.15%) as compared to the SG (47.15%). These results differ from the study by Change et al., which compared the physiological responses to stress of doctors during real and virtual-reality simulated resuscitations, finding that the VR simulations increased the heart rate but not the levels of cortisol, as opposed to real situations [20]. Other authors have conducted similar studies, measuring stress in students. However, this was performed through the use of the cortisol marker, not salivary alpha-amylase [19,20]. The selection of SAA instead of cortisol to measure acute stress in our study was due to its liberation being more rapid and direct [21, 22].

The absolute values of SAA observed in students exposed to driving simulations obtained post-interventions medians of SG 112.09 $\pm$ 72.55 μU/mL vs. VRG 145.70 $\pm$ 82.86 μU/mL, with our results being almost twice to those obtained in a study where the concentration of SAA increased by 35% to 51.3 $\pm$ 47.1 μU/mL after a simulation scenario [22]. On the other hand, all of these values in the area of simulation were significantly lower than those reported in medical professionals during real-life emergencies [23], with mean values higher than 381.4 μU/mL $\pm$ 341.8. This difference underlines that although the simulations were able to induce a significant physiological activation, they did not completely replicate the extreme level of stress characteristic of real situations, which makes them safe and controlled tools for training.

4.2. Neurophysiological analysis

The neurophysiological results showed significant differences between the two groups. The VRG showed a broader and more complex brain activation, particularly in regions related with emotional integration, memory, and the making of decisions, such as the medial prefrontal cortex and hippocampus. On the other hand, the SG showed a more localized and analytical pattern of activation. In addition, a higher activation was produced in the limbic circuits and frontoparietal networks, which facilitates a deeper and more meaningful learning. Other studies performed similar analyses during a MOOC course to understand when the students were concentrated [24], and this method of analysis has been used to measure aspects such as attention and confusion [25].

4.3. Perception of risk

The perception of risk changed in both groups in our study. In our data, it was observed that a low previous perception of risk tends to be present. These results are in agreement with that published on the method of support of feelings, named affect heuristic, which indicates that our decision are based on emotions or moods [26]. In a recent study, the authors pointed out that instead of objectively evaluating a situation, we trust our "gut feeling" and respond according to how we feel [27].

Improving our understanding of how weather conditions affect the perception of risk and the behavior of drivers can contribute towards reducing the incidence and severity of accidents. However, although studies have been published on the risk with low lighting or other weather conditions [6], only one study was found that used immersive training as the research method [19]. The method by Näätänen and Summala introduces the concept of "time headway". According to this theory, drives adopt driving guidelines that they subjectively perceive as being free of risk [28].

5. Limitations and future lines

The main limitation of the study is the lack of longitudinal follow-up to assess knowledge retention and behavioral transfer. Another limitation is the absence of a non-exposed control group. In addition, the exclusive use of university students limits the generalizability of the findings to other populations, such as older adults, experienced drivers, or individuals with water-related phobias. Future studies should include more diverse samples and explore the application of this training to other emergency scenarios such as earthquakes or fires.

6. Conclusions

This study aimed to assess the impact of virtual reality on risk perception, stress levels, and neurophysiological responses in the context of a simulated flood-driving emergency. The findings demonstrate that immersive VR experiences can induce significant changes in perceived risk and provoke more intense physiological activation, measured through salivary alpha-amylase, as well as more complex neurophysiological responses compared to screen-based simulations.

In particular, participants in the VR group reported higher levels of perceived danger, showed increased emotional and attentional engagement, and activated brain areas involved in emotional regulation and decision-making, such as the medial prefrontal cortex and hippocampus. These results are consistent with previous research highlighting the educational benefits of VR, while adding value through the integration of biometric and neurophysiological measures.

While both training formats proved useful, VR's immersive quality appears to enhance users' awareness and preparedness in emergency scenarios. The combination of objective biomarkers (SAA) and EEG data provides a more comprehensive framework for evaluating learning under stress.

In conclusion, this study reinforces the potential of VR as a powerful tool in emergency education and risk prevention. Future research should explore long-term learning retention and test these interventions across more diverse populations and emergency contexts.

CRediT authorship contribution statement

Carmen Amalia Lopez Lopez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Federico Semeraro:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Antonio Hernández Férnández:** Writing – original draft, Supervision, Methodology, Investigation. **Claudia De Barros Camargo:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pablo López Guardiola:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation. **Jose Joaquin Ceron Madrigal:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Conceptualization. **María Botía González:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Ana Belén Ocampo Cervantes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Manuel Pardo Rios:** Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Conceptualization. **Daniel Guillén Martínez:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethics

The work was approved by the Research Ethics Committee from the UCAM (Universidad Católica de Murcia) with code CE112309. All participants received written and oral information about the study objectives and procedures (including the driving simulation/VR exposure and saliva collection), potential risks and discomforts, expected benefits, confidentiality and data protection measures, and their right to withdraw at any time without any consequences. Written informed consent was obtained from all participants prior to enrolment. Data were coded/anonymized and used exclusively for research purposes.

Funding

This work has been funded by the Ministry of Science, Innovation and Universities in the research project entitled *Design of a Metaverse for Higher Education in Health Sciences* (PID2022-138884NA-I00), reference MCIN/AEI/10.13039/501100011033/FEDER, EU. María Botía (21789/FPI/22) has been funded by the Séneca Foundation, Region of Murcia (Spain).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Manuel Pardo Rios reports financial support was provided by Spain Ministry of Science and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their gratitude to the *Regional Flood Control District of Clark Country* in the state of Nevada (USA). The authors would also like to thank the help of the professionals of the Virtual Reality Center of the UCAM whose members are M. Pardo, P. Guardiola, D. Guillen, A. Lanchares, A. Pedreño and J. Alonso.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2026.e44924.

Data availability

The data are available upon justified request.

References

[1] Organización Mundial de la Salud, Informe Sobre La Seguridad Vial En El Mundo 2021, OMS, Ginebra, 2021. Disponible en: https://www.who.int.
[2] Instituto Nacional de Estadística (INE), Estadísticas De Accidentes De Tráfico, 2023, INE, Madrid, 2023. Disponible en, https://www.ine.es.
[3] Z. Haghdoost, S. Yousefzadeh-Chabok, E. Homaie Rad, Turn around, don't drown: a systematic review of risk factors for motor vehicle-related drowning in floods and its preventive strategies, Disaster Med. Public Health Prep. 18 (2024) e134, https://doi.org/10.1017/dmp.2024.116.
[4] H.C. Ketenci, S. Özsoy, H.I. Aydoğdu, M. Altınok, Drowning in submerged cars caused by traffic accidents, Ulus Travma Acil Cerrahi Derg 28 (8) (2022 Aug) 1115–1121, https://doi.org/10.14744/tjtes.2021.35915.
[5] M. Ferrandini Price, E. García-Navarro, A. Pérez-Peñaranda, J.L. Fernández-Alemán, F. García-Sánchez, Á. Jiménez-Molina, Comparative study of a simulated incident with multiple victims and immersive virtual reality, Nurse Educ. Today 71 (2018) 48–53, https://doi.org/10.1016/j.nedt.2018.09.006.
[6] J. Liu, C. Wang, Z. Liu, Z. Feng, N.N. Sze, Drivers' risk perception and risky driving behavior under low illumination conditions: modified driver behavior questionnaire (DBQ) and driver skill inventory (DSI), J. Adv. Transp. 2021 (5) (2021) 1–13, https://doi.org/10.1155/2021/5568240.
[7] X. Li, Y. Wang, Z. Chen, The role of emotions in decision-making: a cognitive neuroscience perspective, Front. Psychol. 13 (2022) 1012339, https://doi.org/10.3389/fpsyg.2022.1012339.
[8] C. Morawetz, P.N.C. Mohr, H.R. Heekeren, S. Bode, The effect of emotion regulation on risk-taking and decision-related activity in prefrontal cortex, Soc. Cognit. Affect Neurosci. 14 (10) (2019 Oct 1) 1109–1118, https://doi.org/10.1093/scan/nsz078. PMID: 31680150; PMCID: PMC6970147.
[9] C. Cerezo Espinosa, F. Segura Melgarejo, R. Melendreras Ruiz, A.J. García-Collado, S. Nieto Caballero, L. Juguera Rodríguez, et al., La realidad virtual como método de enseñanza de la reanimación cardiopulmonar, Emerge 31 (1) (2019) 43–46.
[10] J. Oliveira, J. Aires Dias, R. Correia, R. Pinheiro, V. Reis, D. Sousa, D. Agostinho, M. Simões, M. Castelo-Branco, Exploring immersive multimodal virtual reality training, affective states, and ecological validity in healthy firefighters: Quasi-experimental study, JMIR Serious Games 12 (2024 Oct 24) e53683, https://doi.org/10.2196/53683. PMID: 39446479; PMCID: PMC11544332.
[11] P. Cheng, Y. Huang, P. Yang, H. Wang, B. Xu, C. Qu, et al., The effects of serious games on cardiopulmonary resuscitation training and education: systematic review with meta-analysis of randomized controlled trials, JMIR Serious Games 12 (2024) e52990, https://doi.org/10.2196/52990.
[12] J.A. Caballero-Garriazo, J.R. Rojas-Huacanca, A. Sánchez-Castro, A.F. Lázaro-Aguirre, Revisión sistemática sobre la aplicación de la realidad virtual en la educación universitaria, Rev. Electrón. Educ. 27 (3) (2023) 463–484, https://doi.org/10.15359/ree.27-3.17271.
[13] M. Pardo Ríos, et al., Metahealth: a national swot análisis for the development of a metaverse and virtual reality in health sciences education, Teach. Learn. Nurs. (2025), https://doi.org/10.1016/j.teln.2025.01.009 e579e586.
[14] J.Y.W. Liu, Y.H. Yin, P.P.K. Kor, D.S.K. Cheung, I.Y. Zhao, S. Wang, et al., The effects of immersive virtual reality applications on enhancing the learning outcomes of undergraduate health care students: systematic review with meta-synthesis, J. Med. Internet Res. 25 (2023) e39989, https://doi.org/10.2196/39989.
[15] F. Tecles, M. Fuentes-Rubio, A. Tvarijonaviciute, S. Martínez-Subiela, J. Fatjó, J.J. Cerón, Assessment of stress associated with an oral public speech in veterinary students by salivary biomarkers, J. Vet. Med. Educ. 41 (1) (2014) 37–43, https://doi.org/10.3138/jvme.0513-073R1.
[16] S. Białka, M. Copik, A. Ubych, R. Marciniak, J. Smereka, L. Szarpak, H. Misiołek, Effect of high-fidelity simulation on alpha-amylase activity and concentrations of secretory immunoglobulin class A, cortisol, and testosterone among medical students, Endocrine 73 (2) (2021 Aug) 431–438, https://doi.org/10.1007/s12020-021-02696-z.
[17] K. Iwaasa, Preparación para desastres: las tecnologías digitales brindan experiencias realistas de desastres; los métodos analógicos también ayudan a prepararse para inundaciones y terremotos, The Japan News. 25 de noviembre de (2024). Disponible en: https://japannews.yomiuri.co.jp/original/perspectives/20241125-224162/.
[18] T.P. Chang, Y. Beshay, T. Hollinger, J.M. Sherman, Comparisons of stress physiology of providers in real-life resuscitations and virtual reality–simulated resuscitations, Simulat. Healthc. J. Soc. Med. Simulat. 14 (2) (2019) 104–112, https://doi.org/10.1097/SIH.0000000000000356.

[19] M. Suh, Salivary cortisol profile under different stressful situations in female college students: moderating role of anxiety and sleep, J. Neurosci. Nurs. 50 (5) (2018 Oct) 279–285, https://doi.org/10.1097/JNN.0000000000000394.

[20] D. Pérez-Valdecantos, A. Caballero-García, T. del Castillo-Sanz, H.J. Bello, E. Roche, A. Córdova, Stress salivary biomarkers variation during the work day in emergencies in healthcare professionals, Int. J. Environ. Res. Publ. Health 18 (8) (2021) 3937, https://doi.org/10.3390/ijerph18083937.

[21] D. Roca, D. Escribano, L. Franco-Martínez, M.D. Contreras-Aguilar, L.J. Bernal, J.J. Cerón, et al., Evaluation of the effect of a live interview in journalism students on salivary stress biomarkers and conventional stress scales, Int. J. Environ. Res. Publ. Health 19 (4) (2022) 1920, https://doi.org/10.3390/ijerph19041920.

[22] J. Niles, C. McCabe, C. Moulton, M. Kampmeyer, S. Kharasch, R.J. Henneberry, Cortisol and alpha-amylase as stress response indicators during pre-hospital emergency medicine training with repetitive high-fidelity simulation and scenarios with standardized patients, Simulat. Healthc. J. Soc. Med. Simulat. 14 (2) (2019) 123–130.

[23] Claramonte M. Pons, S. Nieto Caballero, D. Escribano Tortosa, M.D. Contreras-Aguilar, J.J. Ceron Madrigal, J.J. Hernández Morante, et al., The stress experienced in an emergency medical service (EMS): a descriptive study, Int. Emerg. Nurs. 74 (2024 Jun) 101450, https://doi.org/10.1016/j.ienj.2024.101450.

[24] Á. Becerra, R. Daza, R. Cobos, A. Morales, J. Fierrez, Estudio de la experiencia de usuario mediante un sistema de dashboards de análisis de aprendizaje multimodal, arXiv preprint arXiv:2307.10346 (2023 Jul 19). Disponible en, https://arxiv.org/abs/2307.10346.

[25] P. Natnithikarat, T. Wilaiprasitporn, S. Kongwudhikunakorn, Combining EEG and NLP features for predicting students' lecture comprehension using ensemble classification, arXiv preprint arXiv:2311.11088 (2023 Nov 18). Disponible en, https://arxiv.org/abs/2311.11088.

[26] M.L. Finucane, A. Alhakami, P. Slovic, S.M. Johnson, The affect heuristic in judgments of risks and benefits, J. Behav. Decis. Making 13 (1) (2000) 1–17, https://doi.org/10.1002/(SICI)1099-0771(200001/03)13:1<1::AID-BDM333>3.0.CO;2-S.

[27] K. Skagerlund, M. Forsblad, P. Slovic, D. Västfjäll, The affect heuristic and risk perception: stability across elicitation methods and individual cognitive abilities, Front. Psychol. 11 (2020) 970, https://doi.org/10.3389/fpsyg.2020.00970.

[28] La percepción del riesgo en la conducción: modelos y teorías, Reconstrucción De Accidentes De Tráfico, 2020 Feb 5. Disponible en: https://reconstruccionaccidentestrafico.com/la-percepcion-del-riesgo-en-la-conduccion-modelos-y-teorias/.

VIII – ESTUDIO V

Immersive virtual reality for assessing decision making in mass casualty incident and tactical combat casualty care scenarios among military personnel

VIII - ESTUDIO V

Immersive virtual reality for assessing decision making in mass casualty incident and tactical combat casualty care scenarios among military personnel

Original research

OPEN ACCESS

Immersive virtual reality for assessing decision-making in mass casualty incident and tactical combat casualty care scenarios among military personnel

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► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/military-2026-003286).

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Received 25 February 2026
Accepted 22 April 2026

To cite: Lopez Lopez CA, Semeraro F, Ocampo Cervantes AB, *et al*. *BMJ Mil Health* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/military-2026-003286

ABSTRACT

Introduction Military personnel frequently act as first responders in complex tactical-medical scenarios where they must make critical decisions under pressure and coordinate with civilian emergency services. Traditional simulation methods have limitations in replicating the stress and cognitive load inherent to these contexts. Virtual reality (VR) allows the recreation of high-demand scenarios, enabling the assessment of decision-making under operational pressure.

Methods A pre–post quasi-experimental study was conducted with 38 active-duty military personnel, who completed two VR scenarios: a mass casualty incident (MCI) and a tactical combat casualty care (TCCC) scenario, following a counterbalanced crossover design. The primary outcome was the accuracy of decision-making across two VR scenarios (MCI and TCCC). Secondary outcomes included physiological stress response through salivary biomarkers, neurophysiological metrics in a subsample and subjective experience assessed through a focus group. The analysis included descriptive statistics, paired t or non-parametric tests, linear mixed models for biomarkers and a qualitative thematic analysis.

Results In the tactical scenario, participants showed a 76.7% accuracy rate, with variability in decisions under fire and airway prioritisation. In the MCI scenario, high accuracy was observed in triage items but errors occurred in more complex situations. Biomarkers showed moderate increases with no significance in univariate analyses but mixed models revealed effects of scenario type and exposure order. EEG metrics identified resilient, intermediate and vulnerable profiles, with signs of mental fatigue in high-demand phases.

Conclusions VR appears to be a useful tool for evaluating decision-making under pressure and for complementing training in tactical-medical scenarios, although this study does not provide direct evidence of improved learning outcomes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Military first responders must make rapid decisions in mass-casualty and tactical combat casualty care settings, but conventional training does not reliably reproduce the operational pressure, uncertainty and cognitive load of these environments.

WHAT THIS STUDY ADDS

⇒ In 38 active-duty military personnel completing two counterbalanced immersive virtual reality scenarios, this study identified specific vulnerabilities in care under fire, airway prioritisation and complex triage decisions.

⇒ It also showed that scenario type and exposure order influenced physiological activation, while exploratory EEG data suggested heterogeneous cognitive regulation profiles under pressure.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ These findings support immersive virtual reality as a complementary platform for assessing and rehearsing tactical-medical decision-making in military and first-responder training.

⇒ They also strengthen the case for controlled studies testing whether virtual reality-based gains translate into better retention, procedural performance and operational outcomes.

INTRODUCTION

Military personnel, frequently the first people present at the scene of an emergency, are a fundamental element for the management and initial containment of the crisis.[1 2] Adequate training is essential, as these professionals must not only be prepared to act effectively in high-risk environments but must also coordinate with civilian Emergency Medical Services (EMS).[3] In this context, the ability to make decisions under pressure is key in the most critical moments of the intervention.[4]

Training in high-risk, complex operational environments brings new challenges, given that the traditional methods of training cannot always precisely reproduce the intensity, uncertainty and cognitive load of the combat scenarios or emergencies.[4 5] Virtual reality (VR) has become consolidated as a complementary resource able to provide an answer to these challenges, as it allows recreating complex and highly demanding scenarios in a controlled and safe environment.[5 6] In addition, it allows obtaining objective metrics of learning and in real-time, which makes it possible to assess the performance and training progress of the participants.[7 8]

Table 1 Distribution of responses and percentage of correct answers at the decision points embedded in the TCCC virtual reality scenario

Question		Answers	%	(n)
1	You come under enemy fire. There is a wounded victim on the ground, actively bleeding. What do you do first?	Return fire and take cover	54	21
		Move the victim to cover	38	14
		Apply a tourniquet immediately	8	3
2	The victim is trying to move. Sporadic fire is still being received. How do you proceed?	Contact the victim and instruct them to apply a tourniquet if possible	89	34
		Rescue him and put a tourniquet on him as soon as possible	11	4
3	The victim cannot take cover, is losing consciousness, and is bleeding heavily. What do you do?	Gain fire superiority and use smoke grenades	64	24
		Rescue quickly to treat the bleeding	36	14
		Open the airway and place a nasopharyngeal airway	0	0
4	The victim is almost unconscious and continues to bleed from the thigh. What is the next step?	Transporting the victim and applying the tourniquet	100	38
		I prioritise stopping communications	0	0
		Open an airway to avoid cardiac arrest	0	0
5	The bleeding has been controlled, but the victim remains unconscious. What action should be taken?	Open the airway and insert a nasopharyngeal airway	76	29
		Start CPR immediately	18	7
		Place a second tourniquet	6	2
6	The airway is open and the tourniquet is effective. Continue providing care to the victim.	Reassess tourniquet and protect from hypothermia	74	28
		Transition from tourniquet to haemostatic agent	24	9
		Start whole blood infusion	3	1
7	After reassessing MARCH, how would you proceed?	Request evacuation via nine lines message	80	30
		Orotracheal intubation to control the airway	13	5
		Cleaning the wound is a priority	7	3

Shaded cells indicate the pre-specified correct response at each decision point, as defined a priori during scenario design according to TCCC/MARCH principles.
MARCH, Massive haemorrhage, Airway, Respiration, Circulation, Hypothermia; TCCC, tactical combat casualty care.

In the last few years, organisations such as the *Medical Technology Enterprise Consortium*, financed by the Defense Department of the United States for the development of advanced medical technologies, have developed immersive simulations applied to tactical medicine, including haemorrhage management, triage and management of the wounded in combat.[9 10] Current evidence[11 12] still reveals important gaps, particularly the limited number of studies assessing the impact of VR on decision-making and the scarce incorporation of haptic stimuli, which may enhance realism and emotional load.

The primary aim of the present study was to assess the accuracy of decision-making in two immersive VR scenarios: a mass casualty incident (MCI) scenario and a tactical combat casualty care (TCCC) scenario. The TCCC scenario followed structured algorithms such as Massive haemorrhage, Airway, Respiration, Circulation, Hypothermia (MARCH), a prioritisation sequence used to guide the management of life-threatening conditions in combat settings. The secondary aim was to explore participants' responses to these high-demand operational situations through objective, subjective, physiological and neurocognitive indicators.

METHODOLOGY

Study design

A pre–post quasi-experimental study with repeated measures was conducted between September and December 2025. All participants completed two VR scenarios: a mass-casualty incident (MCI) scenario and a tactical combat casualty care (TCCC) scenario. Randomisation was applied only to scenario order, using a counterbalanced cross-over design to control for sequence, learning or fatigue effects. Both scenarios simulated high operational stress and assessed decision-making under pressure.

The MCI scenario required participants to prioritise victim triage and treatment in a high-pressure environment (link: https://youtube.com/shorts/KPbsNHtXIdE). The TCCC scenario involved tactical decision-making and response to an active shooter, assessing combat-related operational skills and coordination under extreme conditions (link: https://youtu.be/wJuJsu-VzvwE). Scenario duration depended on response time within a structured decision sequence, averaging 6–7 min for MCI and 7–8 min for TCCC. Correct responses enabled progression to the next step.

The MCI scenario was completed without haptic feedback, whereas the TCCC scenario used a Woojer Vest 3. This was predefined according to acoustic characteristics: the vest is mainly activated by low-frequency sounds, which were present in the TCCC scenario but not in the MCI scenario. The scenarios were developed by TCCC instructors and recorded with Insta360 X4 cameras in 8K resolution at the General Albacete Fuster Marine Infantry School in Cartagena, Murcia, Spain.

Participants were recruited by convenience. An a priori sample size estimation for paired comparisons assumed Cohen's d=0.5, alpha=0.05 and 80% power. Approximately 34 paired observations were required; therefore, the final sample of 38 participants was considered adequate for this exploratory study.

Participants

The sample consisted of 38 active-duty military personnel stationed at the General Albacete Fuster Marine Infantry School in Cartagena, Murcia, Spain. Participants were recruited by convenience during an advanced TCCC level 3 training course, and all eligible attendees were invited to participate.

Inclusion criteria were active-duty military personnel enrolled in the course. All participants had previously completed mandatory first responder training, ensuring a common baseline in emergency and tactical care. Previous deployment or field experience was not systematically collected.

No formal exclusion criteria were established beyond standard VR precautions, including dizziness, visual fatigue, previous discomfort with VR devices, photosensitivity or epilepsy, all assessed by self-report during the initial briefing. Participants

Table 2 Distribution of responses, accuracy and missing cases in the 14 triage decision points (Q1–Q14) of the MCI virtual reality scenario (N=38)

Number	Correct category	Distribution of answers (n/%)	Accurate (n)	Accuracy (%)	Total answers (n)	Missing cases (n)	%
Q1	Yellow	Yellow: 34 (89.5%). Red: 2 (5.3%). Black: 2 (5.3%). Green: 0 (0.0%).	34	89.5	38	0	0.0
Q2	Yellow	Red: 33 (89.2%). Yellow: 3 (8.1%). Green: 1 (2.7%).	3	8.1	37	1	2.6
Q3	Red	Red: 29 (76.3%). Yellow: 6 (15.8%). Green: 2 (5.3%). Black: 1 (2.6%).	29	76.3	38	0	0.0
Q4	Red	Red: 28 (77.8%). Yellow: 4 (11.1%). Black: 4 (11.1%).	28	77.8	36	2	5.3
Q5	Yellow	Yellow: 22 (59.5%). Red: 8 (21.6%). Green: 5 (13.5%). Black: 2 (5.4%).	22	59.5	37	1	2.6
Q6	Yellow	Yellow: 36 (94.7%). Red: 1 (2.6%). Black: 1 (2.6%).	36	94.7	38	0	0.0
Q7	Red	Red: 29 (80.6%). Yellow: 7 (19.4%).	29	80.6	36	2	5.3
Q8	Green	Black: 14 (37.8%). Yellow: 11 (29.7%). Green: 10 (27.0%). Red: 2 (5.4%).	10	27.0	37	1	2.6
Q9	Red	Red: 29 (76.3%). Yellow: 7 (18.4%). Green: 2 (5.3%).	29	76.3	38	0	0.0
Q10	Red	Red: 17 (48.6%). Yellow: 17 (48.6%). Green: 1 (2.9%).	17	48.6	35	3	7.9
Q11	Yellow	Red: 21 (56.8%). Yellow: 12 (32.4%). Green: 2 (5.4%). Black: 2 (5.4%).	12	32.4	37	1	2.6
Q12	Red	Red: 19 (50.0%). Yellow: 16 (42.1%). Green: 3 (7.9%). Black: 0 (0.0%).	19	50.0	38	0	0.0
Q13	Black	Black: 34 (94.4%). Red: 2 (5.6%). Green: 0 (0.0%). Yellow: 0 (0.0%).	34	94.4	36	2	5.3
Q14	Red	Yellow: 15 (40.5%). Green: 14 (37.8%). Red: 8 (21.6%). Black: 0 (0.0%).	8	21.6	37	1	2.6

Correct category: indicates the prespecified triage category assigned to each case and used as the reference standard for accuracy calculations.
MCI, mass casualty incident.

were informed about possible symptoms, monitored throughout the sessions and allowed to withdraw at any time. No participant was excluded for health-related reasons.

VR equipment and intervention

The intervention used Meta Quest 3 VR goggles,[13] on-ear noise-cancelling headphones to ensure a distraction-free listening experience, and, for the TCCC scenario, a Woojer Vest 3 haptic vest. The scenarios were delivered through the Wonda VR platform as 360° immersive experiences with sequential decision points embedded in the narrative.

At each step, participants selected one available option, and the platform automatically recorded the response. Decision accuracy was defined as selection of the prespecified correct option at each decision point. The timed nature of the experience referred to real-time scenario progression, although response time was not analysed as an independent outcome. Before starting, participants received a standardised safety and equipment briefing lasting approximately 2 min.

Procedures

Each participant followed a standardised procedure. A baseline saliva sample was collected before the first scenario, followed by scenario completion and a postscenario saliva sample. After an approximately 1-hour recovery period, during which saliva sampling and preparation for the next scenario were completed, the procedure was repeated for the second scenario.

Saliva samples were obtained using Salivette devices according to standardised acute stress protocols, avoiding prior food intake and exercise. After centrifugation, samples were stored at −20°C until salivary alpha-amylase and cortisol levels were analysed using validated enzymatic methods.

A subsample of six participants underwent EEG recording as an exploratory component to assess mental workload, attention and brain activity patterns during decision-making under pressure (online supplemental Material 1). During each rotation, the participant assigned to VR device number 1 was selected for EEG recording, ensuring a consistent procedure independent of participant characteristics.

Variables and instruments

Performance in the MCI scenario was assessed using 14 predefined triage questions and two initial life-saving intervention items, designed to evaluate decision-making accuracy under simulated conditions.

The primary outcome was decision-making accuracy, defined as the selection of the prespecified correct option at each decision point within the VR scenarios. Secondary variables included physiological response, assessed through prescenario and postscenario salivary amylase as a stress indicator, and neurocognitive response in the EEG subsample, including theta, alpha and beta activity, frontal alpha asymmetry and engagement index.

Discussion group

At the end of the study, immediately after both VR scenarios, a focus group was conducted with all participants to explore their experience. The discussion followed a semistructured guide covering five domains: realism, perceived stress, training usefulness, operational applicability and technical limitations. These questions were separate from the VR decision points, which were used only to assess decision-making accuracy.

The focus group was moderated by two experts, one in VR medical training and another in TCCC training. All interventions were audio-recorded and transcribed using TurboScribe AI. Two authors checked the transcript, coded the data and conducted a thematic analysis. Final categories were agreed by consensus.

Statistical analysis

A descriptive analysis was performed for all variables. Quantitative variables were summarised as mean and SD, or median and IQR, according to distribution; qualitative variables as frequencies and percentages. Normality was assessed using the Shapiro-Wilk test.[14]

For stress biomarkers, prescenario and postscenario amylase and cortisol values were compared using Student's paired t-test when normality was met, or the Wilcoxon signed-rank test otherwise.[15] Given the repeated measures design with two scenarios per participant and counterbalanced order, linear mixed models were fitted for amylase and cortisol with a random intercept per

Table 3 Comparison of physiological stress biomarkers (SAA and cortisol) pre and post exposure to virtual reality experiences, with global and subgroup analysis according to haptic vest use

Scenario	Test	n	Mean pre (SD)	Mean post (SD)	% Change	P value	Z	r
TCCC	SAA	37	188330.27 (132 840.87)	203858.38 (160 471.64)	8.2 %	0.255	1.14	0.19
	Cortisol	36	0.25 (0.15)	0.26 (0.11)	1.2 %	0.509	0.66	0.11
MCI	SAA	36	191464.44 (130 804.83)	212738.33 (138 633.65)	11.1 %	0.157	1.41	0.24
	Cortisol	36	0.25 (0.14)	0.27 (0.14)	6.9 %	0.200	1.28	0.21

MCI, mass casualty incident; SAA, salivary alpha amylase; TCCC, tactical combat casualty care.

subject. Timing, scenario type, order of performance and relevant interactions were included as fixed effects to control for sequence effects. A two-tailed significance level of $p<0.05$ was established.

RESULTS

Accuracy of decision-making in the TCCC scenario

The decision-making results for TCCC are summarised in table 1. Overall, the mean accuracy rate was 76.7% (54%–100% range). In attention under fire, only slightly more than half of the participants adequately prioritised fire coverage and control. In the tactical care in the field, a higher accuracy was recorded, with consensus in carrying and tourniquet, in addition to good performance in the airway. In the tactical evacuation, most reassessed the tourniquet, prevented hypothermia and requested evacuation, although a small group persisted with decisions not aligned with the MARCH algorithm.[16]

Accuracy of decision-making in the MCI scenario

Performance results for the MCI scenario are summarised in table 2. The presence of missing responses (omissions) was also recorded for each item. Participants showed high accuracy in key triage items (generally >75%), although marked errors were observed in Q2, Q8 and Q14. Omissions were more frequent in complex items, particularly Q10. These omissions cannot be attributed solely to stress and may also reflect variability in knowledge or experience in a scenario involving multiple casualties. In the life-saving manoeuvres, the tourniquet showed a high accuracy, but the prioritisation of the airway was clearly deficient, with less than a 25% identifying the oropharyngeal airway as the correct intervention.

Discussion group

The qualitative analysis identified five key dimensions of the experience (realism, operational stress, active participation, training value and technical limitations), collected in online supplemental Material 2. The MCI scenario was perceived as generating greater presence and stress, which may be related to its first-person perspective and to participants' lower perceived familiarity with mass-casualty triage. As a whole, the military personnel assessed VR as a useful training tool, although they pointed to the need to improve the haptic intensity, visual realism and the dynamic adaptation of the surroundings.

Assessment of stress through alpha amylase and cortisol

Table 3 shows the mean increases in amylase and cortisol after viewing the VR scenarios, although none of the pre–post comparisons showed statistical significance through univariate tests (paired t-test or Wilcoxon's test).

To explore the physiological variation, considering the experimental context, the linear mixed models were fitted (table 4), including the measurement time (pre/post), the type of scenario (MCI or TCCC) and the order of execution (first or second), with a random intercept per subject. In these models, the type of scenario showed a significant effect on physiological activation, with higher values in the TCCC scenario as compared with MCI, especially for salivary amylase.

Table 4 Results of linear mixed models (LMM) for amylase and cortisol

Variable	Coefficient	SD	Z	P	95% CI
Model 1: Amylase					
Type: TCCC	50.700	14.700	3.441	**0.001**	21.8 to 79.6
PrePost (Post vs Pre)	7.300	5.300	1.386	0.166	−3.0 to 17.7
Order (2nd vs 1st)	12.400	5.300	2.327	**0.020**	2.0 to 22.9
Type×Order	−32.200	9.700	−3.310	**0.001**	−51.2 to −13.1
PrePost×Type	−14.200	10.100	−1.415	0.157	−34.0 to 5.5
PrePost×Order	−6.100	4.400	−1.368	0.171	−14.7 to 2.6
PrePost×Type × Order	10.700	6.300	1.699	0.089	−1.7 to 23.1
Model 2: Cortisol					
Type: TCCC	0.507	0.147	3.441	0.001	0.218 to 0.796
PrePost (Post vs Pre)	0.073	0.053	1.386	0.166	−0.030 to 0.177
Order (2nd vs 1st)	0.124	0.053	2.327	0.020	0.020 to 0.229
Type×Order	−0.322	0.097	−3.310	0.001	−0.512 to −0.131
PrePost×Type	−0.142	0.101	−1.415	0.157	−0.340 to 0.055
PrePost×Order	−0.061	0.044	−1.368	0.171	−0.147 to 0.026
PrePost×Type × Order	0.107	0.063	1.699	0.089	−0.017 to 0.231

Bold values indicate statistical significance at p<0.05.
TCCC, tactical combat casualty care.

Likewise, the order of execution was associated with a significant increase in both biomarkers when the scenarios were performed in second place. The interaction between the type of scenario and order was also significant, indicating that the differences between the MCI and TCCC depend on the exposure sequence. As a set, the mixed models show evidence that the physiological activation is modulated by the type of scenario and order of exposure, allowing for the detection of contextual effects that were not identifiable through simple univariate analyses.

Neurophysiological assessment

The EEG analysis showed differences in attention and mental effort patterns between scenarios. In the MCI scenario, a global decrease in sustained attention was observed as the scenario progressed. Participants showed notable variability in their ability to maintain attention, reflected in prolonged attentional lapses, averaging 6.8% and reaching up to 14.35%, consistent with the higher perceived stress reported in the discussion group.

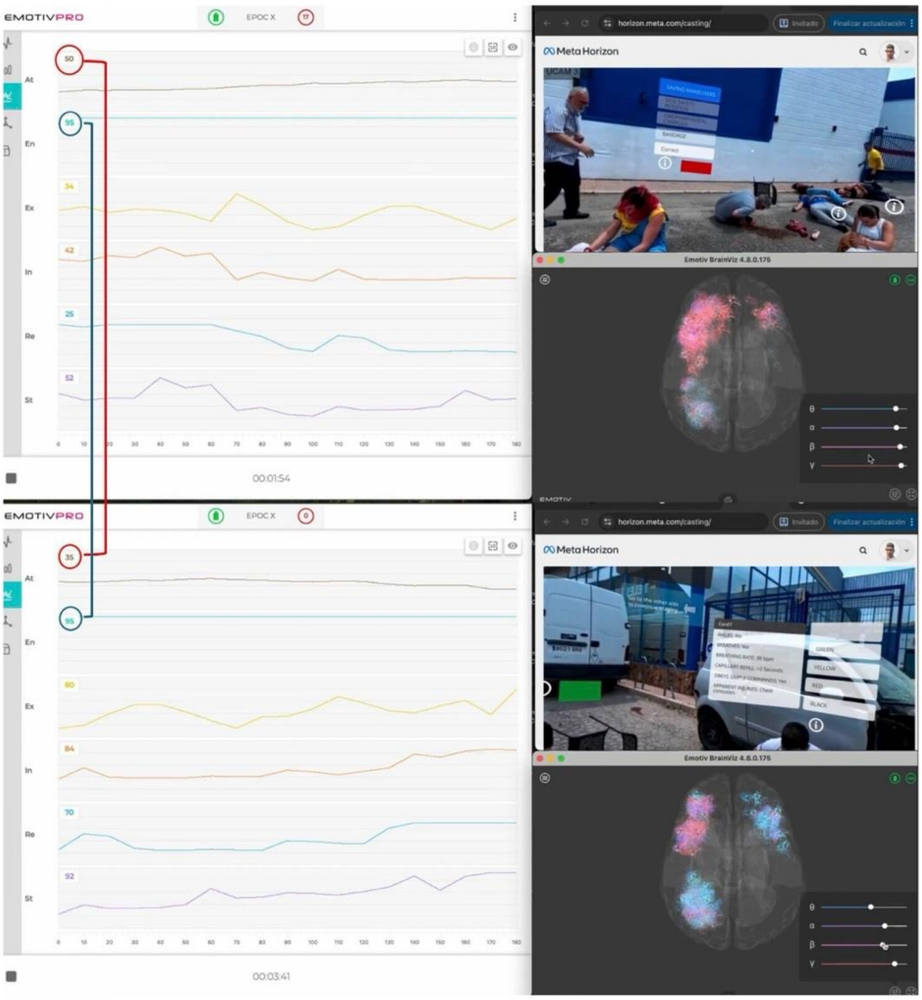

Figure 1 Neurophysiological variations during decision-making in the virtual reality experience about mass casualty incident.

DISCUSSION

The present study explored immersive VR for assessing decision-making under pressure in MCI and TCCC scenarios. The results suggest that VR can complement tactical-medical training by reproducing realistic operational demands and identifying areas for improvement that may not be detected through traditional methods.[4 5 11] Although participants generally applied the algorithms correctly, errors occurred in critical phases, especially in decisions under fire, specific triage items and airway prioritisation.

In the TCCC scenario, participants performed better in structured phases, such as haemorrhage control and tourniquet use. However, decisions under active fire were more variable, particularly when choosing between self-protection and evacuating a wounded peer. This agrees with studies showing that protocolised actions are applied more consistently, whereas decisions requiring tactical judgement show greater variability, even among experienced personnel.[17]

Similarly, in the MCI scenario, performance was better in structured decisions, while more errors appeared when complex clinical assessment was required. This is consistent with VR-based MCI studies suggesting that the challenge lies not in knowing the triage algorithm, but in applying it under workload and cognitive pressure, especially when multiple casualties must be prioritised simultaneously.[5 18 19] These findings support VR as an environment for practising decision-making under pressure, as scenarios can be repeated and progressively adapted in difficulty.[7 20]

The qualitative findings reinforced these results. Scenario design influenced the training experience: the first-person MCI scenario generated greater emotional impact and presence, whereas the TCCC scenario was perceived as more active and decision-oriented. Participants valued VR as a complementary training tool, although they noted limitations in visual realism and haptic feedback. This aligns with reviews highlighting multisensory integration as important for improving realism and transfer to real settings.[20–22]

From a physiological perspective, salivary biomarkers showed that stress response varied by scenario type and exposure order. The TCCC scenario was associated with stronger activation, while the second scenario increased stress response regardless of content, suggesting a cumulative effect. These findings are consistent with studies describing salivary amylase as a marker of sympathetic activation during cognitively demanding tasks, whereas cortisol shows a slower, context-dependent response.[23–25] Previous VR studies also indicate that these biomarkers may reveal effects related to stimulus intensity, workload and exposure sequence in multivariate models, even when simple comparisons are not significant.[23 24] The greater activation in the TCCC scenario is consistent with studies reporting stronger physiological responses in tactical scenarios involving higher threat perception and decision pressure than structured clinical tasks.[26 27] However, because haptic feedback was only included in the TCCC scenario, its independent contribution cannot be separated from scenario content. Therefore, findings should be interpreted as part of the overall immersive configuration rather than as evidence of an isolated haptic effect. Qualitative feedback also suggested that haptic intensity may have been insufficient to produce a strong perceived effect.

The EEG data provided a complementary perspective on mental workload and attention.[28] The MCI scenario was associated with greater attentional demands, possibly related to participants' lower familiarity with mass-casualty triage, although this remains exploratory. However, the peripheral physiological response, measured through alpha-amylase, did not increase in parallel, supporting the idea that perceived stress and cognitive effort are not always directly reflected by peripheral markers. This reinforces the value of combining central and peripheral neurophysiological indicators.[23 24 26]

In contrast, the TCCC scenario showed increased engagement during critical decision phases, together with signs of cognitive fatigue when demand was sustained. The analysis identified three cognitive regulation profiles under pressure: resilient, intermediate and vulnerable. This is consistent with neuroergonomic approaches that characterise individual differences in mental workload and stress regulation to guide adaptive interventions.[17] Combining VR with neurophysiological measures may, therefore, help personalise and optimise tactical medical training.[29]

Strengths and limitations

The present study integrates behavioural, subjective, physiological and neurocognitive measures, providing a comprehensive perspective on performance under stress in tactical-medical scenarios. However, several limitations should be considered. These include the relatively small sample size, absence of a control group and focus on cognitive decision-making without assessment of psychomotor skills. This limits direct translation to real-world performance, as manual dexterity is critical in tactical medical care and was not captured by the VR platform, which was designed to assess decision-making rather than procedural execution.

In addition, previous deployment or field experience was not systematically collected and may have influenced individual responses. Omissions during the scenarios cannot be attributed exclusively to stress, as they may also reflect differences in knowledge or experience. Although scenario order was counterbalanced and included in the statistical models, residual effects related to increasing familiarity with the VR procedure or the tactical context cannot be excluded. These factors may have influenced participants' motivation, performance and physiological stress response.

Implications and future lines

The findings suggest that VR may be a valuable resource for training decision-making in highly demanding tactical-medical situations, enabling the identification of vulnerabilities that may not emerge in traditional simulation. By integrating objective, subjective and physiological metrics, VR could support more personalised training models focused on real performance under pressure. Future studies should explore adaptive scenarios based on users' cognitive and physiological state, the incorporation of psychomotor skills and the scalability of these tools in training programmes for military and emergency personnel.

Conclusions

The results suggest that immersive VR may be a valuable complementary tool for assessing performance and identifying critical errors during tactical-medical decision-making under pressure. While these findings support its use in military and emergency training contexts, they should not be interpreted as direct evidence of improved learning, which should be examined in future controlled studies.

Contributors MPR conceived and coordinated the study and acted as principal investigator. MPR, MSG, CALL, ABOC, MPR, SNC, FS, PMAA and DGM contributed to the study design and development of the virtual reality scenarios. MSG, CALL, MPC, PMAA and DGM contributed to participant recruitment, data collection and data management. MGS, CALL, ABOC, MPC and DGM contributed to data analysis and interpretation. MPR, MGS, CALL and DGM drafted the initial manuscript. All authors contributed to the critical revision of the manuscript, approved the final version submitted for publication and agreed to be accountable for all aspects of the work. Guarantor: MPR is the guarantor of the study and accepts full responsibility for the work, had access to the data, and controlled the decision to publish. AI-assisted tools, including ChatGPT, were used for language editing, formatting support, and improving clarity of expression. They were not used to generate data, conduct analyses, interpret results or make scientific conclusions. All content was critically reviewed and approved by the authors, who remain fully responsible for the manuscript.

Funding This study is funded by Ministerio de Ciencia, Innovación y Universidades (PID2022-138884NA-I00).

Competing interests None declared.

Patient consent for publication Consent obtained directly from patients.

Ethics approval This study involves human participants and was approved by UCAM EC Reference Number CE112309. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer-reviewed.

Data availability statement Data are available upon reasonable request. AI-assisted tools, including ChatGPT, were used for language editing, formatting support and improving clarity of expression. They were not used to generate data, conduct analyses, interpret results or make scientific conclusions. All content was critically reviewed and approved by the authors, who remain fully responsible for the manuscript.

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REFERENCES

1 Alharbi KA. Role synergy in prehospital emergency care. *Translational Practice in Medicine* 2025;5:1–15. Available: https://tpmap.org/submission/index.php/tpm/article/download/477/353/999
2 GoArmy. 68w combat medic specialist. U.S. Army; 2019. Available: https://www.goarmy.com/careers-and-jobs/ground-forces/68w-combat-medic-specialist
3 Caffery SJ, Ferrari BD, Hackett MG. Military Medical Simulations-Scoping Review. *Mil Med* 2025;190:e554–60.
4 Bailey SKT, Brannick MT, Bowling F, *et al*. Comparing Capabilities of Simulation Modalities for Training Combat Casualty Care: Perspectives of Combat Medics. *Mil Med* 2024;189:e1738–44.
5 Heldring S, Jirwe M, Wihlborg J, *et al*. Using High-Fidelity Virtual Reality for Mass-Casualty Incident Training by First Responders - A Systematic Review of the Literature. *Prehosp Disaster Med* 2024;39:94–105.
6 Fernández-Arias P, del Bosque A, Lampropoulos G, *et al*. Applications of AI and VR in High-Risk Training Simulations: A Bibliometric Review. *Appl Sci (Basel)* 2025;15:5424.
7 Jongbloed J, Chaker R, Lavoué E. Immersive procedural training in virtual reality: A systematic literature review. *Computers & Education* 2024;221:105124.
8 Abbas JR, Chu MMH, Jeyarajah C, *et al*. Virtual reality in simulation-based emergency skills training: A systematic review with a narrative synthesis. *Resuscitation Plus* 2023;16:100484.
9 Medical Technology Enterprise Consortium. Medical simulation and training technologies for military and tactical medicine. 2023. Available: https://mtec-sc.org/
10 SimX Inc. SimX awarded U.S. Air force contract to develop vr medical support training simulations for aeromedical evacuation and critical care air transport training. PR Newswire; 2023. Available: https://www.prnewswire.com/news-releases/simx-awarded-us-air-force-contract-to-develop-vr-medical-support-training-simulations-for-aeromedical-evacuation-and-critical-care-air-transport-training-301783417.html
11 Dawson DE, *et al*. Virtual simulation for tactical medical decision-making. *Mil Med* 2023;188:e1909–17.
12 Tanaka A. Augmented reality for tactical combat casualty care training. In: *Lecture Notes in Computer Science Springer*. 2018. Available: https://doi.org/10.1007/978-3-319-91467-1_19
13 Meta Platforms Technologies, LLC. Meta quest 3: product specifications and technical documentation. Menlo Park (CA): Meta; 2023. Available: https://www.meta.com/quest/quest-3
14 Shapiro SS, Wilk MB. An analysis of variance test for normality (complete samples). *Biometrika* 1965;52:591–611.
15 Wilcoxon F. Individual Comparisons by Ranking Methods. *Biometrics Bulletin* 1945;1:80.
16 Butler FK Jr, Holcomb JB, Giebner SD, *et al*. Tactical combat casualty care 2007: evolving concepts and battlefield experience. *Mil Med* 2007;172:1–19.
17 Hancock PA, Matthews G. Performance under stress: individual differences and adaptive capacity. *Hum Factors* 2021;63:3–17.
18 Lochmannová A. Exploring the role of virtual reality in preparing emergency responders for mass casualty incidents. *Isr J Health Policy Res* 2025;14:22.
19 Kman NE, Panchal AR, Patterson J, *et al*. Virtual Reality Simulation for Assessment of Hemorrhage Control and SALT Triage Accuracy in First Responders. *Disaster med public health prep* 2024;18.
20 Eide KL, Keating B, Braastad A, *et al*. Immersive Virtual Reality Simulation for Tactical Mass-Casualty Triage: An Observational Study of Usability, Realism, and Decision-Making in RAMP Training. *Disaster med public health prep* 2026;20.
21 Ocaña M, Luna A, Yarad Jeada V, *et al*. Are vr and ar really viable in military education?: a position paper. 2023. Available: https://www.researchgate.net/
22 Abensur Vuillaume L, Goffoy J, Dubois N, *et al*. Collaborative virtual reality environment in disaster medicine: moving from single player to multiple learners. *BMC Med Educ* 2024;24:422.
23 van StegerenAH, Wolf OT, Kindt M. Salivary alpha-amylase and cortisol as markers of acute stress: a review of findings and methodological considerations. *Psychoneuroendocrinology* 2020;114:104599.
24 Ali N, Nater UM, Engert V. Salivary alpha-amylase as a marker of stress in real-life contexts: a systematic review. *Neurosci Biobehav Rev* 2021;127:843–62.
25 Höller Y, Bathke AC, Kronbichler M, *et al*. Stress-related changes in salivary alpha-amylase and cortisol during immersive virtual reality exposure. *Comput Hum Behav* 2022;128:107110.
26 Gómez-García J, Ruz-Rojas A, Muñoz-Leiva F, *et al*. Physiological stress response in immersive virtual reality environments: a systematic review. *Sensors (Basel)* 2023;23.
27 Tremmel C, Herff C, Sato T, *et al*. Estimating Cognitive Workload in an Interactive Virtual Reality Environment Using EEG. *Front Hum Neurosci* 2019;13:401.
28 Hori K, Watanabe K, Sugawara J. Physiological responses to decision-making under stress: effects of threat and time pressure. *Hum Factors* 2021;63:1406–19.
29 Dehais F, Lafont A, Roy R, *et al*. A neuroergonomics approach to mental workload, engagement and stress. *Appl Ergon* 2020;88:103162.

IV – RESUMEN GLOBLAL Y DISCUSIÓN

IX – RESUMEN GLOBAL Y DISCUSIÓN

La presente tesis doctoral por compendio de publicaciones representa un esfuerzo sistemático por analizar cómo la realidad virtual inmersiva y, en un plano más amplio, las tecnologías inmersivas, pueden contribuir a transformar la educación en ciencias de la salud y la preparación ante situaciones de alta complejidad (1-3). Aunque los cinco estudios incluidos se desarrollan en escenarios distintos, educación superior sanitaria, percepción del riesgo en conducción extrema, estrés y neurofisiología en inundaciones, toma de decisiones en escenarios táctico-sanitarios e hipotermia accidental en contexto civil-militar, todos convergen en una misma idea: el valor de la realidad virtual para formar, evaluar y comprender la respuesta humana en entornos exigentes. Esta aproximación se alinea con la literatura reciente, que sitúa la RV no como una tecnología periférica, sino como una estrategia pedagógica con potencial para entrenar competencias técnicas y no técnicas en contextos donde la simulación convencional resulta limitada (2,4-7).

Desde una perspectiva integradora, los resultados de esta tesis permiten sostener una idea central: la realidad virtual no constituye un fin en sí misma, sino un instrumento pedagógico y evaluativo especialmente útil cuando se integra en un diseño formativo riguroso y orientado a competencias (2,4-5). Esta interpretación coincide con las ERC Guidelines 2025 on Education for Resuscitation, que sitúan las metodologías de technology-enhanced learning, la simulación, la evaluación estructurada, el feedback y el debriefing en el núcleo de la formación contemporánea, y también con las revisiones recientes sobre RV en educación médica, que insisten en que el valor de estas herramientas depende de su alineación con objetivos docentes, métodos de evaluación y contexto de implementación (2,4-5). Dicho de otro modo, la evidencia más actual no respalda una visión tecnocéntrica, sino una integración crítica y pedagógicamente intencionada de la tecnología (2,5-8).

El primero de los estudios del compendio, METAHEALTH, aporta una base estratégica especialmente relevante para interpretar el resto de la tesis. Sus resultados muestran que la introducción del metaverso y de la RV en educación superior en ciencias de la salud se percibe como una oportunidad para mejorar resultados de aprendizaje, favorecer la adquisición y retención de habilidades y ampliar las posibilidades de simulación y colaboración; sin embargo, también identifica debilidades y amenazas consistentes, como el coste tecnológico, la curva de aprendizaje, las barreras de infraestructura y las preocupaciones éticas y de privacidad (10).Esta doble lectura, potencial transformador y necesidad de implementación cuidadosa, es plenamente coherente con la literatura reciente (1,2,5). La revisión de Mergen et al. concluye que la RV ha dejado de circunscribirse a procedimientos técnicos y se está extendiendo a escenarios complejos y a habilidades no técnicas, pero subraya igualmente la necesidad de integrar estas herramientas en el currículo con criterios de viabilidad y calidad educativa (2). De forma similar, las revisiones sistemáticas más recientes sobre RV inmersiva y sobre su uso como herramienta de evaluación insisten en que las oportunidades de automatización, estandarización y aprendizaje activo conviven con desafíos de coste, software, usabilidad y alineación pedagógica (4,5).

Los dos estudios centrados en conducción extrema e inundaciones refuerzan otro hallazgo fundamental de la tesis: la realidad virtual no solo sirve para entrenar procedimientos, sino también para modificar la percepción del riesgo y activar procesos emocionales, fisiológicos y neurocognitivos implicados en la toma de decisiones (estudio II, estudio III). En adolescentes, la experiencia inmersiva produjo un aumento significativo de la percepción del riesgo y reveló diferencias de género en la disposición a modificar conductas y en los patrones de activación cerebral (estudio II). En el estudio cuasi-experimental sobre inundaciones, la RV mostró mayor capacidad que el formato audiovisual no inmersivo para modificar ítems clave de percepción del riesgo, junto con incrementos de alfa-amilasa salival y patrones neurofisiológicos más complejos, especialmente en áreas relacionadas con integración emocional y toma de decisiones (estudio III).Tomados en conjunto, estos resultados sugieren que la inmersión no actúa únicamente sobre el plano cognitivo declarativo, sino sobre procesos más amplios de implicación afectiva y valoración del peligro (13,32,45). La evidencia externa reciente respalda esta interpretación: los estudios sobre inmersión y aprendizaje en educación médica subrayan que la presencia y la agencia pueden potenciar el compromiso y el procesamiento significativo (13), mientras que el metaanálisis sobre reactividad de estrés en realidad virtual demuestra que la RV es capaz de inducir respuestas fisiológicas medibles en biomarcadores simpáticos y endocrinos (32). Asimismo, la revisión sobre marcadores neurobiológicos en educación en ciencias de la salud recuerda que variables como HR, HRV, cortisol o alfa-amilasa no son equivalentes a "aprendizaje" por sí mismas, pero sí aportan información valiosa sobre la dinámica emocional y cognitiva del entorno formativo (45).

Desde el punto de vista conceptual, estos resultados apoyan la idea de que la realidad virtual puede funcionar como un catalizador de aprendizaje situado y afectivamente significativo (13,41). No parece actuar solo por exposición a contenidos, sino por su capacidad para colocar al usuario en una situación donde debe percibir, interpretar y responder a señales ambientales de forma integrada (13,38). Esta observación enlaza con el marco teórico desarrollado en la tesis sobre inmersión, presencia, interacción, emociones y toma de decisiones, y ayuda a explicar por qué los cambios observados en percepción del riesgo son más intensos cuando la experiencia es inmersiva que cuando se presenta en pantalla convencional (13,38). No obstante, también obliga a una interpretación prudente: una mayor activación fisiológica o emocional no implica automáticamente un mejor aprendizaje, sino que debe entenderse en relación con el diseño del escenario, el tipo de tarea y la capacidad del usuario para regular su respuesta (32,41,45).

Los estudios sobre toma de decisiones en escenarios táctico-sanitarios y reanimación en hipotermia accidental aportan un tercer eje de gran relevancia: la utilidad de la RV como plataforma de evaluación del desempeño bajo presión (estudio IV, estudio V). En personal militar, la RV permitió identificar con precisión vulnerabilidades en fases críticas del TCCC y del triaje en incidentes con múltiples víctimas, especialmente en decisiones bajo fuego, priorización de vía aérea y situaciones clínicas complejas (estudio IV). Además, los biomarcadores y los registros EEG sugirieron que el tipo de escenario y el orden de exposición modulan la activación fisiológica y que existen perfiles diferenciales de regulación cognitiva bajo presión (estudio IV). En el estudio de hipotermia, la RV mostró ser factible y altamente aceptada en un ejercicio OTAN civil-militar, con elevada utilidad percibida, facilidad de uso y detección de brechas específicas en pasos del algoritmo de hipotermia, junto con señales exploratorias de *engagement* y asimetría alfa frontal previas a respuestas incorrectas (estudio V). Estos hallazgos refuerzan la idea de que la RV puede utilizarse no solo para enseñar, sino para observar, objetivar y analizar cómo deciden los usuarios en tareas complejas (5,6,7,73).

La literatura científica reciente apoya de forma clara esta interpretación. La revisión sistemática de Neher et al. concluye que la RV tiene un uso prometedor como herramienta de evaluación en educación médica y de enfermería, especialmente en escenarios de emergencias y en tareas basadas en desempeño, al permitir automatizar parte del proceso evaluativo y registrar de forma objetiva conductas complejas (5). Del mismo modo, las revisiones sobre realidad extendida y realidad virtual de alta fidelidad en incidentes con múltiples víctimas coinciden en que estos entornos pueden mejorar exactitud de triaje, tiempos de respuesta, experiencia del usuario y entrenamiento de primeros intervinientes, aunque recomiendan interpretarlos como complemento de otros formatos y no como sustituto absoluto (6,7). En el ámbito militar, el scoping review de Caffery et al. muestra que la simulación sigue siendo un eje central de la preparación médica militar y destaca la necesidad de seguir fortaleciendo la evidencia específica sobre qué modalidades y métricas aportan mayor valor en escenarios operativos (73).

A la luz de todos los estudios, esta tesis permite formular tres proposiciones integradoras.La primera es que la realidad virtual es una herramienta pedagógica transversal, capaz de adaptarse a contextos educativos, preventivos y operativos muy distintos, desde la educación superior sanitaria hasta la conducción extrema, la medicina táctica o la hipotermia accidental, siempre que el diseño del escenario sea congruente con el objetivo formativo o evaluativo (2,4,6,7). La segunda es que su mayor valor no parece residir en reemplazar metodologías previas, sino en añadir realismo, repetibilidad, inmersión y capacidad de registro objetivo a tareas donde el factor humano y la complejidad contextual son determinantes (5.7). La tercera es que la evaluación del aprendizaje inmersivo exige una mirada multimodal, que combine rendimiento observable, percepción del usuario y, cuando sea pertinente, indicadores fisiológicos y neurocognitivos (45,50,51,56). Estas tres proposiciones se apoyan tanto en los resultados de tu compendio como en las revisiones recientes sobre RV en educación médica, evaluación en entornos inmersivos y marcadores de estrés en educación en salud (4,5,45).

Las implicaciones prácticas de estos hallazgos son relevantes. En el ámbito universitario, los resultados apoyan la incorporación de RV y metaverso como recursos complementarios para simulación clínica, entrenamiento de competencias no técnicas, colaboración interprofesional y evaluación (1,5,10). En prevención y educación para la seguridad, sugieren que las experiencias inmersivas pueden ser útiles para modificar la percepción del riesgo y promover respuestas más adaptativas ante amenazas ambientales (13,42,45). En emergencias, desastres y contextos civil-militares, la evidencia de esta tesis respalda el uso de RV para ensayar decisiones críticas, detectar vulnerabilidades y complementar el entrenamiento de primeros intervinientes (6,7,73). Estas aplicaciones son coherentes con la orientación actual del ERC 2025 hacia metodologías activas, simulación, technology-enhanced learning y evaluación estructurada de competencias (8).

Como todo trabajo, esta tesis presenta limitaciones que deben considerarse en la interpretación de los resultados. En primer lugar, el compendio incluye diseños metodológicos heterogéneos: cualitativos, cuasi-experimentales y observacionales, lo que enriquece la perspectiva global pero dificulta la comparación directa entre estudios. En segundo lugar, varios trabajos tienen muestras moderadas o contextos de reclutamiento específicos, lo que limita la generalización. En tercer lugar, en los estudios con biomarcadores y EEG, la interpretación debe ser necesariamente prudente por el carácter exploratorio de parte de estas medidas y por la conocida complejidad para vincular directamente activación fisiológica con aprendizaje o rendimiento. Finalmente, aunque los resultados apoyan la utilidad de la RV, no todos los estudios permiten afirmar mejoras directas de aprendizaje a largo plazo o transferencia completa al contexto real, cuestión que la propia literatura reciente sigue señalando como una laguna prioritaria.

En consecuencia, las líneas futuras de investigación deberían orientarse a ensayos multicéntricos con muestras más amplias, comparaciones entre distintos niveles de inmersión, seguimientos longitudinales que evalúen retención y transferencia, y modelos adaptativos que integren datos de desempeño, experiencia de usuario y fisiología en tiempo real. También sería especialmente relevante avanzar en estudios de implementación y coste-efectividad, dado que una parte de las barreras detectadas en METAHEALTH y en la literatura internacional se sitúan precisamente en la sostenibilidad institucional, la capacitación docente y la infraestructura tecnológica.

Esta tesis doctoral muestra que la realidad virtual y las tecnologías inmersivas no deben entenderse como una moda tecnológica, sino como herramientas con capacidad real para enriquecer la educación en ciencias de la salud, la prevención y la preparación ante contextos complejos. Su valor no reside en la novedad, sino en su potencial para recrear escenarios difíciles de entrenar, modificar la percepción del riesgo, objetivar el desempeño y abrir nuevas vías para comprender la relación entre cognición, emoción, fisiología y decisión. Considerados de forma conjunta, los cinco estudios del compendio aportan una base conceptual y empírica sólida para seguir avanzando hacia un modelo formativo más inmersivo, evaluable y adaptado a la complejidad real de los contextos sanitarios y de emergencia contemporáneos.

X – CONCLUSIONES

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10.1. CONCLUSIONES GENERALES

El potencial transformador de la RV en la educación.

La RV ha demostrado ser una herramienta educativa efectiva en diversos campos, como la seguridad vial y la medicina de emergencia, al modificar la percepción del riesgo, mejorar la toma de decisiones bajo estrés y activar áreas cerebrales clave para la evaluación y la toma de decisiones. Sin embargo, es crucial complementar estas experiencias inmersivas con enfoques adicionales de capacitación que aborden momentos de vulnerabilidad cognitiva, lo cual maximiza su impacto.

La importancia de un enfoque personalizado y adaptable.

Los estudios destacan la necesidad de considerar características demográficas y patrones neuronales individuales al diseñar intervenciones educativas basadas en RV. El uso de sistemas adaptativos que respondan en tiempo real a la activación cerebral de los usuarios puede aumentar significativamente la efectividad de la formación, especialmente en contextos de alta presión, como simulaciones de emergencias y situaciones de riesgo.

La RV como complemento, no sustituto, de la formación física.

Aunque la RV es altamente eficaz para mejorar la percepción del riesgo y la toma de decisiones, no debe reemplazar el entrenamiento físico en situaciones críticas. La combinación de la simulación inmersiva con dispositivos de retroalimentación en vivo y entrenamiento físico sigue siendo esencial para desarrollar habilidades cognitivas y prácticas completas en los escenarios de emergencia, asegurando una sinergia adecuada entre la tecnología y la práctica real.

10.2. CONCLUSIÓN ESTUDIO I

El metaverso y la Realidad Virtual (RV) tienen un potencial transformador para la salud, seguridad y medio ambiente (HSE), pero deben abordarse desafíos como los costos, la capacitación y los estándares éticos. La inversión estratégica y marcos éticos sólidos son esenciales para su implementación exitosa.

10.3. CONCLUSIÓN ESTUDIO II

Este estudio demuestra el potencial transformador de la RV como herramienta educativa en la seguridad vial, respaldada tanto por evidencia conductual como neurofisiológica.La integración pionera de neuroimagen con experiencias inmersivas ha permitido no solo confirmar la efectividad de la RV para modificar la percepción del riesgo, sino también comprender los mecanismos neuronales subyacentes que explican las diferencias en su impacto entre diferentes grupos de participantes.Los patrones observados de activación cerebral, junto con las diferencias de género en las respuestas conductuales, sugieren que el impacto de la RV en la percepción del riesgo opera a través de vías neuronales específicas que varían según el género y la experiencia previa.Esto tiene implicaciones directas para el diseño de intervenciones educativas, sugiriendo la necesidad de un enfoque personalizado que considere no solo las características demográficas, sino también los patrones individuales de procesamiento neural del riesgo.

10.4. CONCLUSIÓN ESTUDIO III

La Realidad Virtual inmersiva fue viable y bien aceptada para evaluar la toma de decisiones en la reanimación por hipotermia durante un ejercicio civil-militar.El desempeño observado destacó lagunas específicas en la toma de decisiones relacionadas con la hipotermia. Se necesitan estudios controlados y longitudinales para evaluar el progreso en el aprendizaje y la efectividad del entrenamiento.

10.5. CONCLUSIÓN ESTUDIO IV

Los resultados demuestran que las experiencias inmersivas de RV pueden inducir cambios significativos en la percepción del riesgo y provocar una activación fisiológica más intensa, medida a través de la amilasa salival, así como respuestas neurofisiológicas más complejas en comparación con las simulaciones basadas en pantallas.

En particular, los participantes del grupo de RV informaron niveles más altos de peligro percibido, mostraron un mayor compromiso emocional y de atención, y activaron áreas cerebrales involucradas en la regulación emocional y la toma de decisiones, como la corteza prefrontal medial y el hipocampo.Estos resultados son consistentes con investigaciones previas que resaltan los beneficios educativos de la RV, al agregar valor mediante la integración de medidas biométricas y neurofisiológicas.

Si bien ambos formatos de entrenamiento resultaron útiles, la cualidad inmersiva de la RV parece mejorar la conciencia y preparación de los usuarios en escenarios de emergencia. La combinación de biomarcadores objetivos (amilasa salival) y datos de EEG proporciona un marco más completo para evaluar el aprendizaje bajo estrés.

En conclusión, este estudio refuerza el potencial de la RV como una herramienta poderosa en la educación de emergencias y la prevención de riesgos. La investigación futura debería explorar la retención del aprendizaje a largo plazo y probar estas intervenciones en poblaciones más diversas y contextos de emergencia.

10.6. CONCLUSIÓN ESTUDIO V

Este estudio sugiere que la RV inmersiva puede ser una herramienta complementaria valiosa para evaluar el desempeño e identificar errores críticos durante la toma de decisiones táctico-médicas bajo presión.Aunque estos hallazgos respaldan su uso en contextos de entrenamiento militar y de emergencia, no deben interpretarse como evidencia directa de una mejora en el aprendizaje, lo cual debe ser examinado en estudios controlados futuros.

XI - REFERENCIAS BIBLIOGRÁFICAS

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1. Lewis, K. O., Popov, V., & Fatima, S. S. (2024). From static web to metaverse: Reinventing medical education in the post-pandemic era. *Annals of Medicine, 56*(1), 2305694. https://doi.org/10.1080/07853890.2024.2305694
2. Mergen, M., Graf, N., & Meyerheim, M. (2024). Reviewing the current state of virtual reality integration in medical education: A scoping review. *BMC Medical Education, 24*, 788. https://doi.org/10.1186/s12909-024-05777-5
3. Alsharari, A. F., Salihu, D., & Alshammari, F. F. (2025). Effectiveness of virtual clinical learning in nursing education: A systematic review. *BMC Nursing, 24*(1), 432. https://doi.org/10.1186/s12912-025-03076-y
4. Junga, A., Schulze, H., Scherzer, S., Ritter, C., & Heinlein, F. (2024). Immersive learning in medical education: Analyzing behavioral insights to shape the future of VR-based courses. *BMC Medical Education, 24*, 1413. https://doi.org/10.1186/s12909-024-06337-7
5. Zhang, W., Ding, Z., Bakaev, M., Rakhimova, D., & Wang, Y. (2025). Immersive virtual reality based on head-mounted display in medical education: A systematic review. *BMC Medical Education, 25*, 1593. https://doi.org/10.1186/s12909-025-08154-y
6. Cardós-Alonso, M. del C., Otero-Varela, L., Redondo, M., Uzuriaga, M., González, M., Vázquez, T., Blanco, A., Espinosa, S., & Cintora-Sanz, A. M. (2024). Extended reality training for mass casualty incidents: A systematic review on effectiveness and experience of medical first responders. *International Journal of Emergency Medicine, 17*(1), 99. https://doi.org/10.1186/s12245-024-00685-3
7. Heldring, S., Jirwe, M., Wihlborg, J., Berg, L., & Lindström, V. (2024). Using high-fidelity virtual reality for mass-casualty incident training by first responders: A systematic review of the literature. *Prehospital and Disaster Medicine, 39*(1), 94–105. https://doi.org/10.1017/S1049023X24000049
8. Kaggwa, M. M., Chaimowitz, G. A., Agboinghale, P., Nkoba, N. K., & Ndanyi, A. (2025). Virtual reality training programs in disaster preparedness: A systematic review. *Discover Education, 4*, 325. https://doi.org/10.1007/s44217-025-00771-5
9. Hsieh, J. Y., Lin, P. C., Sun, W. N., Lin, T. R., Kuo, C. C., & Hsu, H. T. (2025). Effectiveness of immersive virtual reality in nursing education for nursing students and nursing staff: A systematic review and meta-analysis. *Nurse Education Today, 151*, 106725. https://doi.org/10.1016/j.nedt.2025.106725

10. Pardo Ríos, M., López López, C. A., Castro Delgado, R., Morales Moreno, I., Guillén Martínez, D., López Guardiola, P., & Juguera Lucina, L. (2025). Meta-health: A national SWOT analysis for the development of a metaverse and virtual reality in health sciences education. *Teaching and Learning in Nursing, 20*, e579–e586. https://doi.org/10.1016/j.teln.2025.01.009
11. Asoodar, M., Janesarvatan, F., Yu, H., & Charkhandeh, M. (2024). Theoretical foundations and implications of augmented reality, virtual reality, and mixed reality for immersive learning in health professions education. *Advances in Simulation, 9*, 36.
12. Zhang, R., Jin, X., Liu, M., & Tong, H. Y. (2025). The effectiveness of augmented reality/mixed reality in medical education: A meta-analysis. *BMC Medical Education, 25*(1), 1586. https://doi.org/10.1186/s12909-025-08166-8
13. Makransky, G., & Petersen, G. B. (2021). The Cognitive Affective Model of Immersive Learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review, 33*, 937–958. https://doi.org/10.1007/s10648-020-09586-2
14. Tene, T., Vique López, D. F., Valverde Aguirre, P. E., Orna Puente, L. M., & Vacacela Gomez, C. (2024). Virtual reality and augmented reality in medical education: An umbrella review. *Frontiers in Digital Health, 6*, 1365345. https://doi.org/10.3389/fdgth.2024.1365345
15. Neher, A. N., Bühlmann, F., Müller, M., Berendonk C, Sauter T.C, & Birrenbach T. (2025). Virtual reality for assessment in undergraduate nursing and medical education: A systematic review. *BMC Medical Education, 25*, 292. https://doi.org/10.1186/s12909-025-06867-8
16. Sinurat, S., Karo, M. B., Simbolon, R., Saragih, I. D., Tarihoran, D. E. T. A. U., Sharma, S., & Chou, F. H. (2025). The efficacy of virtual-reality teaching and learning method in enhancing interprofessional knowledge, clinical skill performance, and self-confidence in nursing education: A systematic review and meta-analysis. *Nurse Education Today, 149*, 106661. https://doi.org/10.1016/j.nedt.2025.106661
17. Mentira, S. S., Helle, N., Sletteland, N. V., Vikman, M. D., & Bonsaksen, T. (2023). Implementation of virtual reality in health professions education: Scoping review. *JMIR Medical Education, 9*, e44695.
18. Lee, J. W. Y., Tan, J. Y., & Bello, F. (2025). Technology acceptance model in medical education: Systematic review. *JMIR Medical Education, 11*, e67873.
19. Johnston, M., O'Mahony, M., O'Brien, N., Connolly, M., Iohom, G., Kamal, M., Shehata, A., & Shorten, G. (2024). The feasibility and usability of mixed reality teaching in a hospital setting based on self-reported perceptions of medical students. *BMC Medical Education, 24*, 701. https://doi.org/10.1186/s12909-024-05591-z

20. Erbaş, A., Akyüz, E., & Ergöl, Ş. (2024). The effects of virtual reality used in healthcare education on cybersickness and sense of presence: A systematic review. *Presence: Virtual and Augmented Reality, 33*, 161–178. https://doi.org/10.1162/pres_a_00414
21. Jallad, S. T., Natsheh, I., Abu Helo, L., Ibdah, D. M., Salah, A., Muhsen, R., Shehadeh, Y., & Froukh, N. (2024). Nursing student's perceptions, satisfaction, and knowledge toward utilizing immersive virtual reality application in human anatomy course: Quasi-experimental. *BMC Nursing, 23*, 601. https://doi.org/10.1186/s12912-024-02254-8
22. Jeon, H., Shin, H., & Woo, J. (2024). User experience and interface assessment for metaverse platforms on nurses and nursing students: A cross-sectional study. *Nurse Education Today, 139*, 106222. https://doi.org/10.1016/j.nedt.2024.106222
23. Mørk, G., Bonsaksen, T., Larsen, O. S., Kunnikoff, H. M., & Lie, S. S. (2024). Virtual reality simulation in undergraduate health care education programs: Usability study. *JMIR Medical Education, 10*, e56844.
24. Fugate, J. M. B., Tonsager, M. J., & Macrine, S. L. (2025). Immersive extended reality (I-XR) in medical and nursing for skill competency and knowledge acquisition: A systematic review and implications for pedagogical practices. *Behavioral Sciences, 15*(4), 468. https://doi.org/10.3390/bs15040468
25. Tabatabaei Far, S. S., Ahmadi Marzaleh, M., Soltani, R., & Ghaleh Golab, F. (2026). Applications and challenges of virtual reality in medical sciences education: A systematic review. *Journal of Advances in Medical Education & Professionalism, 14*(1), 21–31.
26. Cossio, S., Chiappinotto, S., Dentice, S., Moreal, C., Magro, G., Dussi, G., Palese, A., & Galazzi, A. (2025). Cybersickness and discomfort from head-mounted displays delivering fully immersive virtual reality: A systematic review. *Nurse Education in Practice*, 104376.
27. Poupard, M., Larrue, F., Bertrand, M., Liguoro, D., Tricot, A., & Sauzéon, H. (2025). Using virtual reality for enhancing neuroanatomy learning by optimizing cognitive load and intrinsic motivation. *Computers & Education, 235*, 105332.
28. Wen, P., Lu, F., & Mohamad Ali, A. Z. (2024). Using attentional guidance methods in virtual reality laboratories reduces students' cognitive load and improves their academic performance. *Virtual Reality, 28*, 110. https://doi.org/10.1007/s10055-024-01012-0
29. Sun, R., Wang, Y., Wu, Q., Wang, S., Liu, X., Wang, P., He, Y., & Zheng, H. (2024). Effectiveness of virtual and augmented reality for cardiopulmonary resuscitation training: A systematic review and meta-analysis. *BMC Medical Education, 24*, 730. https://doi.org/10.1186/s12909-024-05720-8

30. Walls, R., Nageswaran, P., Cowell, A., Sehgal, T., White, T., McVeigh, J., Staykov, S., Basett, P., Mitelpunkt, D., & Sam, A. H. (2024). Virtual reality as an engaging and enjoyable method for delivering emergency clinical simulation training: A prospective, interventional study of medical undergraduates. *BMC Medicine, 22*, 222. https://doi.org/10.1186/s12916-024-03433-9
31. Elkin, R. L., Beaubien, J. M., Damaghi, N., Chang, T. P., & Kessler, D. O. (2024). Dynamic cognitive load assessment in virtual reality. *Simulation & Gaming, 55*(4), 755–775.
32. Campagne, A., Favier, M., Franke, M., Kyeong, S., Rademaker, M., Blascovich, J., et al. (2022). Evoking stress reactivity in virtual reality: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews, 138*, 104709.
33. Robbemond, L. M., Noordzij, M. L., van Driel, C. M. G., & Veling, W. (2026). Physiological responses to virtual reality-based stress regulation and relaxation interventions: A systematic review. *Stress and Health, 42*(2), e70164. https://doi.org/10.1002/smi.70164
34. Pulido-Martos, M., Augusto-Landa, J. M., & Lopez-Zafra, E. (2024). Neurobiological stress markers in educational research: A systematic review of physiological insights in health science education. *Trends in Neuroscience and Education*, 100242.
35. Guillen-Sanz, H., Checa, D., Miguel-Alonso, I., & Bustillo, A. (2024). A systematic review of wearable biosensor usage in immersive virtual reality experiences. *Virtual Reality, 28*, 74. https://doi.org/10.1007/s10055-024-00970-9
36. Wang, D., Peng, Y., Haddouk, L., Vayatis, N., & Vidal, P. (2025). Assessing virtual reality presence through physiological measures: a comprehensive review. *Frontiers in Virtual Reality*.
37. Simón-Vicente, L., Rodríguez-Cano, S., Delgado-Benito, V., Ausín-Villaverde, V., & Cubo Delgado, E. (2024). Cybersickness: A systematic literature review of adverse effects related to virtual reality. *Neurología, 39*(8), 701–709.
38. Linares-Vargas, B. G. P., & Cieza-Mostacero, S. E. (2025). Interactive virtual reality environments and emotions: A systematic review. *Virtual Reality, 29*, 3. https://doi.org/10.1007/s10055-024-01049-1
39. Caldas, O. I., Mauledoux, M., Aviles, O. F., & Rodriguez-Guerrero, C. (2024). Breaking presence in immersive virtual reality toward behavioral and emotional engagement. *Computer Methods and Programs in Biomedicine, 248*, 108124. https://doi.org/10.1016/j.cmpb.2024.108124
40. Jicol, C., Cheng, H. Y., Petrini, K., & O'Neill, E. (2023). A predictive model for understanding the role of emotion for the formation of presence in virtual reality. *PLoS ONE, 18*(3), e0280390. https://doi.org/10.1371/journal.pone.0280390
41. Makransky, G., & Mayer, R. E. (2022). Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia

learning. Educational Psychology Review, 34(3), 1771–1798. https://doi.org/10.1007/s10648-022-09675-4

42. Xu, J., Yang, L., & Guo, M. (2024). Designing and evaluating an emotionally responsive virtual patient simulation. *Simulation in Healthcare*, 19(3), 196–203. https://doi.org/10.1097/SIH.0000000000000730
43. Pinto, R., Albuquerque, S., de Castro, M. V., Levendosky, A. A., Fonseca, M., Jongenelen, I., Maia, Â., & Gamito, P. (2024). A virtual reality simulation to examine the relationship between post-traumatic stress symptoms and decision-making in first responders. *Journal of Trauma & Dissociation*, 25(5), 597–612. https://doi.org/10.1080/15299732.2024.2374370
44. António, H., Barros, C., Vieira de Castro, M., Oliveira, J., Gamito, P., Bouchard, S., & Pinto, R. J. (2025). Posttraumatic stress disorder and physiological response in first responders during virtual reality exposure. *Cyberpsychology, Behavior, and Social Networking*, 28(12), 787–793. https://doi.org/10.1177/21522715251394917
45. Gellisch, M., Bablok, M., Brand-Saberi, B., & Schäfer, T. (2024). Neurobiological stress markers in educational research: A systematic review of physiological insights in health science education. *Trends in Neuroscience and Education*, 37, 100242. https://doi.org/10.1016/j.tine.2024.100242
46. Orovas, C., Sapounidis, T., Volioti, C., & Keramopoulos, E. (2025). EEG in education: A scoping review of hardware, software, and methodological aspects. Sensors, 25(1), 182. https://doi.org/10.3390/s25010182
47. Salatino, A., & Burin, D. (2024). Editorial: Virtual, mixed and augmented reality in cognitive neuroscience and neuropsychology, volume II. *Frontiers in Psychology*, 15, 1444412. https://doi.org/10.3389/fpsyg.2024.1444412
48. Kazemi, R., & Lee, S. (2023). Human factors/ergonomics (HFE) evaluation in the virtual reality environment: A systematic review. *International Journal of Human–Computer Interaction*, 39, 4533–4549.
49. Tao, L., Cukurova, M., & Song, Y. (2025). Learning analytics in immersive virtual learning environments: A systematic literature review. *Smart Learning Environments*, 12, 43.
50. Zhou, W., Hu, X., & Wei, W. (2025, July). Multimodal learning analytics using wearable devices in immersive virtual reality learning environments: A systematic review on learning indicators and ethical considerations. In *2025 IEEE International Conference on Advanced Learning Technologies (ICALT)* (pp. 96–100). IEEE. https://doi.org/10.1109/ICALT64023.2025.00033
51. Fradette, M. J., Dufour, M., & Bouchard, S. (2025). Real-time applications of biophysiological markers in virtual reality exposure therapy: A systematic review. *Virtual Worlds, 5*(3), 48. https://doi.org/10.3390/virtualworlds5030048

52. Dos Santos Silva, V., & Nunes, F. (2025). Evaluating healthcare learning in virtual reality: A systematic review. In Proceedings of the 27th Symposium on Virtual and Augmented Reality (SVR) (pp. 241–250).
53. Li, X., Wang, K., Wang, Y., He, J., & Zhang, J. (2024). Assessing user experiences in virtual reality learning environments. *The Asia-Pacific Education Researcher, 33*(4), 1149–1160. https://doi.org/10.1007/s40299-023-00785-3.
54. Erbaş, A., Akyüz, E., Giustivi, D., & Privitera, D. (2025). Two important factors in virtual reality simulations: Nursing students' experiences of cybersickness and sense of presence. *Clinical Simulation in Nursing, 106*, 101787. https://doi.org/10.1016/j.ecns.2025.101787
55. Halbig, A., & Latoschik, M. E. (2021). A systematic review of physiological measurements, factors, methods, and applications in virtual reality. *Frontiers in Virtual Reality*, 2, 694567. https://doi.org/10.3389/frvir.2021.694567
56. Pedram, S., Kennedy, G., & Sanzone, S. (2023). Toward the validation of VR-HMDs for medical education: A systematic literature review. Virtual Reality, 27, 1–26. https://doi.org/10.1007/s10055-023-00802-2
57. Reale, C., Salwei, M. E., Militello, L. G., Weinger, M. B., Burden, A., Sushereba, C., Torsher, L. C., Andreae, M. H., Gaba, D. M., McIvor, W. R., Banerjee, A., Slagle, J., & Anders, S. (2023). Decision-making during high-risk events: A systematic literature review. *Journal of Cognitive Engineering and Decision Making*, 17(2), 188–212. https://doi.org/10.1177/15553434221147415
58. Voss, S., Brandling, J., Pollard, K., Taylor, H., Black, S., Buswell, M., Cheston, R., Cullum, S., Foster, T., Kirby, K., Prothero, L., Purdy, S., Solway, C., & Benger, J. (2020). A qualitative study on conveyance decision-making during emergency call outs to people with dementia: The HOMEWARD project. *BMC Emergency Medicine*, 20(1), 6. https://doi.org/10.1186/s12873-020-0306-6
59. Gardiner, G., Eli, K., Huxley, C. J., Fothergill, R., Perkins, G. D., Smyth, M. A., Griffiths, F., & Slowther, A.-M. (2024).Negotiating grey areas: An interview-based analysis of paramedic uncertainty and decision-making in cardiac arrest events. *BMC Emergency Medicine*, 24, 154. https://doi.org/10.1186/s12873-024-01057-z
60. Perry, O., Jaffe, E., Goldberg, A., & Bitan, Y. (2024). Incident commander decision making: Quantitative evaluation of instantaneous and considered decisions. Applied Ergonomics, 114, 104139. https://doi.org/10.1016/j.apergo.2023.104139
61. Perry, O., Goldberg, A., Jaffe, E., & Bitan, Y. (2023, November). Mass casualty incident commander decision-making models: Novice vs. expert decision making. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 67*(1), xx–xx. https://doi.org/10.1177/21695067231192921

62. Vloet, L. C. M., Hesselink, G., Berben, S. A. A., Hoogeveen, M., Rood, P. J. T., & Ebben, R. H. A. (2021). The updated national research agenda 2021–2026 for prehospital emergency medical services in the Netherlands: A Delphi study. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 29*(1), 162. https://doi.org/10.1186/s13049-021-00971-6

63. Magnusson, C., Hagiwara, M. A., Norberg-Boysen, G., Kauppi, W., Herlitz, J., Axelsson, C., Packendorff, N., Larsson, G., & Wibring, K. (2022). Suboptimal prehospital decision-making for referral to alternative levels of care: Frequency, measurement, acceptance rate and room for improvement. *BMC Emergency Medicine, 22*(1), 89. https://doi.org/10.1186/s12873-022-00643-3

64. Oving, I., Masterson, S., Tjelmeland, I. B. M., Jonsson, M., Semeraro, F., Ringh, M., Truhlar, A., Cimpoesu, D., Folke, F., Beesems, S. G., Koster, R. W., Tan, H. L., Blom, M. T., & ESCAPE-NET Investigators. (2019). First-response treatment after out-of-hospital cardiac arrest: A survey of current practices across 29 countries in Europe. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 27*(1), 112. https://doi.org/10.1186/s13049-019-0689-0

65. Lockey, D. J., Weaver, A. E., & Davies, G. E. (2013). Practical translation of hemorrhage control techniques to the civilian trauma scene. *Transfusion, 53*(Suppl. 1), 17S–22S. https://doi.org/10.1111/trf.12031

66. Penney, G., Launder, D., Cuthbertson, J., & Thompson, M. B. (2022). Threat assessment, sense making, and critical decision-making in police, military, ambulance, and fire services. *Cognition, Technology & Work, 24*, 423–439. https://doi.org/10.1007/s10111-022-00694-3

67. Westman, A., Kurland, L., & Hugelius, K. (2024). Non-technical skills needed by medical disaster responders: A scoping review. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 32*(1), 25. https://doi.org/10.1186/s13049-024-01197-y

68. Lindeman, A., Næss, L. E., Vesterhus, L., & Bakken, A.-B. M. (2025) Improving preparedness for time critical prehospital care: a descriptive study of the first responder system in Central Norway. *Scand J Trauma Resusc Emerg Med* 33, 11 https://doi.org/10.1186/s13049-024-01316-9

69. Usoro, A., Mehmood, A., Rapaport, S., Ezeigwe, A. K., Adeyeye, A., Akinlade, O., Dias, J., Barnett, D. J., Hsu, E. B., Tower, C., & Razzak, J. (2023). A scoping review of the essential components of emergency medical response systems for mass casualty incidents. *Disaster Medicine and Public Health Preparedness, 17*, e274. https://doi.org/10.1017/dmp.2022.235

70. Strauss, R., Menchetti, I., Perrier, L., Blondal, E., Peng, H., Sullivan-Kwantes, W., Tien, H., Nathens, A., Beckett, A., Callum, J., & da Luz, L. T. (2021). Evaluating the Tactical Combat Casualty Care principles in civilian and military settings: Systematic review, knowledge gap analysis and recommendations for future research. *Trauma Surgery & Acute Care Open, 6*(1), e000773. https://doi.org/10.1136/tsaco-2021-000773

71. Borgers, F., Van Boxstael, S., & Sabbe, M. (2021). Is tactical combat casualty care in terrorist attacks suitable for civilian first responders? *Journal of Trauma and Acute Care Surgery, 91*(4), e86–e92. https://doi.org/10.1097/TA.0000000000003337

72. Remley, M. A., Shackelford, S. A., Rush, S. C., Kue, R. C., Brown, J., Schaffrinna, A., Koch, E. J., Stringer, J., Montgomery, H. R., & Deaton, T. G. (2025). Triage in action: A principles-based approach to mass casualty management in Tactical Combat Casualty Care. *Journal of Special Operations Medicine, 25*(3), 127–131. https://doi.org/10.55460/ZC6P-YS4G.

73. Araghizadeh, H., Peyravi, M., Sharififar, S., & Ahmadi Marzaleh, M. (2021). Coordination of civil and military forces in natural disasters: A systematic review. Journal of Military Medicine, 23(6), 555–563.

74. Gastaldi, S., & Horlait, M. (2022). Health care organizations' interoperability during multi-organizational disaster management: A scoping review. *Prehospital and Disaster Medicine, 37*(3), 401–408. https://doi.org/10.1017/S1049023X22000516

75. Janse, J., Kalkman, J. P., Burchell, G. L., Hopperus Buma, A. P. C. C., Zuiderent-Jerak, T., Bollen, M. T. I. B., & Timen, A. (2022). Civil–military cooperation in the management of infectious disease outbreaks: A scoping review. *BMJ Global Health*, 7(6), e009228. https://doi.org/10.1136/bmjgh-2022-009228

76. García Ulerio, J. G., Al Khatib, M. A., Aammar, B. A., Ragazzoni, L., Barone-Adesi, F., & Caviglia, M. (2025). Simulation technology use in disaster medicine education and training: A scoping review. *Frontiers in Disaster and Emergency Medicine*, 2, 1636285. https://doi.org/10.3389/femer.2025.1636285

77. Emaliyawati, E., Ibrahim, K., Trisyani, Y., Nuraeni, A., Sugiharto, F., Miladi, Q. N., Abdillah, H., Christina, M., Setiawan, D. R., & Sutini, T. (2025). Enhancing disaster preparedness through tabletop disaster exercises: A scoping review of benefits for health workers and students. *Advances in Medical Education and Practice, 16*, 1–11. https://doi.org/10.2147/AMEP.S504705

78. Abbas, J. R., Chu, M. M. H., Jeyarajah, C., Isba, R., Payton, A., McGrath, B., Tolley, N., & Bruce, I. (2023). Virtual reality in simulation-based emergency

skills training: A systematic review with a narrative synthesis. *Resuscitation Plus, 16*, 100484. https://doi.org/10.1016/j.resplu.2023.100484

79. Shaw, T. A., Grisham, J., Kotora, J., Knight, R. M., Sleeman, J., Durnin, K., Montgomery, H. R., & Deaton, T. G. (2025). Airway management in Tactical Combat Casualty Care: TCCC Change 24-1. *Journal of Special Operations Medicine*, 24(4), 45–56. https://doi.org/10.55460/C0YI-YZNK

80. Suda, A. J., Franke, A., Hertwig, M., & Gooßen, K. (2025). Management of mass casualty incidents: a systematic review and clinical practice guideline update. *Eur J Trauma Emerg Surg* **51**, 5 https://doi.org/10.1007/s00068-024-02727-0

81. Tin, D., Granholm, F., Hata, R., & Ciottone, G. (2023). Rethinking mass-casualty triage. *Prehospital and Disaster Medicine, 38*(3), 424–425. https://doi.org/10.1017/S1049023X23000390
82. Jenkins, J. L., McCarthy, M. L., Sauer, L. M., Green, G. B., Stuart, S., Thomas, T. L., & Hsu, E. B. (2008). Mass-casualty triage: Time for an evidence-based approach. *Prehospital and Disaster Medicine, 23*(1), 3–8. https://doi.org/10.1017/S1049023X00005471
83. Saadatmand, V., Ahmadi Marzaleh, M., Abbasi, H. R., Peyravi, M. R., & Shokrpour, N. (2023). Emergency medical services preparedness in mass casualty incidents: A systematic review. *American Journal of Disaster Medicine, 18*(1), 79–91. https://doi.org/10.5055/ajdm.0461
84. Hugelius, K., & Becker, J. (2024). Common challenges in the prehospital management of mass-casualty incidents: A systematic integrative review. *Prehospital and Disaster Medicine, 39*, 301–309.
85. Cuthbertson, J., Weinstein, E., Franc, J. M., Jones, P., Lamine, H., Magalini, S., Gui, D., Lennquist, K., Marzi, F., Borrello, A., Fransvea, P., Fidanzio, A., Benítez, C. Y., Achaz, G., Dobson, B., Malik, N., Neeki, M., Pirrallo, R., Castro Delgado, R.,... Caviglia, M. (2023). Sudden-onset disaster mass-casualty incident response: A modified Delphi study on triage, prehospital life support, and processes. *Prehospital and Disaster Medicine, 38*(5), 570–580. https://doi.org/10.1017/S1049023X23006337.
86. Baetzner, A. S., Wespi, R., Hill, Y., Gyllencreutz, L., Sauter, T. C., Saveman, B.-I., Mohr, S., Regal, G., Wrzus, C., & Frenkel, M. O. (2022). Preparing medical first responders for crises: A systematic literature review of disaster training programs and their effectiveness. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 30*, 76. https://doi.org/10.1186/s13049-022-01056-8
87. Shackelford, S. A., Remley, M. A., Keenan, S., Kotwal, R. S., Baker, J. B., Gurney, J., & Friedrichs, P. A. (2022). Evidence-based principles of time, triage and treatment: Refining the initial medical response to massive casualty incidents. *Journal of Trauma and Acute Care Surgery, 92*(Suppl), S160–S164.

88. El Ghoul, W. (2026). Civilian prehospital care in armed conflict: A scoping review. *Prehospital and Disaster Medicine, 41*(S1), S118–S118. https://doi.org/10.1017/S1049023X26104427
89. AlHajri, M. A. M., Alnami, I. J., Alzahrani, A. S., & Alnemi, H. A. A. (2025). Tactical casualty care and emergency evacuation for health security personnel: An updated review. *Saudi Journal of Medicine and Public Health, 2*(2), 3276–3281. https://doi.org/10.64483/202522576
90. Aldawsari, S. M. S. A. U., Al-Dossari, M. N. B., Alharbi, K. S., & Alfaran, K. M. F. (2025). Tactical EMS zonal framework for health security operations: An updated review. *Saudi Journal of Medicine and Public Health, 2*(2), 3270–3275. https://doi.org/10.64483/202522575
91. Montgomery, H. R. (2025). Committee on Tactical Combat Casualty Care (CoTCCC) update. *Journal of Special Operations Medicine, 24*(4), 135. https://doi.org/10.55460/ZVDM-AM8I
92. Borgers, F., Van Boxstael, S., & Sabbe, M. (2021). Is tactical combat casualty care in terrorist attacks suitable for civilian first responders? *Journal of Trauma and Acute Care Surgery, 91*(4), e86–e92. https://doi.org/10.1097/TA.0000000000003337
93. Vrancken, S. M., Borger van der Burg, B. L. S., DuBose, J. J., Glaser, J. J., Hörer, T. M., & Hoencamp, R. (2022). Advanced bleeding control in combat casualty care: An international, expert-based Delphi consensus. *Journal of Trauma and Acute Care Surgery, 93*(2), 256–264. https://doi.org/10.1097/TA.0000000000003525
94. Remley, M. A., Shackelford, S. A., Rush, S. C., Kue, R. C., Brown, J., Schaffrinna, A., Koch, E. J., Stringer, J., Montgomery, H. R., & Deaton, T. G. (2025). Triage in action: A principles-based approach to mass casualty management in Tactical Combat Casualty Care. *Journal of Special Operations Medicine, 25*(3), 127–131. https://doi.org/10.55460/ZC6P-YS4G
95. Bayramoglu, B., Kaplan Zamanov, B., Güzel Öztürk, S., Kaftancı, I., & Tayfur, I. (2025). Assessment of the effectiveness of Tactical Combat Casualty Care training provided to non-medical military personnel in Türkiye. *Vojnosanitetski Pregled, 82*(6), 368–373. https://doi.org/10.2298/VSP250115032B
96. de Lesquen, H., Paris, R., Fournier, M., Cotte, J., Vacher, A., Schlienger, D., Avaro, J. P., & de La Villéon, B. (2023). Toward a serious game to help future military doctors face mass casualty incidents. *Journal of Special Operations Medicine*.
97. Paal, P., Pasquier, M., Darocha, T., Lechner, R., Kosinski, S., Wallner, B., Zafren, K., & Brugger, H. (2022). Accidental hypothermia: 2021 update. *International Journal of Environmental Research and Public Health, 19*(1), 501. https://doi.org/10.3390/ijerph19010501
98. Swol, J., Darocha, T., Paal, P., Brugger, H., Podsiadło, P., Kosiński, S., Puślecki, M., Ligowski, M., & Pasquier, M. (2022). Extracorporeal life support in

accidental hypothermia with cardiac arrest—A narrative review. *ASAIO Journal, 68*(2), 153–162. https://doi.org/10.1097/MAT.0000000000001518

99. Mendrala, K., Podsiadło, P., & Darocha, T. (2025). Extracorporeal life support in accidental hypothermia. *JAMA, 334*(20), 1846–1847. https://doi.org/10.1001/jama.2025.14593
100. McLellan, H., Rijnhout, T. W. H., Peterson, L. M., Stuhlmiller, D. F. E., Edwards, J., Jarrouj, A., Samanta, D., Tager, A., & Tan, E. C. T. H. (2023). Prehospital active and passive warming in trauma patients. *Air Medical Journal, 42*(4), 252–258. https://doi.org/10.1016/j.amj.2023.03.005
101. Barsten, T. W., Sunde, E., Thomassen, Ø, & Mydske, S. (2024). Methods and equipment available for prehospital treatment of accidental hypothermia: A survey of Norwegian prehospital services. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 32*, 131. https://doi.org/10.1186/s13049-024-01302-1
102. Alenazi, A., & Couper, K. (2024). Reply to: Hypothermic cardiac arrest: Criteria for extracorporeal cardiopulmonary resuscitation. *Resuscitation, 204*, 110417. https://doi.org/10.1016/j.resuscitation.2024.110417
103. Rousson, V., Hall, N., & Pasquier, M. (2024). HOPE survival probability cutoff for ECLS rewarming in hypothermic cardiac arrest. *Resuscitation Plus, 18*, 100616. https://doi.org/10.1016/j.resplu.2024.100616
104. Pasquier, M., Hugli, O., Hall, N., Rousson, V., & Darocha, T. (2022). Outcome prediction for hypothermic patients in cardiac arrest. *Journal of Intensive Care, 10*, 37. https://doi.org/10.1186/s40560-022-00630-7
105. Hall, N., Métrailler-Mermoud, J., Rousson, V., Conforti, C., Dupasquier, A., Carron, P.-N., Grabherr, S., Schrag, B., Kirsch, M., Falat, C., Delay, D., Frochaux, V., & Pasquier, M. (2025). Use of the HOPE score to assess survival outcome of hypothermic cardiac arrest selected by ECLS rewarming. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 33*(1), 132. https://doi.org/10.1186/s13049-025-01445-9
106. Leuci, L., Daminelli, F., Gamberini, L., Boroli, F., Rauch, S., Roveri, G., Barcella, B., Dallari, C., Sbrana, G., & Carenzo, L. (2025). Prehospital management of accidental hypothermia: A nationwide survey among Italian helicopter emergency medical services. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 33*, 156. https://doi.org/10.1186/s13049-025-01474-4
107. Das, S., Barua, S., & Hossain, A. (2024). Unraveling the complex relationship between weather conditions and traffic safety. *Journal of Transportation Safety & Security*, 16, 572–611.
108. Ahmadizadeh Fini, A., & Ahmadizadeh Fini, E. (2024). A review of risk assessment for driving in rainy weather. *Journal of Injury and Violence Research, 16*(3 Suppl. 1), Paper No. 4.

109. Elyoussoufi, A., Walker, C. L., Black, A. W., & DeGirolamo, G. J. (2023). The relationships between adverse weather, traffic mobility, and driver behavior. *Meteorology, 2*(4), 489–508. https://doi.org/10.3390/meteorology2040028
110. Zhang, Y., Guo, Z., Zhu, B., Fan, Z., & Zhang, H. (2021). Analysis of compensatory driving behavior under fog weather conditions. En *Green and Intelligent Technologies for Sustainable and Smart Asphalt Pavements*. CRC Press.
111. Shi, M., Wang, B., Cao, Z., & Zhao, Y. (2023). A study on the visual effects of bad weather on drivers in cold urban areas. In *Proceedings of SPIE 12591: Sixth International Conference on Traffic Engineering and Transportation System (ICTETS 2022)*. SPIE. https://doi.org/10.1117/12.2668651
112. Wei, T., Zhu, T., Bai, H., Zhao, L., & Wang, X. (2025). Effects of driver gender, driving experience, and visibility on car-following behavior. *Transportation Research Record, 2679*(1), 2166–2182. https://doi.org/10.1177/03611981241258988
113. Garcia, K. R., & Chen, J. (2023). Driver Decisions Based on Flood Warning Information. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 67, 739–740.
114. Garcia, K. R., & Chen, J. (2024). Detail Matters: Drivers' Responses to Flood Warnings in Simulated Driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 68, 191–192.
115. Sappl, H., & Kubjatko, T. (2021). Evaluation of the Hazard Perception Skills of Young Drivers. *LOGI – Scientific Journal on Transport and Logistics*, 12, 78–89.
116. Yamani, Y., Samuel, S., Yahoodik, S., & Fisher, D. L. (2021). Identifying and remedying failures of hazard anticipation in novice drivers. *Theoretical Issues in Ergonomics Science, 23*(4), 1–14. https://doi.org/10.1080/1463922X.2021.1971323
117. Faiz, T., Tsun, M. T. K., Al Mahmud, A., & Sim, K. Y. (2024). A scoping review on hazard recognition and prevention using augmented and virtual reality. *Computers, 13*(12), 307. https://doi.org/10.3390/computers13120307

XII – ANEXOS

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ANEXO 1. DOCUMENTO DE APROBACIÓN DE LOS ESTUDIOS POR EL COMITÉ DE ÉTICA DE LA UNIVERSIDAD SAN ANTONIO DE MURCIA.

UCAM
UNIVERSIDAD CATÓLICA SAN ANTONIO

COMITÉ DE ÉTICA DE LA UCAM

DATOS DEL PROYECTO

Título:	"Creación y evaluación de experiencias de gamificación, realidad virtual y realidad aumentada"	
Investigador Principal	**Nombre**	**Correo-e**
Dr.	Manuel Pardo Ríos	mpardo@ucam.edu

INFORME DEL COMITÉ

Fecha	**24/11/2023**	**Código**	**CE112309**

Tipo de Experimentación

Investigación experimental clínica con seres humanos	
Investigación experimental no clínica con seres humanos	X
Utilización de tejidos humanos procedentes de pacientes, personas sanas, tejidos embrionarios o fetales	
Utilización de tejidos humanos, tejidos embrionarios o fetales procedentes de bancos de muestras o tejidos	
Investigación observacional, psicológica o comportamental en humanos	X
Uso de datos personales	X
Experimentación animal	
Utilización de agentes biológicos de riesgo para la salud humana, animal o las plantas	
Uso de organismos modificados genéticamente (OMGs)	

Comentarios Respecto al Tipo de Experimentación
Nada Obsta

Comentarios Respecto a la Metodología de Experimentación
Nada Obsta

UNIVERSIDAD CATÓLICA SAN ANTONIO UCAM COMITÉ DE ÉTICA · MURCIA ·

Universidad Católica San Antonio. Vicerrectorado de Investigación. Salida nº 8476 27/11/2023

UCAM
UNIVERSIDAD CATÓLICA
SAN ANTONIO

COMITÉ DE ÉTICA DE LA UCAM

Sugerencias al Investigador

A la vista de la solicitud de informe adjunto por el Investigador y de las recomendaciones anteriormente expuestas el dictamen del Comité es:

Emitir Informe Favorable	X
Emitir Informe Desfavorable	
Emitir Informe Favorable condicionado a Subsanación	

MOTIVACIÓN
Incrementará conocimientos en su área

Vº Bº El Presidente,

El Secretario,

UNIVERSIDAD CATÓLICA SAN ANTONIO
UCAM
COMITÉ DE ÉTICA
· MURCIA ·

Fdo.: José Alberto Cánovas Sánchez

Fdo.: José Alarcón Teruel

ANEXO 2. CONSENTIMIENTO INFORMADO DE PARTICIPACIÓN VOLUNTARIA EN LOS ESTUDIOS.

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ANEXO II

CONSENTIMIENTO INFORMADO

RCP con Realidad Virtual

Yo, ..., con DNI:..

DECLARO:

Haber sido informado/a del estudio y procedimientos de la investigación del Proyecto titulado: **Creación y evaluación de experiencias de gamificación y realidad virtual.**

Los investigadores que van a acceder a mis datos personales y a los resultados de las pruebas son: **Manuel Pardo Ríos, Carmen Amalia López López, Robert Greif, Rafael Castro Delgado, Cristina Cerezo Espinosa, Daniel Guillén Martínez, Lucía López Ferrándiz y Ana Belén Ocampo Cervantes.**

Asimismo, he podido hacer preguntas del estudio, comprendiendo que me presto de forma voluntaria al mismo y que en cualquier momento puedo abandonarlo sin que me suponga perjuicio de ningún tipo.

CONSIENTO:

1.-) Someterme a las siguientes pruebas: **Experiencias formativas con gafas de realidad virtual y videojuegos, realización de test o cuestionarios, y/o hacer alguna demostración o simulación (p.e. hacer una reanimación sobre un maniquí).**

2.-) El uso de los datos obtenidos según lo indicado en el párrafo siguiente:
En cumplimiento del Reglamento (UE) 2016/679 del Parlamento Europeo y del Consejo, de 27 de abril de 2016 y Ley Orgánica 3/2018, de 5 de diciembre, de Protección de Datos Personales y Garantía de los Derechos Digitales, le comunicamos que la información que ha facilitado y la obtenida como consecuencia de las pruebas a las que se va a someter pasará a formar parte del fichero automatizado INVESALUD, cuyo titular es la FUNDACIÓN UNIVERSITARIA SAN ANTONIO, con la finalidad de INVESTIGACIÓN Y DOCENCIA EN LAS ÁREAS DE CONOCIMIENTO CIENCIAS EXPERIMENTALES Y CIENCIAS DE LA SALUD. Tiene derecho a acceder a esta información y cancelarla o rectificarla, dirigiéndose al domicilio de la entidad, en Avda. de los Jerónimos de Guadalupe 30107 (Murcia). Esta entidad le garantiza la adopción de las medidas oportunas para asegurar el tratamiento confidencial de dichos datos.

En…………………………..……………………………….. a……….de…………………………….de 202…

El / La participante, El / La investigador/a,

Fdo:.. Fdo:...

ANEXO 3. DOCUMENTOS PARA LA RECOGIDA DE DATOS EN LOS

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Impacto de la Realidad Virtual en el cambio de percepción del riesgo y estrés en situaciones de conducción durante inundaciones: estudio cuasi-experimental de simulación.

CUESTIONARIO PRETEST. Estudio nº

Nombre y Apellidos ______________________ **Edad** _______

Sexo ○ **M** ○ **F** **Carnet de Conducir** ○ **SI** ○ **NO** **Años conduciendo:**

NIVEL DE ESTUDIOS: ○ Sin estudios ○ Educación primaria ○ Educación secundaria ○ Formación profesional ○ Estudios universitarios ○ Estudios postgrado

INSTRUCCIONES

Lea detenidamente cada enunciado y conteste del 1 al 5 la opción con la cual te identificas más.

Muy en desacuerdo	En desacuerdo	Indiferente	De acuerdo	Muy de acuerdo
1	2	3	4	5

1. Conducir en condiciones de lluvia intensa representa un riesgo significativo para mi seguridad.

○ ○ ○ ○ ○

2. Me siento seguro conduciendo en condiciones de lluvia intensa.

○ ○ ○ ○ ○

3. Considero que la probabilidad de tener un accidente en condiciones de lluvia intensa es alta.

○ ○ ○ ○ ○

4. Sé cómo reaccionar en caso de que mi vehículo se inunde.

○ ○ ○ ○ ○

5. Me preocupa conducir en condiciones de lluvia intensa.

○ ○ ○ ○ ○

6. Los riesgos de conducir en condiciones de inundación son subestimados por la mayoría de los conductores.

○ ○ ○ ○ ○

ESTUDIOS

7. Tengo suficiente conocimiento sobre las medidas de seguridad al conducir en condiciones de inundación.

8. Es probable que quedara atrapado en una inundación al conducir durante una tormenta intensa

9. La posibilidad de sufrir un accidente al conducir en condiciones de inundación me hace sentir inseguro.

10. La experiencia de conducir en lluvia intensa es estresante.

UCAM UNIVERSIDAD CATÓLICA DE MURCIA

Impacto de la Realidad Virtual en el cambio de percepción del riesgo y estrés en situaciones de conducción durante inundaciones: estudio cuasi-experimental de simulación.

CUESTIONARIO POSTEST. Estudio nº

Nombre y Apellidos ______________________ **Edad** _______

Sexo M F **Carnet de Conducir** SI NO **Años conduciendo:**

NIVEL DE ESTUDIOS: Sin estudios · Educación primaria · Educación secundaria · Formación profesional · Estudios universitarios · Estudios postgrado

INSTRUCCIONES

Lea detenidamente cada enunciado y conteste del 1 al 5 la opción con la cual te identificas más.

Muy en desacuerdo	En desacuerdo	Indiferente	De acuerdo	Muy de acuerdo
1	2	3	4	5

1. Después de la simulación, considero que conducir en condiciones de lluvia intensa representa un riesgo significativo para mi seguridad.

2. Me siento más seguro conduciendo en condiciones de lluvia intensa después de esta experiencia.

3. Creo que la probabilidad de tener un accidente en condiciones de lluvia intensa es alta.

4. Me siento preparado para reaccionar en caso de que mi vehículo se inunde.

5. Mi preocupación por conducir en condiciones de lluvia intensa ha aumentado

6. Considero que los riesgos de conducir en condiciones de inundación han sido subestimados.

7.Siento que he adquirido más conocimiento sobre las medidas de seguridad al conducir en condiciones de inundación.

8. Creo que la probabilidad de quedar atrapado en una inundación mientras conduzco es alta.

9. La posibilidad de sufrir un accidente en condiciones de inundación ahora me parece más evidente

10. La experiencia de la simulación me pareció estresante.

NASA TASK LOAD (TLX)

El método NASA Task Load Index (TLX) de Hart y Staveland evalúa la carga de trabajo en cinco escalas de 7 puntos. Los incrementos de estimaciones altas, medias y bajas para cada punto dan como resultado 21 gradaciones en las escalas.

Nombre | **Tarea |** **Fecha**

Demanda mental
¿Cómo de exigente mentalmente ha sido la tarea?
Muy baja | | | | | | | | | | | | | | | | | | | | | Muy alta

Demanda física
¿Cómo de exigente físicamente ha sido la tarea?
Muy baja | | | | | | | | | | | | | | | | | | | | | Muy alta

Demanda temporal
¿Cómo apresurado/a o con prisa ha sido el ritmo de la tarea?
Muy baja | | | | | | | | | | | | | | | | | | | | | Muy alta

Desempeño
¿Cómo de exitoso/a has sido en lograr lo que se te pidió hacer?
Perfecto | | | | | | | | | | | | | | | | | | | | | Fracaso

Esfuerzo
¿Cuánto has tenido que esforzarte para alcanzar tu nivel de desempeño?
Muy bajo | | | | | | | | | | | | | | | | | | | | | Muy alto

Frustración
¿Cómo de inseguro/a, desanimado/a, irritado/a, estresado/a y molesto/a has estado?
Muy baja | | | | | | | | | | | | | | | | | | | | | Muy alta

ANEXO 4. INVITACIÓN A EXPERTOS PARA EL DISEÑO DE UN ÁRBOL DE DECISIONES EN RCP BÁSICA Y DEA

DISEÑO DE UN DIAGRAMA DE ÁRBOL DE DECISIÓN

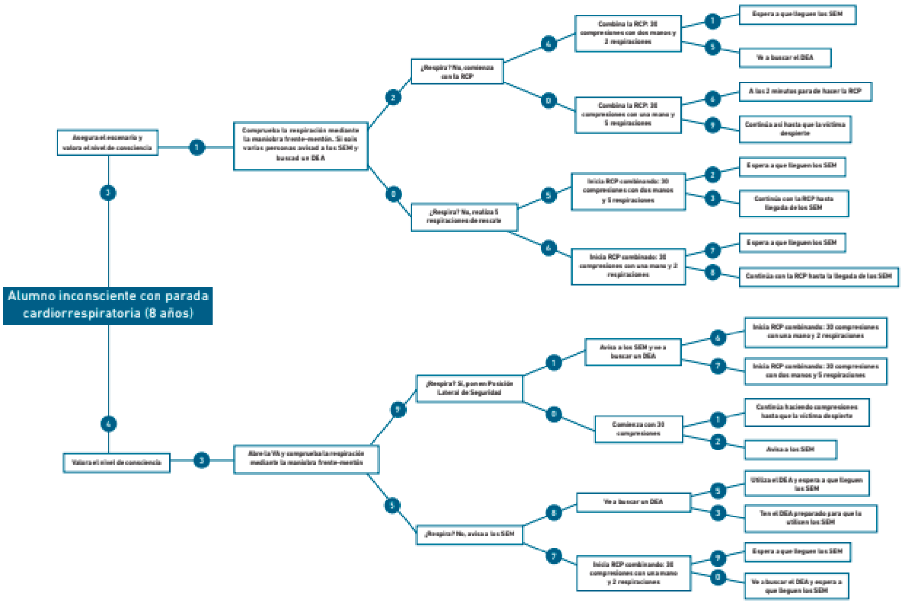
Te hemos seleccionado para el **diseño de un diagrama de árbol de decisión** fundamentado en la metodología del aprendizaje basado en problemas, para la elaboración de un **"caso de reanimación cardiopulmonar básica y DEA".**

¿Qué vamos a hacer?

Vamos a diseñar un caso de **Realidad Virtual Inmersiva** grabado con cámaras 360 Grados. Aquí puedes ver una demo:

https://drive.google.com/file/d/1Bu80aw3AKrakh_E5b1zwLtiNxMByPyNv/view?usp=sharing

Para diseñar ese caso te pedimos tu ayuda y experiencia. Queremos que el caso se haga por **consenso de expertos**. Para ello hacemos una primera parte que es el diseño del árbol de decisiones que es la base sobre la que luego grabaremos el escenario. Aquí te ponemos ejemplo de otros árboles de decisión.



¿Qué se espera de tu parte?

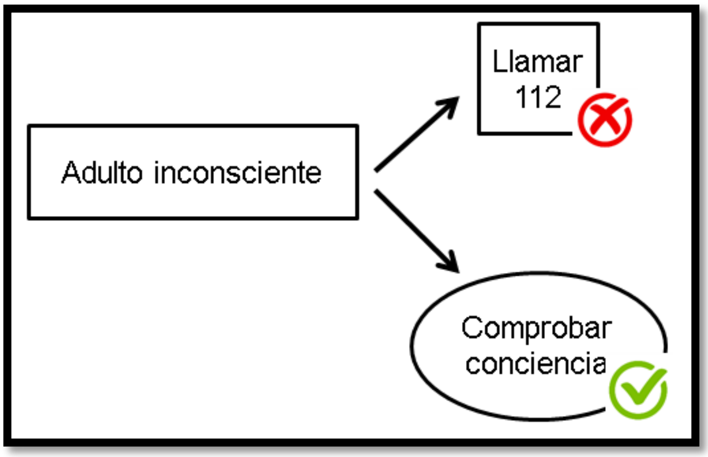
- ❖ DISEÑAR UN ÁRBOL DE DECISIÓN SOBRE RCP BÁSICA Y DEA.
- ❖ DISEÑALÓ SOBRE UN PAPEL TAMAÑO A4 O MAYOR.
- ❖ PUEDES USAR TU CREATIVIDAD E IDEAS.
- ❖ PUEDES USAR LÁPIZ, ROTULADOR, BOLÍGRAFO… LO QUE MÁS TE GUSTE PERO QUE SE PUEDA LEER Y ENTENDER FÁCILMENTE.
- ❖ EN LAS SIGUIENTES DIAPOSITIVAS TE VAMOS A INTENTAR EXPLICAR TODO CLARAMENTE. AÚN ASI, SI TIENES DUDAS PUEDES CONTACTARNOS Y TE HAREMOS LAS ACLARACIONES QUE NECESITES.
- ❖ UNA VEZ LO HAYAS ACABADO NOS MANDAS UNA FOTO CON CALIDAD, ESCANEADO AL MISMO CORREO ELECTRÓNICO) O NOS LO REMITES POR CORREO POSTAL (Dr. Manuel Pardo Ríos, Universidad Católica de Murcia, Avd Los Jerónimos s/n, Guadalupe, 30107, Murcia.

Si se publicara algún trabajo te podemos ofrecer aparecer en **“Grupo de trabajo Rinvemer”** dentro de los documentos que se publiquen.

¿Cómo hacer un árbol de decisiones para RCP básica?

El escenario comenzará con un caso clínico de un **adulto inconsciente**. El usuario, en este caso, encontrará a una persona en el suelo.

Al usuario se le dará a escoger entre **varias opciones,** teniendo que escoger entre ellas. Para un mayor entendimiento, las opciones se representarán con un **cuadrado** o un

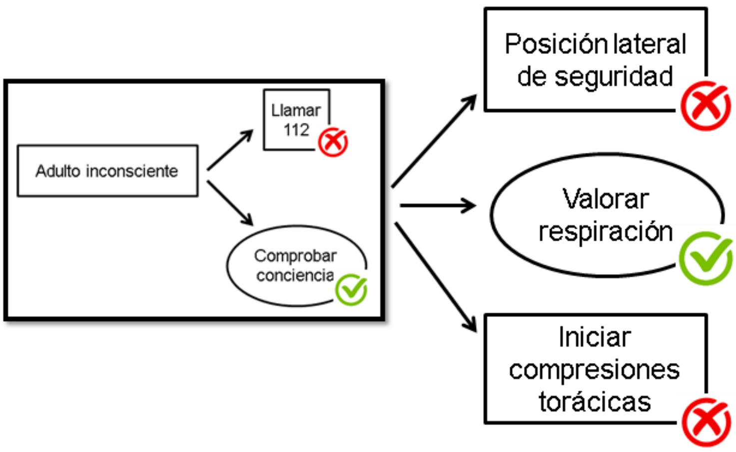


Si la opción se representa con un **cuadrado:**

- Sumaremos 1 error.
- Volverá a la casilla anterior.
- Recibirá un feedback.

Si la opción es representada por un **círculo**, se considerará correcta y continuará avanzando por el árbol de decisiones.

- Podemos dar múltiples opciones de respuesta.
- Lo importante es que sea coherente con la realidad y con lo que puede pensar un reanimador, ya sea lego o profesional.
- Varias opciones puede ser buenas y/o varias pueden ser incorrectas.

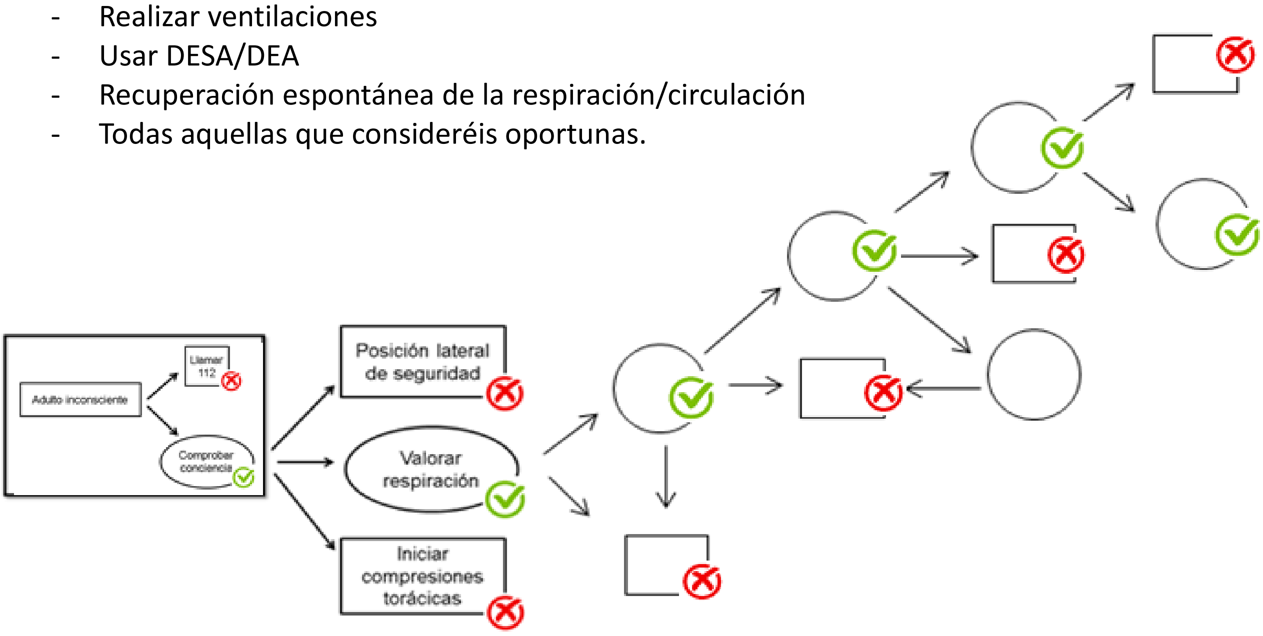


Cada **<u>elección correcta</u>** se acompañará de la realización de la

Al elegir la **respuesta correcta,** en este caso **"Valorar respiración",** el alumno realizará las siguientes acciones de forma guiada:

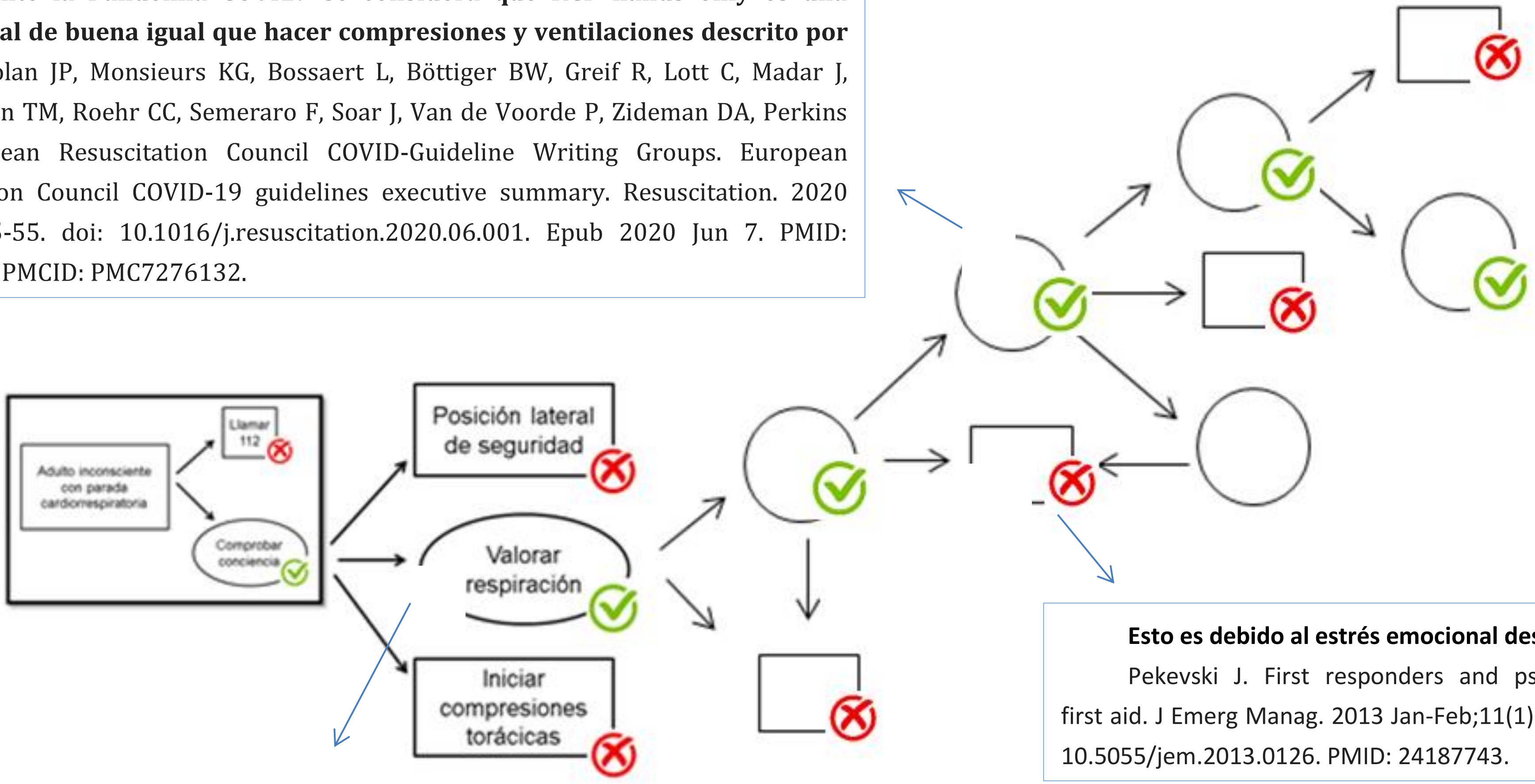
- Maniobra frente mentón.
- Ver, oír y sentir.
- Durante 10 segundos

- Podemos elaborar tantas combinaciones y opciones como queramos.
- Podéis ser creativos y no hay que pensar solo en un camino, ni de izquierda a derecha, arriba y abajo.
- El sistema avanzará por la opción correcta y reconducirá al usuario pudiendo otorgar un feedback.
- Dentro de las múltiples opciones a barajar que podéis incluir, si lo consideráis:
  - Hacer compresiones
  - Realizar ventilaciones
  - Usar DESA/DEA
  - Recuperación espontánea de la respiración/circulación
  - Todas aquellas que consideréis oportunas.



- Si podemos incluimos la ciencia. Si crees que hay **referencias** científicas o bibliográficas que nos ayudan o justifican tu elección u opciones no dudes en incluirlas. Te ponemos in ejemplo…

Durante la Pandemia COVI19 se considera que RCP hands only es una opción igual de buena igual que hacer compresiones y ventilaciones descrito por ERC en Nolan JP, Monsieurs KG, Bossaert L, Böttiger BW, Greif R, Lott C, Madar J, Olasveengen TM, Roehr CC, Semeraro F, Soar J, Van de Voorde P, Zideman DA, Perkins GD; European Resuscitation Council COVID-Guideline Writing Groups. European Resuscitation Council COVID-19 guidelines executive summary. Resuscitation. 2020 Aug;153:45-55. doi: 10.1016/j.resuscitation.2020.06.001. Epub 2020 Jun 7. PMID: 32525022; PMCID: PMC7276132.

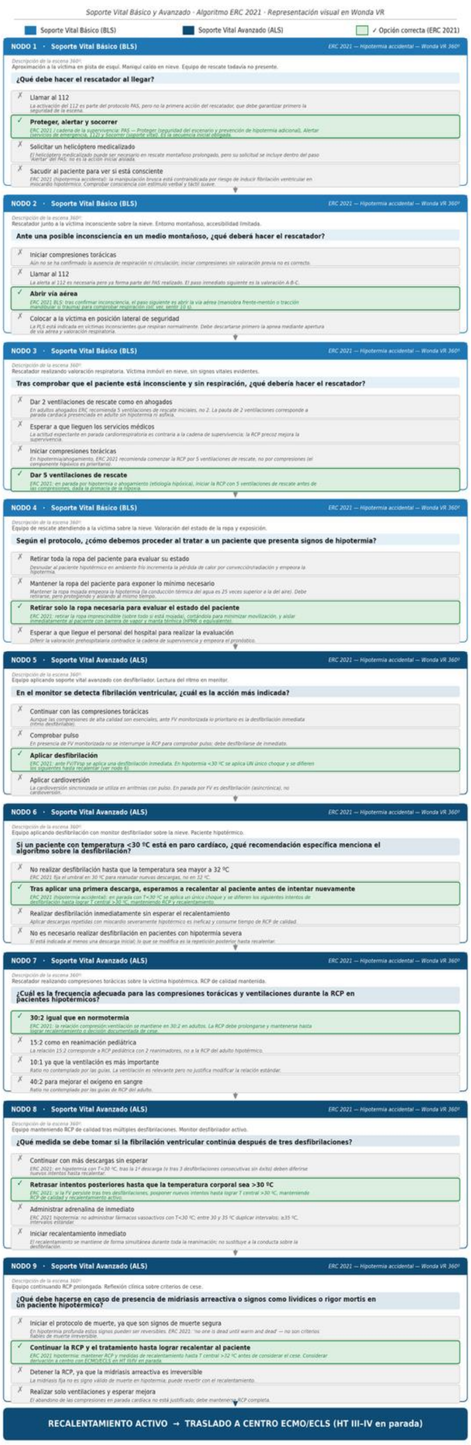


Esto es debido al estrés emocional descrito por Pekevski J. First responders and psychological first aid. J Emerg Manag. 2013 Jan-Feb;11(1):39-48. doi: 10.5055/jem.2013.0126. PMID: 24187743.

ERC mantiene para legos solo valorar la respiración y no tomar pulsos. Michels G, Bauersachs J, Böttiger BW, Busch HJ, Dirks B, Frey N, Lott C, Rott N, Schöls W, Schulze PC, Thiele H. Leitlinien des European Resuscitation Council (ERC) zur kardiopulmonalen Reanimation 2021: Update und Kommentar [Guidelines of the European Resuscitation Council (ERC) on cardiopulmonary resuscitation 2021: update and comments]. Anaesthesist. 2022 Feb;71(2):129-140. German. doi: 10.1007/s00101-021-01084-6. PMID: 34984492.

Puedes añadir las referencias en el algoritmo con flechas o bien, si lo ves más fácil, hazlo cómo las citas en Vancouver en el texto asociando un número a cada

ANEXO 5. ÁRBOL DE DECISIÓN EN HIPOTERMIA CON



REPRESENTACIÓN VISUAL EN LA PLATAFORMA WONDA VR

ANEXO 6. ÁRBOL DE DECISIÓN EN ESCENARIO TÁCTICO CON REPRESENTACIÓN VISUAL EN LA PLATAFORMA WONDA VR