REVISTA Ação Ergonômica

R. Ação Ergon., 19(2), 2025.
ISSN 2965-7318. doi: 10.4322/rae.v19n2.e202506.en

COGNITIVE ERGONOMICS AND EYE TRACKING IN UNDERSEA WELL DRILLING: AN INTEGRATIVE REVIEW

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Summary

Eye-tracking technology has been explored in various contexts to monitor human behavior through eye movements. In the oil and gas industry, where operations require high concentration and rapid decision-making, it enables the identification of patterns of visual attention, cognitive load, and fatigue—all of which are determining factors for performance and safety. However, its use, especially in critical operations, is poorly documented, representing a gap in scientific knowledge. This study aimed to identify the use of eye-tracking in subsea well drilling and understand the interaction between humans and work systems as directed by ergonomics. Through an integrative literature review, six steps were followed: identification of the topic and research question; inclusion and exclusion criteria; selection of studies from scientific databases; categorization and synthesis of the studies; analysis and interpretation of the results; and presentation of the review. Six studies that applied eye-tracking to well control activities were identified. The results indicate its effectiveness in investigating cognitive processes such as situational awareness, decision-making, and visual attention patterns. Predictive models identified unsafe behaviors with high accuracy, highlighting their potential to optimize training and improve the ergonomics of control systems in high-risk operations. The studies were conducted in simulated environments, reinforcing the need for validation in real-world scenarios. Future research could explore remote operations centers and consider the impact of work organization and organizational culture in this sector.

Keywords: Eye tracking, *offshore drilling*, cognitive ergonomics, oil and gas industry, *offshore*

1. Introduction

Subsea well drilling is an essential process in the exploration and production of oil and gas in reservoirs located below the seabed. It involves drilling into geological formations on the seabed to reach hydrocarbon deposits located at depths ranging from a few hundred to thousands of meters below the surface.

Offshore drilling operations are highly complex due to a number of factors, such as the isolated offshore environment, the need for high-tech equipment, rigorous risk management

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and regulations, and critical real-time decision-making. In this scenario, operational safety and efficiency are of the utmost importance. Subsea well drilling activities require a high level of skill and knowledge, and the work environment is characterized by specific conditions, where critical decisions must be made in real time and as quickly as possible. In this context, referring to "human error" as the primary cause of accidents is seen as an oversimplification that disregards the complexity and variability of the actual work (Daniellou et al., 2010). Serious or fatal accidents occur due to a combination of failures in various prevention barriers or problems related to organizational or design issues, rarely resulting from an isolated individual failure.

The oil and gas industry faces growing challenges related to safety and efficiency in subsea well drilling operations. These challenges arise from the complexity of the activity, human labor, and the interaction of multiple factors (technical, organizational, human, social, and economic). Therefore, human factors such as attention, decision-making, and situational awareness are crucial. Prescribed work, for example, no matter how detailed, does not fully account for the reality and unpredictable variability of everyday life. Safety in the field is not based solely on compliance with rules ("standardized safety"), but on "safety in action," which is the ability to respond appropriately in real time through the adaptation of procedures and the experience of individuals (Daniellou et al., 2010).

Since workers in this industry constantly need to deal with complex human-machine interfaces and highly technological instrumentation, ergonomics, which investigates the interaction between humans, systems, and work environments, is essential to understanding work activities. According to Iida & Guimarães (2016), work determinants include internal factors such as age, physical/mental state, and professional experience, and external factors such as working conditions, standards, organization, and equipment used.

For the ergonomist, it is essential to understand not only the visible aspects of work, such as movements and postures, but also the invisible elements that influence work activity, such as reasoning, mental activity, know-how, emotions, and sensations involved (Ferreira, 2024). Thus, in this complex context of the oil and gas industry, cognitive ergonomics stands out. Through it, it is possible to investigate how individuals' mental, emotional, and affective processes are involved in their interactions with systems, environments, interfaces, or objects (Silva et al., 2021). Cognitive ergonomics addresses issues such as attention distribution, which examines how workers manage multiple tasks simultaneously; decision-making, analyzing how choices are made in different contexts; and the development of learning skills (Cañas et al., 2011). According to Torres (2021), cognitive ergonomics studies the mental processes (such as perception, memory, reasoning, and motor responses) involved in interactions between workers and systems. Its main topics of study include mental load, decision-making, human-machine interaction, human reliability, workplace stress, and teamwork. This approach aims to increase efficiency and promote the safety and mental well-being of workers (Cañas et al., 2011).

In a complex sociotechnical system, when dealing with decision-making, this involves the need for interaction between technical skills (engineering, administration, drilling) and non-technical skills (communication, leadership, teamwork, situational awareness), so that it is appropriate and promotes both improved performance and operational safety (Flin et al., 2008).

Therefore, technologies such as eye tracking *have been* used to monitor and evaluate human behavior. *Eye tracking technology* consists of a system that uses glasses equipped with optical sensors connected to specialized software capable of capturing and analyzing an individual's eye movements in real time. This technology allows for the precise identification of where, when, and for how long a person fixes their gaze on different points in a visual field. This makes it possible to map the trajectory of the gaze, determine areas of greater attention or neglect, and assess visual behavior during task execution. Eye tracking technology has been used since the 1970s to investigate decision-making processes (Kodappully et al., 2016). According to Merino et al. (2020), humans perform a series of actions, make decisions, and exhibit behaviors directly linked to eye movements and gaze fixation. When reflecting on the domains of specialization in ergonomics, it is clear that there are two domains related to the use of *eye tracking* : the physical (sensory capacity of vision, since the eyes are made up of several muscles that control their movements) and the cognitive (attention, decision-making, mental load, among others).

Eye *tracking , as a technology used in scientific research, can be employed in non -* critical activities, such as shopping (Gallina et al., 2022) and computing (Costa, 2024), and also in complex contexts, as a tool for assessing mental load, recognizing loss of situational awareness, detecting distractions, inattention, and fatigue (Li et al., 2023). Gobbi et al. (2017) report that the main measures that *eye tracking* can provide are gaze fixations (number, time, and dispersion of fixations), saccades (based on fixations from one point to another), and blinks (number and duration). Studies in aviation using eye-tracking cameras and goggles to analyze pilot behavior during real flights, military operations, and general aviation demonstrate that eye tracking can be safely applied to tasks in safety-critical domains, without impacting operations or task execution (IOGP, 2024, p. 6).

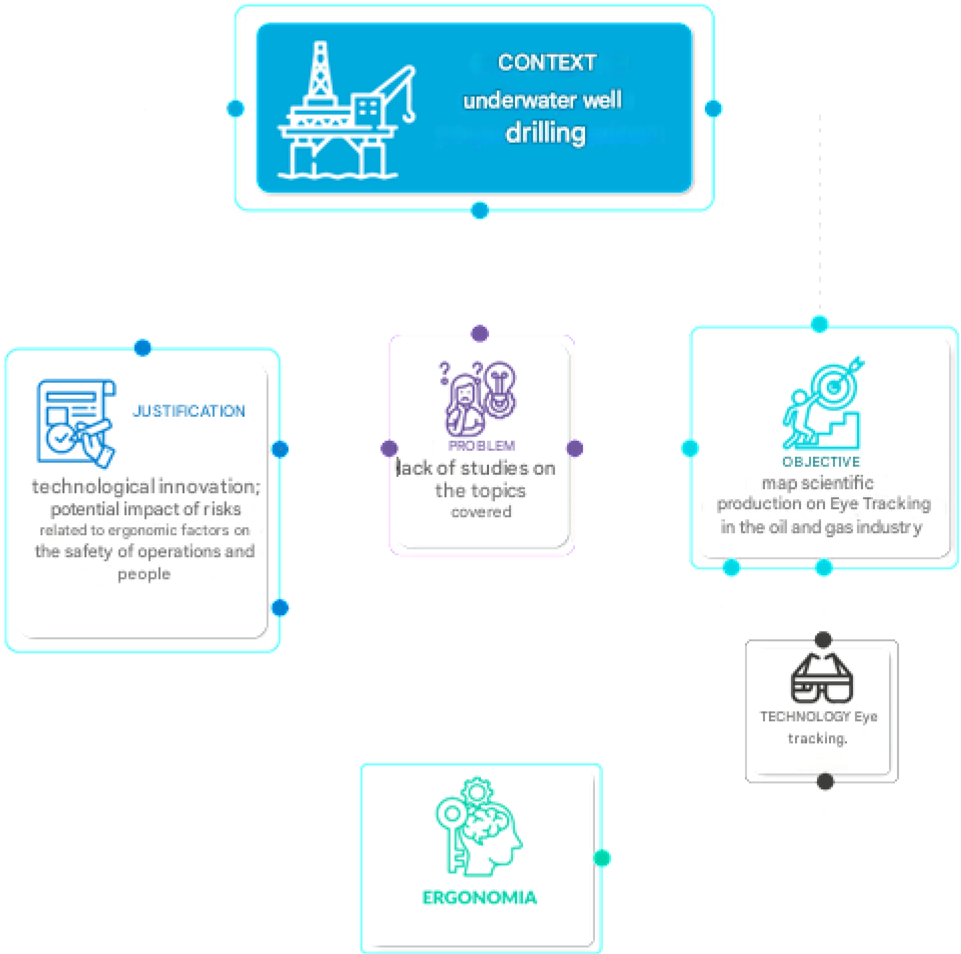
However, its use in safety-critical operations has been rare, with no records of its use in real-time well operations (IOGP, 2024, p. 6). Studies indicate that technologies such as eye tracking have demonstrated potential in other critical sectors, such as the aviation, maritime, and construction industries, and their application in *offshore operations* should be encouraged (Martinez- Marquez et al., 2021). In the context of *offshore* drilling operations, loss of well control is a critical risk, requiring high vigilance from operators. For Ikuma et al. (2014), the main processes that influence an operator's performance are: perceiving relevant information (measured by eye movement), integrating data with task goals (assessed through perceived workload ratings), and predicting future events and system states (assessed through situational awareness measures).

In this scenario, eye tracking can help identify safety issues and consequently increase human reliability, optimizing operator attention and decision-making in high-risk operations (IOGP, 2024, p. 6). Lack of guidance and inadequate execution in abnormal situations can be identified through experimental studies using eye tracking to understand the cognitive behavior of control room operators (Kodappully et al., 2016). Thus, there is a need to explore the use of eye tracking to assess and improve worker performance in critical *offshore* well control situations.

Given this need, based on the practical relevance and potential impact of technology in a high-risk sector, the objective of this research was to identify the use of eye tracking in subsea well drilling and understand the interaction between humans and work systems as directed by ergonomics.

The rationale for this study is based both on the potential of technological innovation through the use of *eye tracking* to understand cognitive processes, and on the potential impact of risks related to ergonomic factors, such as fatigue, which impacts attention, situational awareness, operational safety, and decision-making. The topic of safety and human performance in *offshore oil exploration operations* remains underexplored in countries with intense exploration activity like Brazil, which plays a crucial role in global oil and gas production. In 2023, Brazil was the 8th largest oil producer in the world, trailing only the largest producers—the United States, Saudi Arabia, Russia, Canada, Iraq, China, and Iran (IBP, 2024). Despite its contributions to the sector, Brazil still has gaps in scientific publications and studies focused on human factors and technologies such as eye tracking in real-world offshore drilling contexts. Figure 1 demonstrates the synthesis and interconnection of the research themes.

Figure 1 - Summary and connection of research themes

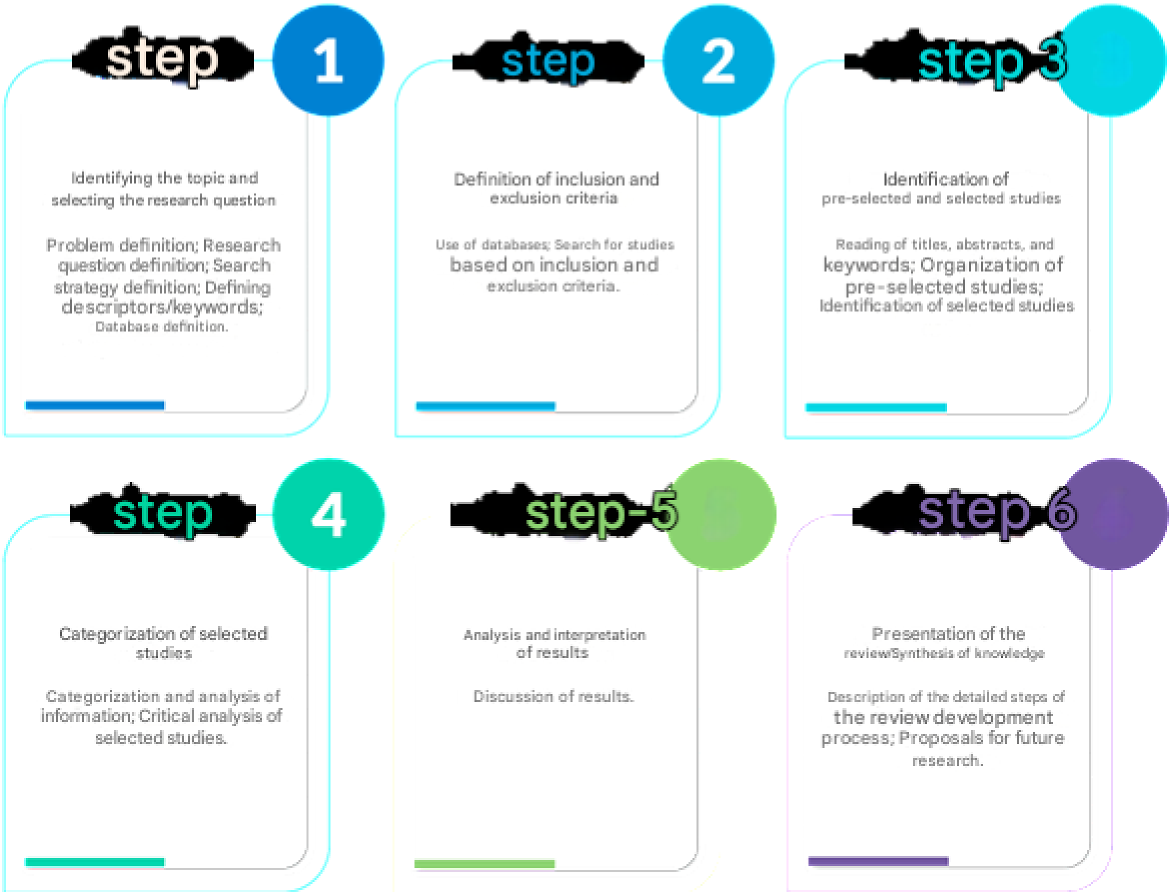


Source: Prepared by the authors (2024)

2. METHOD

This integrative literature review, conducted in October 2024, uses an integrated methodology that encompasses the review, analysis, and synthesis of representative literature on a topic, aiming to generate new theoretical frameworks and perspectives on a subject (Torraco, 2005). Integrative reviews have the methodological rigor of systematic reviews, enabling review studies in various areas of knowledge (Mattos, 2015). This research method allows for an analysis of the knowledge already developed in previous studies on a specific topic (Broome, 2000). It also promotes a holistic understanding of the various factors that influence a given topic by identifying patterns, trends, and gaps in the research landscape, thus enabling the guidance of future research (Konstantinidis, 2024). Thus, to develop this review, we followed the six steps of the integrative review process discussed by Botelho et al. (2011) and applied by Paulo et al. (2023), as shown in Figure 2 and described below.

Figure 2 - Visual summary of the steps of the Integrative Literature Review



Source - Prepared by the authors based on Botelho et al. (2011).

1st Stage: Identifying the topic and formulating the research question

According to Mendes et al. (2008), this initial stage should include defining the problem and formulating the research question. Whittemore & Knafl (2005) emphasize that with clear identification of the problem and a well-defined purpose, it is possible to establish the focus and identify delimitations in the integrative review process. Thus, once the problem and research question have been defined, the next steps involve formulating the search strategy through the identification of descriptors or keywords, as well as defining the databases (Broome , 2006).

2nd Stage: Defining inclusion and exclusion criteria

At this stage, the inclusion and exclusion criteria for the research were determined. According to Mattos (2015), establishing these criteria carefully and transparently indicates that the final conclusions of the review are in-depth, high-quality, and reliable. Examples of inclusion and exclusion criteria include: time frame, document types, language, and open or closed access content (Botelho et al., 2011).

3rd Stage: Identification of pre-selected and selected studies

At this stage, the reviewer seeks to organize and summarize the information concisely, creating a database that is easy to access and handle (Mendes et al., 2008).

4th Stage: Categorization and evaluation of selected studies

According to Ganong (1987), this step is equivalent to data analysis in conventional research. The synthesis matrix is a tool used to assist in the interpretation and construction of the integrative review and depends primarily on the researcher's creativity and organization for data presentation (Klopper et al., 2007).

5th Stage: Analysis and interpretation of results

For Torraco (2005), critical data analysis identifies the strengths and main contributions of the literature, as well as deficiencies, omissions, inaccuracies, and other problematic aspects. Thus, by highlighting strengths and identifying gaps in the existing literature, the analysis and interpretation of results is a fundamental step in improving the knowledge base and identifying avenues for future research.

6th Stage: Presentation of the review and synthesis of knowledge

Finally, this stage aims to carefully describe all the steps previously performed, presenting the main results achieved. According to Botelho et al. (2011), an integrative review should enable replication of the study. For Konstantinidis (2024), synthesizing the results into a model can portray the integration process, implications for practice, and recognize the limitations inherent in the review.

3. Analysis and discussion of results

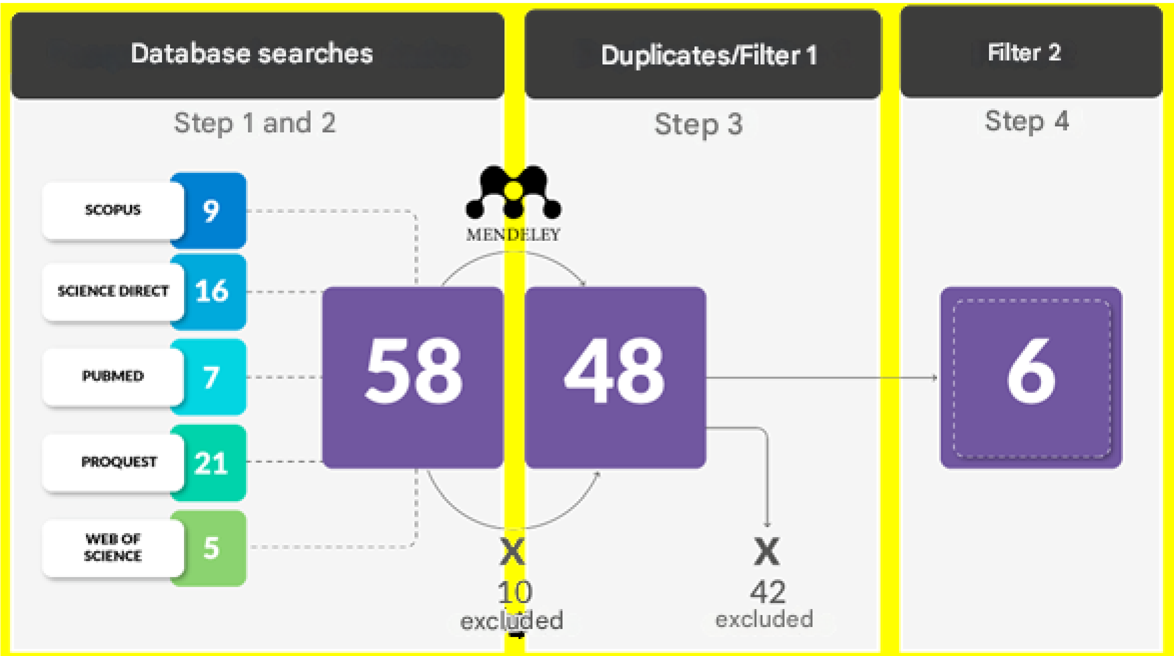
In the **first stage** of this study, the theme, problem, and research question were defined. The research topics identified were: cognitive ergonomics, eye-tracking technology, and subsea well drilling. The research problem identified was the lack of knowledge about scientific literature involving the use of eye-tracking technology in the oil and gas industry. With the theme and problem defined, the following research question was established: what studies are being conducted using eye-tracking in subsea well drilling activities?

The definition of the search strings was guided by recurring descriptors in the literature on ergonomics in *offshore environments*, and the selected databases were chosen for their recognized academic relevance and broad coverage of scientific publications in the areas of occupational health, engineering, and ergonomics. As a search strategy, search *strings were created* in two languages: English *(" eye tracking" OR "gaze tracking") AND (" drilling " OR " well" drilling " OR " drilling" operations " OR " oil drilling ") AND ("offshore" OR " oil rigs or offshore operations ")* ; and in Portuguese: ("eye tracking" OR "gaze tracking") AND ("drilling" OR "well drilling" OR "drilling operations" OR "oil drilling") AND (" *offshore* " OR "oil rigs" OR " *offshore operations"*). The international databases chosen were: *Scopus, Dissertations & Theses ProQuest, Web of Science, Sciencedirect, Scielo and PUBMED*; and the national databases: Brazilian Digital Library of Theses and Dissertations - BDTD and Capes Catalog of Theses and Dissertations.

As a result of the **second stage**, the following inclusion criteria were defined: time frame from 2014 to 2024, open access documents of the article type, *conference papers*, theses, and dissertations, with all documents selected in English, Portuguese, and Spanish. English was included because it is the primary language of global scientific production, especially in the fields of engineering, ergonomics, and petroleum, while Portuguese and Spanish were considered to include studies conducted in Latin American countries with operations in the *offshore industry*. The exclusion criteria were: book chapters, closed/paid access documents, and review articles (systematic, integrative, and narrative), with the aim of prioritizing original studies and those with primary data.

With the criteria established, the **third stage** of the research was carried out. 58 documents were found: *Dissertations & Theses ProQuest (21), Sciencedirect (16), Scopus (9), PUBMED (7), Web of Science (5), Scielo (0),* Brazilian Digital Library of Theses and Dissertations - BDTD (0) and Capes Catalog of Theses and Dissertations (0). All 58 documents were entered into the *Mendeley software.* for reference management, and at this point, a check was performed for duplicate files, which totaled 10. Next, the documents were filtered by reading the titles, abstracts, and keywords to identify those most closely aligned with the research. After this filtering, six documents presented studies that used eye-tracking technology in subsea well drilling activities. Figure 3 presents the systematization of the filtering process for the research found.

Figure 3 - Search filtering found



Source - Prepared by the authors based on Botelho et al. (2011)

With the articles selected, **stage 4 began**, in which a detailed reading of the documents was carried out, followed by categorization and data extraction. Still in stage 4, the synthesis matrix was assembled for each of the selected studies (table 2):

Table 2 - Headquarters synthesis resulting

SYNTHESIS MATRIX 1	(Naqvi *et al* ., 2019)
Title	*Using content analysis through simulation-based training for offshore drilling operations: Implications for process safety*
Country	USA
Publication Vehicle	*Process Safety and Environmental Protection*
Percentile of the publication vehicle	95%
Objective	Present the potential use of content analysis as a tool to optimize simulation-based training, which can be applied to improve human factors in drilling and well control activities.

Method	The authors performed a content analysis of an offshore drilling simulation scenario using the University of Oklahoma's virtual reality simulator (VRDS), with two novices and two experts acting as driller assistants. During the *trip-in activity*, an anomaly was introduced to test participants' adaptation. Conversations recorded with eye-tracking goggles were transcribed and qualitatively analyzed, categorizing interactions as solicitation, confusion, and endorsement. Semantic maps generated by the *software* Pajek highlighted differences between novices and experts, highlighting the impact of experience on communication and response to anomalous scenarios. The analysis was validated by an experienced engineer, ensuring accurate results.
Results	The results of the content analysis were translated into semantic maps. By comparing the semantic maps of novices and experts, significant differences in communication patterns and operational efficiency were identified, with experts exhibiting less confusion and higher operational performance. The study demonstrated how human factors impact performance, contributing to the optimization of simulation-based training in the *offshore drilling industry*.
Real context or simulated	Simulated
Limitations	The small number of participants (four) limits the generalizability of the results. Furthermore, the study was conducted in a simulated environment and may not fully reflect the conditions of a real operation.
Futures studies	Include a larger number of participants. *offshore* drilling operations to validate the findings obtained in the simulated environment. Integrate content analysis with other process tracking tools, such as eye tracking, to optimize well control simulation scenarios. Optimize training and evaluation frameworks by incorporating human factors analysis.

SYNTHESIS MATRIX 2	(Chen *et al.,* 2024)
Title	*Identification method for safety hazard behavior in offshore drilling operators*
Country	China
Publication Vehicle	*Ocean Engineering*
Percentile of the publication vehicle	87%
Objective	To develop a method based on eye tracking and the *TPE- LightGBM model* to identify risk behaviors in *offshore drilling operators* , focusing on fatigue and inexperience.
Method	*TPE- LightGBM* machine learning model to identify risky behaviors among offshore drilling operators. Eye movement data from 42 operators (aged 21 to 30) were collected during simulated operations, covering eye fixation, saccades, and pupil diameter. The scenario was divided into sensitive areas, such as the drilling head, and analyzed using heat maps. Five critical eye tracking parameters were selected, including total fixation time and mean pupil diameter. The *LightGBM model* was optimized with the TPE algorithm to tune hyperparameters ensuring high efficiency. Ten-fold cross-validation confirmed the accuracy of the model, which used 72% of the data for training and 28% for testing.
Results	*TPE- LightGBM* model has been shown to be effective in identifying in real time risk behaviors in *offshore drilling operators*, such as fatigue and inexperience, without false positives or negatives. The average data acquisition time during fatigue operations was significantly longer (248.41 seconds) compared to normal operations (174.38 seconds), reflecting the loss of efficiency of fatigued operators. The model outperformed other algorithms, such as *XGBoost and Random Forest*, in terms of accuracy and efficiency. While the fine-tuned *LightGBM model* showed no false alarms, the other algorithms underperformed in terms of accuracy, with *XGBoost* generating 2 false alarms and *Random Forest* , 6. These results demonstrate the potential of integrating ocular data with advanced algorithms to monitor risk behaviors, with promising applications in both simulations and real-world

	scenarios in the future.
Real context or simulated	Simulated
Limitations	The study was conducted in a controlled environment with good lighting and head stability, limiting its applicability to real-world operations where there is constant movement and variable lighting. The sample of 42 operators was relatively small, limiting the generalizability of the results to the broader *offshore operator population.* Furthermore, while the method has proven effective in simulations, it lacks validation in real-world scenarios, where factors such as weather, variable workload, and fatigue can significantly impact performance.
Futures studies	Develop methods that allow identifying risk behaviors in real environments, where operators have greater mobility. Integrate content analysis with other tools, such as augmented reality or artificial intelligence technologies, to provide additional support in identifying risk behaviors in real time. Include a larger and more diverse sample of operators, encompassing different levels of experience and exposure to different operating conditions.

SYNTHESIS MATRIX 3	(Naqvi *et al.,* 2020)
Title	*Simulation-based training to enhance process safety in offshore energy operations: Process tracing through eye-tracking*
Country	USA
Publication Vehicle	*Process Safety and Environmental Protection*
Percentile of the publication vehicle	95%
Objective	Apply the eye-tracking methodology in offshore well control simulations to identify patterns of information acquisition, comparing the performance of novice and experienced operators.
Method	*DrillSim:50* portable simulator, widely recognized for well control certifications by the IADC and IWCF. Data collection was performed using eye-tracking goggles that recorded fixations and saccades during the simulation, involving 14 participants (12 novices and 2 experts) from the University of Oklahoma. The simulation included moments of interest (TOIs) at critical stages, such as *kick* detection and control. and well circulation. Performance was evaluated based on fixation patterns in areas of interest (AOIs), and data were analyzed using *Tobii software.* to compare performance between novices and experts.
Results	The study revealed significant differences between the information acquisition patterns of experienced and novice participants. Experts focused their fixations on critical areas and maintained greater situational awareness, while novices dispersed their fixations and attention, leading to errors and loss of well control. The results suggest that eye tracking is an effective tool for identifying patterns of attention and situational awareness among operators of different experience levels. This demonstrates that simulation-based training, complemented by eye-tracking technologies, can be useful for identifying weaknesses in novice operators' performance and improving their training.
Real context or simulated	Simulated
Limitations	The relatively small sample of 14 participants, of whom only two were considered experts, limits the generalizability of the results. Although the simulator has been widely used for training, there is still a significant difference between the simulation environment and actual *offshore operating conditions,* which may affect the applicability of the results in the field.
Futures studies	Validation in Real Operations: Application of the eye tracking methodology in real operations to validate the results under field conditions. Sample Expansion: Expand the sample to include operators with varying levels of experience.

SYNTHESIS	(Raza *et al.,* 2019)

MATRIX 4	
Title	*Situational awareness measurement in a simulation-based training framework for offshore well control operations*
Country	USA
Publication Vehicle	*Journal of Loss Prevention in the Process Industries*
Percentile of the publication vehicle	84%
Objective	Assess and measure the situational awareness of offshore drilling operators in a simulation-based training environment using eye-tracking techniques, voice analysis, questionnaires, and performance metrics.
Method	*DrillSim:50* simulator, certified by the IWCF and IADC, for offshore well control training, with 13 trainee engineers divided into pairs (*Driller and Supervisor*). During the simulation, participants were responsible for detecting and mitigating *kicks*, with eye-tracking monitoring their attention to critical areas of the panel. The simulation was paused at three critical moments (*freeze points*) to collect data on task knowledge and situational awareness, using questionnaires and voice log analysis. Performance was assessed with a checklist that analyzed the correct execution of procedures, such as pressure stabilization and well circulation.
Results	Situational awareness was strongly correlated with task knowledge and supervisor confidence. Participants with greater knowledge of control tasks *kick* performed better. Overconfident supervisors tended to make more mistakes, revealing vulnerability in decision-making. The use of eye tracking and communication analytics allowed the identification of critical points that impact situational awareness and performance.
Real context or simulated	Simulated
Limitations	The sample size of 13 participants limits the generalizability of the results to the entire *offshore drilling community*. While the simulator offers a good approximation of real-world situations, it does not fully capture the complexities of the field, such as stress and prolonged fatigue in real operations.
Futures studies	Increase Sample Size: Include a larger, more diverse sample, allowing for greater generalizability of findings. Validation in Real Scenarios: Future studies should seek to apply these methodologies in real operational environments to validate the results observed in simulation.

SYNTHESIS MATRIX 5	(Chen *et al.,* 2023)
Title	*Early warning method of unsafe behavior accidents for offshore drilling operators based on eye-tracking trajectory*
Country	China
Publication Vehicle	*Process Safety and Environmental Protection*
Percentile of the publication vehicle	95%
Objective	*offshore* drilling operators, using eye tracking and the IETTSM-DLD model to predict accidents caused by unsafe behaviors.
Method	The study used eye tracking of 42 driller trainees during simulated *offshore drilling operations* across six drilling behaviors: normal operation, unskilled operation, fatigue operation, action errors, omitted actions, and incorrect order. An IETTSM (*Improved Eye-tracking Trajectory) algorithm Sequence Method*) was used to serialize the eye trajectories, and the DLD (*Damerau-Levenshtein Distance*) algorithm was used to analyze the trajectory deviations. The proposed model (IETTSM-DLD) to serialize and compare eye fixation trajectories with the standard sequence, aims to generate alerts based on deviations between the real and expected trajectories.

Results	The model achieved an average accuracy of 91.9% for unsafe behavior warnings, and the average time to alert was 120.97 seconds. Operations such as fatigue and incorrect orders achieved 100% accuracy in issuing warnings, while action errors had an accuracy of 61.9%. Unskilled and fatigued operations resulted in the highest number of abnormal behavior alerts, while operations with incorrect actions and incorrect orders generated the fewest alerts. The trajectory of fixation nodes in normal operations was consistently high, reflecting the accuracy and stability of normal operations. The analysis showed that trajectory node aggregation (excessive fixations in certain areas) is a strong indicator of unsafe operations, such as fatigue and lack of qualifications. Operators with scattered trajectories performed poorly, indicating a high risk of operational errors.
Real context or simulated	Simulated
Limitations	This study was conducted in a simulated environment and may not fully capture the complexity of real *offshore operations*. The model assigns the same weight to all nodes in the eye trajectory, without considering the relative importance of each point. This may limit the accuracy of identifying unsafe behaviors in some cases.
Futures studies	Validation in Real Operations: Application in real drilling scenarios, where external factors such as weather and working conditions can influence operator behavior in ways different from those in the simulated environment. Model Improvement: Weighting of eye trajectory nodes, assigning greater or lesser importance to different fixation areas, which can increase accuracy in detecting unsafe behaviors.

SYNTHESIS MATRIX 6	(Raza *et al.,* 2023)
Title	*An Eye Tracking Based Framework for Safety Improvement of Offshore Operations*
Country	Pakistan
Publication Vehicle	*Journal of Eye Movement Research*
Percentile of the publication vehicle	57%
Objective	To propose a methodology based on eye tracking to assess and improve the situational awareness of operators in offshore drilling operations, comparing the performance of experts and novices in simulated environments.
Method	*offshore* well control simulations using the VRDS simulator. The Tobii TX 300 (300 Hz) was used to capture eye movements. Three areas of interest (AOIs) were designated: penetration rate, outflow, and gas volume. Pupil dilation was recorded to assess participants' cognitive response. The duration and count of fixations in the AOIs were measured and compared between the expert and novices. Pupillary diameter during critical moments of the simulation was also analyzed. Kruskal -Wallis tests were used to analyze the difference between novices and experts in the AOIs.
Results	The expert demonstrated greater efficiency by focusing his fixations on the relevant AOIs during critical moments, such as detecting *kicks*, while novices showed dispersed fixations. Expert pupil dilation was greater at critical moments, indicating greater alertness and better situational awareness. Statistical tests confirmed significant differences in fixation duration and count between AOIs, with the expert showing a more efficient response compared to novices.
Real context or simulated	Simulated
Limitations	Small sample: 1 expert and 23 novices, limiting the generalization of the results. Simulated context: factor that does not fully capture the complexities and pressures of the real offshore environment.
Futures studies	Analysis of each individual's situational awareness levels. Sample expansion: include more experts in order to create a more robust comparative basis.

Source - Prepared by the authors based on Botelho et al. (2011)

In **stage 5**, the selected studies were analyzed and interpreted to identify similarities, differences and possibilities for new studies:

3.1 General characteristics of the studies

The six studies analyzed shared a focus on the use of eye-tracking technology to assess and improve safety and performance in subsea well drilling operations. Conducted entirely in simulated scenarios, they used virtual reality and high-precision eye-tracking devices to monitor attention, situational awareness (SA), and behavior patterns. Simulators allow for the isolation of critical variables, such as eye movements and decisions in anomaly situations, but they do not fully replicate the psychological and emotional pressures present in real operations, such as high stress and time pressure.

Regarding the results obtained using *eye -tracking*, in the studies by Chen et al. (2024), five critical ocular parameters were used to characterize risk behaviors: total number of fixation points, total fixation time, total saccade length, total saccade time, and mean pupil diameter. Pupillary dilation, for example, was greater at critical moments, indicating greater alertness and better situational awareness at these moments (Raza et al., 2023). For Chen et al. (2024), variations in pupil diameter can serve as indicators of operator fatigue and engagement levels during drilling operations. In normal operations, the mean pupil diameter indicated a consistent typical range (19.16 px), while in fatigue-involved operations it exhibited a smaller mean diameter (10.04 px), and in inexperienced operations it exhibited a larger pupil diameter (22.85 px), reflecting high levels of concentration. When comparing novices with experts, it was found that experts focused their fixations on critical areas and maintained greater situational awareness, while novices dispersed their fixations and attention, leading to errors and loss of well control (Naqvi et al., 2020). Excessive gaze fixations in certain areas indicated unsafe operations, and operators with dispersed fixation trajectories had lower performance, indicating a high risk of operational errors (Chen et al., 2023).

3.2 Objective and methodology

The studies analyzed pointed to a common goal: to use eye-tracking technology to explore human behavior in critical tasks, seeking to measure and improve situational awareness (SA), efficiency, and safety in *offshore drilling operations.* The methods employed demonstrated positive results in simulated laboratory team training environments and in scientific exploration contexts (Chen et al*.,* 2024). Naqvi et al. (2019) highlighted, through content analysis, the potential of eye-tracking technology to interpret communication patterns in spoken and written data, allowing for the optimization of training and the improvement of human factors. Training optimization, according to Naqvi et al. (2019), occurs by going beyond the simple assessment of technical skills, integrating real-time content analysis to understand operators' cognitive processes and mental states. This allows for the identification of gaps, the provision of targeted *feedback*, and the personalization of learning so that novices can acquire the information strategies and skills of experts more efficiently. Raza et al. (2019) also included in their study a qualitative analysis of voice *logs* (the equipment allows for synchronous voice recording) and behaviors during the simulation, as well as subjective situational awareness (SA) questionnaires. For Krippendorff (2004), content analysis of these communications provides psychological *insights* based on the words used by participants, complementing quantitative assessments. Additionally, Naqvi et al. (2020) focused their studies on objective metrics, such as eye fixations in Areas of Interest (AOIs), to identify behavioral patterns. This approach included comparing performance between novice and experienced professionals, a methodology also employed by Naqvi et al. (2019) and Raza et al. (2023). In a safety-focused approach, Chen et al. (2023) developed a machine learning-based system to predict unsafe behaviors, offering early warning of accidents. Raza et al. (2023) combined qualitative analysis of visual behavior and eye fixations with quantitative data from pupillometry and statistical tests (Kruskal -Wallis). Given this, it is noteworthy that the complexity of research demands answers beyond the quantitative sense of numbers and the qualitative sense of words, with the combination of both methods providing the most comprehensive analyses for complex problems (Creswell & Plano Clark, 2018).

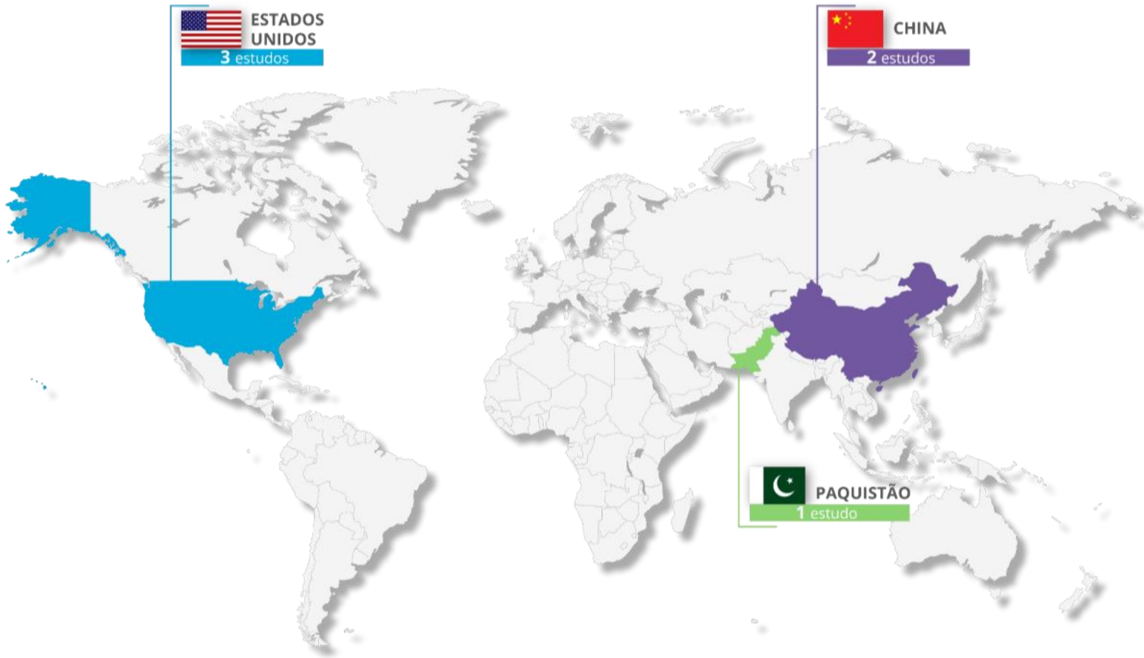
3.3 Participant characteristics

Study participants ranged from novices, trainee operators, and experienced experts, with profiles reflecting the specific objectives of each study. All six studies used novices (undergraduate or graduate students, *trainees*) due to their ease of access to simulated environments, while three studies included experienced operators. Sample sizes varied, with generally small samples, with 13 participants (Raza et al., 2019), 24 individuals (Raza et al., 2023), and the smallest, with 4 participants (Naviq et al., 2019). In contrast, studies such as Chen et al. (2023) and Chen et al. (2024) had a broader approach, with 42 participants. Four studies explicitly included the participation of women (Raza et al., 2019; Naviq et al., 2020; Chen et al., 2023; Chen et al., 2024). Guillem & Mograss (2005) suggest that men and women differ in their cognitive strategies for processing information, with women focusing on detailed elaboration of content and men being more guided by schemas or general themes. Men tend to have a more developed logical region, while women tend to have better cognitive development; men have a better perception of the whole and are better at observing details (De Abreu Agrela Rodrigues, 2022).

3.4 Countries

Of the six studies analyzed, three were from researchers at US universities, two from China, and one from a university in Pakistan (Figure 3). Countries like the United States and China have solid academic and technological infrastructures, as well as significant global presence in the oil and gas industry. There are no studies from Brazilian universities on this topic, indicating a research opportunity.

Figure 3 - World map highlighting the three countries from the six selected studies

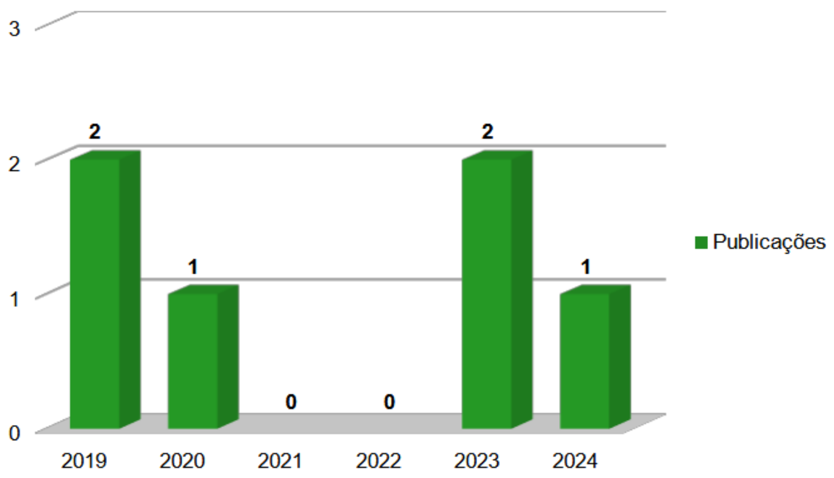


Source - Prepared by the authors (2024)

3.5 Year of publication

The studies were published between 2019 and 2024 (Figure 4), reflecting recent advances in the application of eye-tracking technology in complex operations and highlighting a growing interest in integrating behavioral analysis and risk mitigation technologies in subsea well drilling operations. Recent and internationally relevant publications, such as *report* 656 of 2023 and *report* 656-1 of 2024, highlight the benefits of using eye-tracking technology in well control environments (*offshore* or offshore, *onshore*), demonstrating the importance and relevance of the topic (IOGP, 2023; IOGP, 2024).

Figure 4 - Number of publications per year



Source - Prepared by the authors (2024)

3.6 Implications related to situational awareness, behavior, decision-making, and performance

According to the studies reviewed, behavioral analysis, situational awareness (SA) assessment, decision-making, and operator performance serve as pillars for improving safety and efficiency in *offshore drilling operations*. These aspects are directly related to cognitive ergonomics, a specialized field of ergonomics that seeks to understand and optimize interactions between workers and systems, considering factors such as information processing, mental load, attention, and cognitive abilities. Cognitive processes include attention, decision-making, reasoning, memory, and others. Behavioral analysis can identify unsafe behaviors and training gaps (Chen et al., 2023; Naqvi et al., 2019).

In the studies reviewed, situational awareness is emphasized as a critical factor in performance, and in the context of subsea well drilling, it involves focused attention to details and environmental cues for decision-making and correct well control (Raza et al., 2019). Endsley et al. (2000) report that, in simple terms, situational awareness involves knowing what is happening around one and can be defined as a three-level process: the first is perception, the second is understanding, and the third is prediction of future events (highly related to decision-making). Operators with high situational awareness demonstrate greater accuracy in recognizing anomalies, while novices tend to disperse their attention, compromising efficiency and decision-making (Naqvi et al., 2020; Raza et al., 2023).

Decision-making is impacted by technical knowledge and confidence, with studies showing that overconfident but under-skilled operators often make critical errors (Raza et al., 2019). Operators' overall performance is directly related to their ability to integrate visual (physical domain) and cognitive information, highlighting the importance of simulation-based training to enhance skills and mitigate operational risks. Regarding the locations where the studies were conducted, simulators were used in all. One study mentioned the application of eye-tracking technology in real-time remote operations centers, where highly trained and experienced professionals assist in monitoring platforms from shore (Raza et al*.,* 2023). With the advancement of sensor use, eye-tracking can be a useful tool for improving operational efficiency and accuracy; for example, in case the driller is tired and loses attention from the monitors, warning alarms can be implemented using real-time eye tracking to alert him (Raza et al*.,* 2023).

The results show that situational awareness plays a central role in the performance of operators (drillers), being directly influenced by factors such as training, experience, and workload. Studies such as those by Raza et al. (2019, 2023) and Chen et al . (2023) showed that experts exhibit greater focus and efficiency compared to novices, concentrating their fixations on critical areas and demonstrating a better ability to recognize anomalies. The application of machine learning-based predictive models (Chen et al., 2023; Chen et al., 2024) also reinforces the potential of eye tracking as a real-time monitoring tool, helping to prevent unsafe behavior and improve decision-making in highly complex operations. These findings are relevant for improving training programs and developing systems that integrate real-time *feedback for offshore operators.*

Regarding ergonomics (physical and cognitive domains), the studies reviewed qualify as original research and highlight the relevance of the topic for the scientific community. *Eye tracking* not only measures the sensory capacity and muscular control of the eyes (physical ergonomics), but, more importantly, it infers cognitive processes. It is essential to understand that this technology acts as a bridge between these two domains of ergonomics. Regarding the physical domain, it objectively measures the individual's eye movement behavior, recording data such as the distribution of fixation points, the path of the saccade, the dwell time of the fixation point, as well as changes in pupil size (mean pupil diameter). The quality and accuracy of the collected data are directly influenced by physical factors of the operator and the environment, such as head stability and the need for consistent lighting conditions. Regarding the cognitive domain, the studies presented here focus heavily on cognitive ergonomics, investigating how the operator's mind (perception, attention, decision-making, situational awareness) interacts with complex systems, especially in high-risk situations. *Eye tracking* functions as a "window into the mind," allowing the analysis of cognitive and behavioral processes through the observation of eye movements (Levantini et al., 2020). Physical measurements of eye movement, therefore, serve as indicators of psychological, attentional, and recognition states.

3.7 Summary of results

Finally, **in step 6**, which summarizes the previous steps, the main results are highlighted. The relevance of the research topic is emphasized, as well as the development of the research question and the definition of inclusion and exclusion criteria, as these enabled the mapping and synthesis of scientific studies integrating eye-tracking technology into the context of subsea well drilling in the oil and gas industry.

From the six selected studies, it was clear that all six were conducted in simulated scenarios and monitored attention, situational awareness, and behavior patterns. That said, the five ocular parameters used to identify risk behaviors, such as number of fixations and pupil dilation, stand out; the pupil dilated at critical moments, indicating greater alertness and situational awareness. It was also observed that pupil diameter varied according to the operator's level of fatigue and experience. Experts concentrated fixations on critical areas, while novices dispersed their attention, leading to operational errors. Finally, excessive or scattered fixations were associated with unsafe operations and poorer performance.

The studies analyzed used eye tracking to investigate human behavior in *offshore drilling operations*, focusing on situational awareness (SA), efficiency, and safety. The methods applied included qualitative and quantitative analyses, combining eye tracking, voice logs, subjective questionnaires, and statistical tests. Machine learning models were used to predict unsafe behaviors (Chen et al., 2023). The combination of qualitative and quantitative approaches was highlighted as essential for a complete analysis (Creswell & Plano Clark, 2018).

Participants ranged from novices to *trainees* and experienced experts, with predominantly small sample sizes ranging from 4 to 42 participants. Four studies included women, highlighting possible cognitive differences between genders in how information is processed (De Abreu Agrela Rodrigues, 2022).

Regarding the origin of the studies, three were conducted in the USA, two in China and one in Pakistan, highlighting the lack of Brazilian research in the area, which represents an opportunity for investigation.

4. Conclusion

The studies analyzed reveal that eye tracking is an important tool for investigating aspects related to behavioral assessment, situational awareness (SA), decision-making, and operator (probe) performance, allowing for the identification of patterns of visual attention and behavior in critical situations. Eye movements can, therefore, reveal relevant information about cognitive processes.

The objective of understanding how these technologies have been applied to improve safety and efficiency was met through the analysis of recent studies (n=6), which highlight advances in the use of eye tracking in subsea well drilling operations, such as detecting attention patterns, cognitive load and fatigue, optimizing training, preventing errors and improving safety in environments that require high concentration demands.

However, there remains a need to expand studies to real-world scenarios to validate findings made in simulated environments and explore factors such as stress, urgency, and decision-making, which are difficult to replicate in simulations.

It is recommended that future research explore remote onshore operations centers, which support decision-making in offshore activities, as they represent strategic and promising locations for ergonomic research. Besides the scarcity of studies focused on these environments, their ease of access compared to offshore units stands out, as they do not require boarding, specific safety training, or complex logistics, favoring systematic surveys and field observations. Furthermore, investigations that consider the impact of work organization and organizational culture can provide important insights into human factors in high-risk environments, as both can influence how employees interact, make decisions, and perceive the work environment. These initiatives will contribute to strengthening safety, ergonomics, and efficiency in *offshore operations*, aligning with the growing demands of the oil and gas industry.

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Received: 06/13/2025

Approved: 06/24/2025

Executive Editor: Manoela Lopes