SCIENTIFIC JOURNAL OF MARITIME RESEARCH [POMORSTVO]

University of Rijeka FACULTY OF MARITIME STUDIES

https://doi.org/10.31217/p.40.1.8

Eye Tracking in Maritime Research: A Systematic Review

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ARTICLE INFO

Review article
Received 1 September 2025
Accepted 10 November 2025

Key words:
Eye movement
Gaze movement
Maritime
Shipping
Seafarer

ABSTRACT

Eye-tracking technologies have evolved considerably since their inception, enabling increasingly sophisticated analyses of human visual behavior. These technologies have subsequently been applied to examine the gaze behaviors of maritime professionals. As of 2020, approximately 15 English-language research articles focused on eye-tracking applications in maritime contexts; since then, the number has more than doubled, reflecting growing interest in the field. This review examines 37 studies that met predefined eligibility criteria, encompassing a wide range of research themes and diverse eye-tracking metrics. It synthesizes the potential benefits and limitations of eye-tracking in maritime settings, identifies methodological and practical challenges, and highlights notable research gaps. The findings have implications for researchers, informing study design and metric selection; for maritime educators, enhancing training and assessment methods; and for designers of nautical charts, navigational equipment interfaces, and bridge layouts, supporting the development of more effective and user-friendly designs.

1 Introduction

According to Rayner [1], eye-tracking research extended from the year 1879. Up until 1920, the focus was primarily on eye movements in reading activities. Since then, eye-tracking research has found its way into other fields. In 2013, Muczynski et al. [2] and Godwin et al. [3] published the first English research articles examining the gaze behaviors of maritime professionals in a Web of Science-indexed journal and a Scopus-indexed journal, respectively. Interestingly, both studies focused on the differences between seafarers of varying expertise. From that point onwards, eye-trackers have been used to explore various themes.

As of writing, there are at least 37 English research articles (i.e. [2-38]) dedicated to the applications of video-based eye-tracking technologies in maritime research. This review aims to systematically synthesize the insights made by these articles. In this review, maritime research refers to studies focused on Maritime Education and Training, Maritime Safety and Security, Vessel Traffic Management, Marine Engineering, Maritime Electronics and Information Systems, Human Factors, and other closely related topics. Relevant insights from adjacent fields, such as naval research, offshore engineering, and sports sailing, are also considered where applicable.

2 Methodology

To achieve the objective of this study, a systematic literature review was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [39], which offer a structured approach for conducting and reporting such reviews. The search was conducted using three databases: Scopus and Web of Science as the primary sources, and Google Scholar as a supplementary source. Keywords listed in Table 1 were used to identify relevant journal articles. The selection process was guided by specific inclusion and exclusion criteria outlined in Table 2. No publication year restrictions were applied, allowing the inclusion of studies published up to August 15, 2025.

Table 1 Keywords for the Search Strategy

Categories	No.	Keywords
Eye-tracking	#1	eye track*
	#2	eye movement
	#3	eye behavi*
	#4	gaze track*
	#5	gaze movement
	#6	gaze behavi*
	#7	#1 OR #2 OR #3 OR #4 OR #5 OR #6
Maritime	#8	maritime
	#9	navy
	#10	seafarer
	#11	seaman
	#12	seawoman
	#13	ECDIS
	#14	nautical
	#15	simulator
	#16	navigat*
	#17	engine*
	#18	RADAR
	#19	chart
	#20	equipment
	#21	traffic
	#22	operat*
	#23	marine*
	#24	ship
	#25	bridge
	#26	vessel
	#27	#8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #14 OR (#24 OR #25 W/15 #15) OR (#24 W/50 #16 OR #17 OR #18) OR (#16 W/15 #19 OR #20) OR (#26 W/15 #21) OR (#24 W/15 #22) OR #23)
Other	#28	mammal*
	#29	animal
	#30	species
	#31	#28 OR #29 OR #30
Integration	#32	#7 AND #27 AND NOT #31

Table 2 Eligibility Criteria for Search Strategy

Inclusion Criteria
- Published in peer-reviewed journals
- Written in English
- Full text accessible
- Empirical studies or conceptual/theoretical studies with empirical data
- Related to video-based eye-tracking technologies
- Related to maritime research/Findings relevant to maritime research
Exclusion Criteria
- * Published in predatory journals
- ** Published in journals with vague peer review processes
- Conference papers, theses/dissertations, technical reports, or other grey papers
- Conceptual/theoretical studies without empirical data or other non-empirical studies

* This study used the checklist developed by [40] to identify potential predatory journals. The ISSN Portal [41], the Directory of Open Access Journals (DOAJ) [42], and Beall's List [43] were also used as reference sources.

** Journals that were not identified as predatory but did not clearly specify their peer review process on their websites were classified as having vague peer review processes.

A total of 280 studies were initially identified from Scopus and Web of Science (WoS) using the defined search strategy. After excluding 131 non-English or non–peer-reviewed journal articles and removing 44 duplicates, 105 studies remained. Title and abstract screening excluded 69 studies that were unrelated to video-based eye-tracking in maritime research. Full-text reviews of the remaining 36 studies led to the exclusion of one that did not use video-based eye-trackers. Two additional relevant studies, indexed in Scopus and WoS but not retrieved in the initial search, were identified through Google Scholar. In total, 37 studies were included in the final review, as illustrated in Figure 1.

3 Result

As previously noted, 37 studies met the eligibility criteria for this review. In 2021, Martinez-Marquez et al. [45] published a review paper synthesizing research up to August 2020 on the use of eye-tracking technologies in the maritime, aviation, and construction industries. That paper cited 12 journal articles and 13 conference papers related to the maritime domain. Of the 12 journal articles, nine met this review's eligibility criteria. This indicates that in approximately five years, the number of eligible studies has increased more than fourfold, reflecting the rapid expansion of eye-tracking applications in the maritime sector.

This chapter aims to fulfil the objective of this review by answering the following research questions:

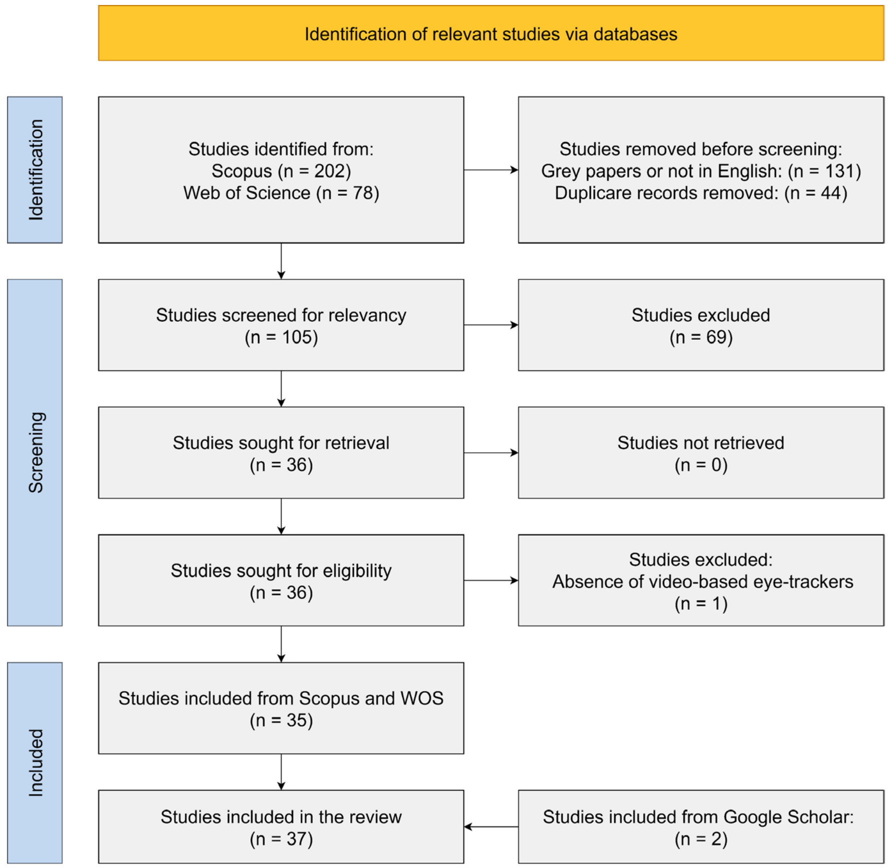

Figure 1 Flow of Studies Identification Process (adapted from [44])

RQ1: What research themes have been explored using eye-tracking technologies in maritime studies?

RQ2: What types of eye-tracking devices and experimental setups have been used in maritime research?

RQ3: How are eye-tracking metrics utilized in different types of maritime research?

RQ4: What potential benefits and practical implications of eye-tracking technologies have been identified in maritime research?

RQ5: What are the practical and methodological challenges in applying eye-tracking technologies in maritime research?

Table 3 Studies and Their Corresponding Research Themes

Research Themes	Studies
Mental Workload	[11], [17], [21], [25], [30], [33], [34]
Scan Strategies & Gaze Patterns	[3], [6], [8], [9], [14], [28], [36], [38]
Training Improvement	[2], [5], [13], [18], [24], [32]
Human-Machine Interfaces	[7], [10], [20], [26], [35]
Fatigue & Vigilance Assessment	[15], [19], [23], [29]
Situation Awareness	[12], [16], [22], [27]
Other	[4], [31], [37]

3.1 RQ1: Research Themes

The eye-tracking studies in maritime research can be categorized into seven research themes, as detailed in the following sub-sections. Table 3 summarizes the distribution of the 37 reviewed studies across these categories.

3.1.1 Mental Workload

Mental workload refers to the cognitive effort required to perform a task. In the maritime domain, managing mental workload is crucial for safe and efficient operations, as excessive workload can impair decision-making and situational awareness. Eye-tracking technology offers an objective and non-intrusive method for assessing mental workload among maritime professionals. Eye-tracking studies in the maritime field have explored mental workload across various experimental contexts, ranging from interface evaluations and simulator-based tasks to real-world ship operations.

Studies using maritime interfaces primarily involved student participants performing procedural or monitoring tasks. Two studies focused on engine room operations [17, 25], while one examined target identification and marking under varying task conditions [21]. Simulator-based studies examined navigational and berthing operations, investigating how workload influenced operator performance and behavior among harbor pilots, deck officers, and naval officers [11, 30, 33]. One onboard study extended this research to real-world operational settings, exploring the relationship between mental workload, safety performance, and distraction [34].

3.1.2 Scan Strategies & Gaze Patterns

Eye-tracking technologies allow researchers to identify efficient scan and look-out strategies employed by maritime operators. They also allow researchers to understand the effects of various factors on seafarers' gaze patterns. In maritime eye-tracking research, scan strategies and gaze behaviors have been examined across various contexts, focusing on the development of effective scanning techniques, the influence of external and individual factors, and the prediction of attention distribution.

A number of studies investigated effective scan strategies by examining look-out behaviors of deck officers and lock operators across simulated and real-world environments, night-time watchkeeping, and CCTV/remote-control tasks [8, 28, 36, 38]. Research also explored how operator characteristics or task conditions, such as expertise, speech intelligibility, and task complexity, influenced visual behavior during simulated and onboard operations [3, 9, 14]. Researchers also developed a stochastic model to predict navigators' attention distribution in simulated operations [6].

3.1.3 Training Improvement

Eye-tracking devices enable the extraction of tacit knowledge from experts, offering insights into cognitive processes that are often difficult to articulate. Additionally, eye-tracking data can serve as a supplementary metric to evaluate the efficacy of training materials. This allows maritime education and training (MET) entities to design more effective training programs for maritime operators. Eye-tracking research within maritime education and training has focused on two principal themes—expert–novice comparisons and the evaluation of training approaches—to enhance the effectiveness of training systems.

Some studies compared operators with varying levels of expertise to identify competency gaps, including deck officers in collision risk scenarios, electronic navigation, and maritime crane operations [2, 13, 18]. Other research used eye-tracking to assess or improve training methods, evaluating maritime student satisfaction, developing training materials for vessel traffic service (VTS) operators, and enhancing VR-based shipboard firefighting training [5, 24, 32].

3.1.4 Human-Machine Interfaces

Electronic equipment has become essential for maritime professionals, especially navigators. Eye-tracking technology offers a valuable means of effectively assessing the usability of navigational tools such as electronic nautical charts, software interfaces, and other bridge equipment critical to safe navigation. Eye-tracking studies in the maritime domain have focused on evaluating navigational system usability, addressing two primary aspects: the GUIs of navigational aids and the design of electronic nautical charts.

A series of studies examined bridge layouts and GUIs of maritime interfaces, including a prototype maritime service website and RADAR/ECDIS systems [7, 10, 20]. Researchers also investigated visual behavior in nautical chart systems, comparing inexperienced and experienced technicians using a prototype chart editor or users interacting with 2D and 3D chart designs [26, 35].

3.1.5 Fatigue & Vigilance Assessment

IMO [46] defines fatigue as "a state of physical and/or mental impairment resulting from factors such as inadequate rest, extended wakefulness, or high workload, which can reduce a seafarer's ability to perform duties safely and effectively." Fatigue can degrade vigilance, which ultimately increases the risk of maritime accidents. Through objective and non-intrusive monitoring, eye-tracking enables the assessment of fatigue and vigilance in maritime personnel. Maritime eye-tracking research has investigated fatigue and vigilance, examining how these factors affect seafarers' performance and safety.

Research addressed fatigue detection by developing methods using eye-tracking data for VTS operators and integrating eye-tracking with other bio-signals to assess mental fatigue in harbor pilots [15, 19]. Studies also explored vigilance assessment, creating models to evaluate VTS operators' vigilance levels and predict contributing factors from eye-tracking data [23, 29].

3.1.6 Situation Awareness

Situation awareness (SA), as defined by Endsley [47], is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." It is critical to maritime safety, as it enables seafarers and operators to make timely and accurate decisions in complex and dynamic environments. Eye-tracking technology facilitates a more objective, accurate, and comprehensive assessment of situation awareness by capturing where and how maritime professionals allocate their visual attention. Maritime eye-tracking research has explored situation awareness by examining how seafarers allocate visual attention in complex operational environments.

Investigations into situation awareness compared the visual behavior of novice and expert operators in training or operational contexts [12, 16] and developed models to assess or detect situation awareness in harbor pilots using eye-tracking data [22, 27].

3.1.7 Other

Additional research explored other aspects of maritime human factors, including the effectiveness of decision support systems in facilitating attention recovery during simulated naval operations [4], team performance assessment using eye-tracking integrated with machine learning [31], and the impact of automation malfunctions on operators' trust in autonomous navigation systems [37].

3.2 RQ2: Types of Eye-tracking Devices & Experimental Setups

3.2.1 Mobile & Remote Eye Trackers

Video-based eye trackers used in maritime research can be categorized into two main types: (1) Mobile Eye Trackers and (2) Remote Eye Trackers. Mobile eye trackers are wearable devices, including headbands, glasses, helmets, and VR headsets. They are commonly used in operation-based experiments, as they allow users to move freely within the experimental setting. Mobile eye trackers are further classified into four subtypes: (a) glasses-type, (b) helmet-type, (c) headband-type, and (d) VR headset. Alternatively, remote eye trackers are devices that track users' eye movements without requiring physical attachment. They are commonly used in screen-based experiments, as they allow users to engage with digital interfaces in a natural manner. Remote eye trackers are divided into three subtypes: (a) table-mounted, (b) tower-mounted, and (c) face analysis software. Table 4 summarizes these eye-tracking systems along with the corresponding studies that utilized them.

Table 4 Eye Trackers and Their Corresponding Studies

Eye Trackers	Studies
Mobile Eye Trackers (n = 29)	
- Glasses-type	[2], *[6], [7], [8], [9], [10], [11], [12], [13], [14], [16], [18], [19], [20], [22], [24], [26], [27], [31], [33], [34], [36], [37], [38]
- Helmet-type	[17], [25], *[28]
- Headband-type	[30]
- VR Headset	[32]
Remote Eye Trackers (n = 8)	
- Table-mounted	[4], [15], [21], [23], [29], [35]
- Tower-mounted	[3]
- Face analysis software	[5]

* [6] did not explicitly state the type of eye tracker used in their study; however, it was assumed to be a glasses-type eye tracker based on their earlier publication (i.e., [2]), which specified the device used.

* [28] also did not explicitly mention the eye tracker type; the classification as a helmet-type device was based on a related conference paper (i.e., [48]) by the same authors that provided this detail.

3.2.2 Screen-based, Operation-based, and Hybrid Setups

The experimental setups used in the reviewed studies can be grouped into three categories: (1) Operation-based, (2) Screen-based, and (3) Hybrid. The operation-based setup refers to experimental designs where participants perform tasks in full-mission simulators, actual ships, or environments that closely resemble real-world operational settings. These experiments aim to capture more realistic behavior under complex, immersive conditions that reflect actual maritime operations. Alternatively, the screen-based setup refers to experimental designs where participants perform tasks presented via a single-screen interface, typically in a controlled laboratory setting. These experiments often involve minimal environmental complexity and focus on user interaction with digital content on one display. Finally, the hybrid setup combines elements of both screen-based and operational-based designs. Table 5 presents the distribution of the reviewed studies across these categories.

Table 5 Experimental Setups and Their Corresponding Studies

Operation-based Setup (n = 23)
[2], [6], [7], [8], [9], [11], [12], [14], [16], [18], [19], [22], [24], [27], [28], [30], [31], [32], [33], [34], [36], [37], [38]
Screen-based Setup (n =13)
[3], [4], [5], [13], [15], [17], [20], [21], [23], [25], [26], [29], [35]
Hybrid Setup (n = 1)
[10]

As illustrated in Table 4, most of the studies employed mobile eye trackers. This trend can be attributed to the fact that most of the experiments, as shown in Table 5, were operation-based. Notably, while all studies utilizing remote eye trackers were classified as screen-based, not all screen-based studies used remote eye trackers. Specifically, five screen-based studies (i.e., [13], [17], [20], [25], and [26]) employed mobile eye trackers.

3.3 RQ3: Eye-tracking Metrics & Research Types

The commonly used eye-tracking metrics in the reviewed studies are: (1) Dwell, (2) Fixation, (3) Saccade, (4) Blink Rate, (5) Pupil Dilation, (6) Heatmap Interpretation, and (7) Scanmap Interpretation. Definitions of these metrics, based on Holmqvist and Andersson [49] and Duchowski [50], are summarized in Table 6. Comprehensive definitions for all eye-tracking metrics used in maritime research can also be found in Holmqvist and Andersson [49] and Duchowski [50].

Table 6 Definitions of Common Eye-tracking Metrics

Dwell: A single visit within an Area of Interest (AOI), from the moment of entry to exit. Dwell time refers to the total duration spent within the AOI during that visit.
Fixation: A period when the eyes remain relatively still, focusing on a specific location for a short duration to acquire visual information.
Saccade: A rapid eye movement between two fixations, during which visual information uptake is suppressed.
Blink Rate: The frequency of blinks over time, typically expressed in blinks per minute; often used as an indicator of cognitive workload or fatigue.
Pupil Dilation: The change in pupil diameter, commonly associated with variations in cognitive load, emotional arousal, or lighting conditions.
Heatmap Interpretation: A visual representation of aggregated gaze data, illustrating areas of high and low visual attention through color intensity.
Scanmap Interpretation: A visualization of the sequence and spatial distribution of fixations and saccades, providing insights into viewing strategy and attention shifts.

In terms of research type, the reviewed studies can be grouped into four categories: (1) Exploratory Research, (2) Predictive Modeling, (3) Usability Testing, and (4) Method Development. Table 7 presents the distribution of the 37 reviewed studies across these categories. The following subsections describe the metrics employed in each category and summarize their main findings.

Table 7 Research Types and Their Corresponding Studies

Exploratory Research (n = 12)
[2], [3], [9], [11], [12], [13], [14], [21], [22], [33], [36], [38]
Predictive Modeling (n = 11)
[6], [15], [17], [19], [23], [25], [27], [29], [30], [31], [34]
Usability Testing (n = 8)
[4], [7], [10], [20], [24], [26], [32], [37]
Method Development (n = 6)
[5], [8], [16], [18], [28], [35]

3.3.1 Exploratory Research

This category includes studies that utilize eye-tracking data to examine correlations, trends, or causal relationships to better understand human behavior, performance, or cognitive processes. The 12 studies in this category cover five research themes, as outlined below. The eye-tracking metrics employed in these studies are summarized in Table 8.

Mental Workload. Eye-tracking metrics that respond to mental workload varied depending on the inducing factors, such as time pressure or task complexity. Blink rate and duration, fixation rate and duration, and saccade rate and duration were primarily sensitive to time pressure [21], whereas pupil dilation, fixation rate, and saccade rate responded to task complexity [11, 21]. However, one study reported that both task complexity and time pressure, individually or combined, significantly affected fixation duration and backtrack counts [33].

Scan Strategies & Gaze Pattern. Differences between novice and expert operators were reflected in several eye-tracking metrics. Experts exhibited shorter fixation durations, more horizontal fixation distribution, and reduced smooth pursuit distance under rough sea conditions, while novices showed no consistent adaptation to environmental challenges [3].

Table 8 Eye-tracking Metrics Used in Exploratory Research

Mental Workload	
[21], [33]	Fixation Duration
[11]	Pupil Dilation
[21]	Blink Rate
	Blink Duration
	Fixation Rate
	Saccade Rate
	Saccade Duration
[33]	Backtrack Count
Scan Strategies & Gaze Pattern	
[3], [14]	Fixation Duration
	Spread of Fixation
[9], [36]	Dwell Duration
[3]	Smooth Pursuit
[38]	Qualitative Analysis of Gaze Pattern
Training Improvement	
[2], [13]	Fixation Count
[2]	Fixation Frequency
	Saccade Frequency
	Blink Frequency
[13]	Fixation Duration
	Heatmap Interpretation
Situation Awareness	
[12], [22]	Fixation Duration
	Heatmap Interpretation
[22]	Fixation Count
	Saccade Count
	Saccade Duration
	Pupil Dilation
	Scanmap Interpretation

Environmental and task-related factors also influenced visual behavior. Reduced speech intelligibility increased dwell time on non-informative areas such as notepads and blank spaces [9], while higher task complexity led to more widely distributed fixations, greater pupil dilation, and longer fixation durations during multiple-ship encounters [14].

Additional studies examined broader patterns of visual behavior and perceived equipment use. Seafarers tended to overestimate reliance on ECDIS and visual observation while underestimating RADAR usage [36], and qualitative analyses identified consistent gaze patterns among lock operators, including anticipating, verifying, overviewing, and movement-directed scanning [38].

Training Improvement. Studies focusing on training improvement by investigating the gaze behavior of maritime professionals across various levels of expertise used eye-tracking metrics such as fixation counts, fixation duration, saccade frequency, and blink frequency. These studies reported that experts generally exhibited more efficient gaze behavior with clustered fixations, whereas novices showed higher fixation counts and durations along with more scattered eye movements [2, 13].

Situation Awareness. Deck officers and pilots with higher SA generally exhibited longer fixation durations on external environment and key AOIs, more concentrated fixations, and higher scanning frequencies, whereas cadets or low-SA operators displayed shorter fixations, more scattered gaze patterns, and tended to focus on navigational equipment [12, 22].

3.3.2 Predictive Modeling

This category includes studies that integrate one or more eye-tracking metrics into machine learning or statistical models to predict or classify states or behaviors. The 11 studies in this category cover five research themes, as outlined below. The eye-tracking metrics employed in these studies are summarized in Table 9.

Mental Workload. Artificial Neural Networks (ANN) and discriminant analysis models distinguished between low, general, and high workload levels [17, 25], while Support Vector Machine (SVM) models achieved precise workload assessment [30]. Correlational models combining eye-tracking and psychological data were also used to examine relationships between workload and safety performance [34].

Scan Strategies & Gaze Patterns. Fixation transitions were used to develop a stochastic model using Markov chains to predict navigators' gaze sequences [6]. However, the study noted that first-order Markov chains were not entirely suitable for this purpose [6].

Fatigue & Vigilance Assessment. Semi-supervised bagged tree models detected fatigue based on gaze velocity, although distinguishing medium-level fatigue from

Table 9 Eye-tracking Metrics Used in Predictive Modeling

Mental Workload	
[17], [25], [30], [34]	Pupil Dilation
[17], [25], [34]	Fixation Rate
[17], [25], [30]	Blink Rate
[17], [25]	Saccade Rate
[30]	Fixation Percentage
[34]	Fixation Duration
Scan Strategies & Gaze Patterns	
[6]	Fixation Transition
Fatigue & Vigilance Assessment	
[19], [29]	Pupil Dilation
[15]	Gaze Velocity
[23]	Time to First Target Fixation
	Fixation Duration of First Target Fixation
	Distance Between Initial Fixation and Target Fixation
	Ratio of Valid Fixation
[29]	Fixation Count
	Fixation Duration
	Fixation Rate
	Fixation Dispersion
	Saccade Count
	Saccade Duration
	Saccade Rate
	Saccade Latency
	Absolute Direction of Saccade
	Change of Saccade Direction
	Scanpath Length
	Scanpath Duration
Situation Awareness	
[27]	Fixation count
	Fixation duration
	Saccade count
	Saccade duration
	Pupil dilation
	Heatmap Interpretation
	Scanmap Interpretation
Teamwork	
[31]	Fixation Duration
	Fixation count
	Saccade velocity
	Saccade amplitude

alertness remained challenging [15]. Convolutional Neural Networks (CNNs) incorporating pupil dilation and other bio-signals achieved high accuracy in single-subject fatigue detection [19]. A diverse set of eye metrics was leveraged to build Shallow ANNs and ensemble models combining gradient-boosted decision trees and ANNs have been used to predict vigilance and analyze contributing features [23, 29].

Situation Awareness. A Random Forest–Support Vector Machine (RF–SVM) model combining fixation and saccade parameters with pupil dilation achieved accurate SA assessment [27].

Other (Teamwork). Fixation duration and count, and saccade velocity and amplitude were used to develop several classification models for assessing team performance, with the SVM model reporting the highest accuracy [31].

3.3.3 Usability Testing

This category includes studies using eye-tracking data to evaluate systems, interfaces, or training materials, often as part of usability testing or validation. The seven studies in this category cover four research themes, as outlined below. The eye-tracking metrics employed in these studies are summarized in Table 10.

Training Improvement. Time to target fixation was used to show that participants who received a targeted VTS training course outperformed controls in detecting critical conditions [24]. Similarly, the number and sequence of gazed objects were used to assess the impact of improvements in a VR shipboard fire drill simulator on interface usability and training effectiveness [32].

Human-Machine Interfaces. Studies demonstrated that eye metrics—including time to first fixation, dwell duration, lookbacks, and backtracks—can reveal inefficiencies in bridge designs and GUIs of navigational equipment [7, 10], identify frequently used features in nautical-chart editing software [26], and assess the usability of maritime service websites [20]. Overall, these studies highlight the potential of eye metrics to supplement traditional usability assessment methods.

Other (Decision Making and Trust in Automation). Eye metrics have been used to examine the effects of decision support systems and automation on operator performance and trust. Dwell duration, fixation duration, first-fixation frequency, fixation concordance rate, and number of transitions were used to assess post-interruption recovery in two decision support systems, TOD and CHT, which were found to negatively affect performance [4]. Similarly, fixation duration and count, saccade amplitude and count, and heatmap interpretation were used to validate a model assessing trust in autonomous ship systems, revealing that malfunctions shift operators' attention primarily to bridge displays and ECDIS and that early malfunctions have a stronger negative impact on trust [37].

Table 10 Eye-tracking Metrics Used in Usability Testing

Training Improvement	
[24]	Time to Target Fixation
[32]	Number of Gazed Objects
	Sequence of Gazed Objects
Human-Machine Interfaces	
[20], [26]	Heatmap Interpretation
[7], [10]	Dwell Duration
[7]	Lookbacks
	Backtracks
[20]	Time to First Fixation
[26]	Fixation Count
	Scanmap Interpretation
Decision Making	
[4]	Dwell Duration
	Fixation Duration
	Frequency of First Fixations
	Fixation Concordance Rates
	Number of Transitions
Trust in Automation	
[37]	Fixation Duration
	Fixation Count
	Saccade Amplitude
	Saccade Count
	Heatmap Interpretation

3.3.4 Method Development

This category includes studies that utilize eye-tracking data to develop new indices, frameworks, or analytical tools, such as scanning strategy models or similarity measures. The seven studies in this category cover five research themes, as outlined below. The eye-tracking metrics employed in these studies are summarized in Table 11.

Scan Strategies & Gaze Pattern. Dwell duration, fixation duration, lookbacks, backtracks, and scanmaps were used to propose an effective scan strategy for navigators [8]. Similarly, scanmaps were used to develop an effective night-time lookout procedure for navigators [28].

Training Improvement. Gaze vectors were integrated into an evaluation method to assess students' satisfaction with MET educational tools [5]. Fixation areas of expert crane operators were used to develop a metric quantifying gaze pattern similarity between novice and expert crane operators [16, 18].

Human-Machine Interfaces. Fixation areas were used to develop an indicator for evaluating the overall effectiveness of nautical charts, which showed that 3D concept maps are more effective than 2D charts [35].

Table 11 Eye-tracking Metrics Used in Method Development

Scan Strategies & Gaze Pattern	
[8], [28]	Scanmap Interpretations
[8]	Dwell Duration
	Fixation Duration
	Lookbacks
	Backtracks
Training Improvement	
[16], [18]	Fixation Areas
[5]	Gaze Vector
Human-Machine Interfaces	
[35]	Fixation Areas

3.4 RQ4: Benefits & Implications of Eye-tracking Technologies

The potential benefits and practical implications of eye-tracking technologies in maritime research can be broadly categorized into four areas: (1) Improved Safety and Prevention of Human Error, (2) Enhanced Training and Assessment, (3) Improved Interface and System Design, and (4) Enhanced Decision-Making Processes. While some studies report that their findings could contribute to multiple areas, this section focuses on the primary benefit identified in each study to avoid redundancy. The following paragraphs elaborate on these categories.

3.4.1 Improved Safety & Prevention of Human Error

One key motivation for applying eye-tracking technologies in maritime research is to quantitatively measure the cognitive states of maritime professionals. Such measurements enable the development of machine learning and statistical models that can predict or classify mental workload, situation awareness, and vigilance. This capability directly supports safety and prevents human error by enabling early detection of risky cognitive states. Most predictive modelling studies suggested this as the primary benefit of their research outputs [6, 15, 17, 19, 23, 25, 27, 29, 30, 34].

Eye-tracking technologies also facilitate in-depth analysis of gaze behaviour, allowing researchers to identify effective gaze strategies by studying experts, as well as to detect risky gaze patterns among inexperienced seafarers. Identifying and promoting effective gaze strategies while addressing risky gaze behaviour can enhance operational performance, reduce navigation errors, and ultimately improve safety at sea. A large portion of studies focusing on scan strategies and gaze patterns among maritime professionals indicated this as their main contribution [6, 8, 9, 14, 28, 38].

3.4.2 Enhanced Training & Assessment

Another key motivation for adopting eye-tracking technologies is the versatility of eye-tracking data for both quantitative and qualitative analyses to supplement conventional methods in assessing the effectiveness of maritime training courses. By providing objective, fine-grained measures of visual attention and cognitive engagement, eye-tracking can identify whether trainees are focusing on the most relevant information, following optimal scan patterns, and avoiding distractions. This enables instructors to pinpoint specific areas where trainees need improvement and tailor feedback accordingly. Most studies on training improvement [2, 5, 13, 18, 24] and several studies on cognitive states [11, 12, 22, 33] indicated this as the primary benefit of their research output.

Moreover, eye-tracking data also allows researchers to compare the gaze behaviour of experts and non-experts, which can inform the design of more effective training courses. Understanding the gaze strategies of experts, such as prioritising certain visual cues, allocating attention efficiently, and anticipating hazards, enables the creation of targeted exercises to develop these skills in less experienced seafarers. Similarly, expert gaze data can serve as a benchmark in designing new training modules to ensure they promote best practices. Several studies note this as the primary benefit of their research output [3, 31, 32].

3.4.3 Improved Interface & System Design

Eye-tracking technologies extend the tools available for usability testing. Eye-tracking data can be used to quantitatively and qualitatively evaluate the effectiveness of bridge layouts, electronic equipment interfaces, software, and electronic nautical charts. These insights help designers identify elements that attract or fail to attract attention, pinpoint sources of visual overload or confusion, and optimize the placement of critical information to align with natural gaze patterns. In addition, eye-tracking data supports the development of predictive models of maritime professionals' behavior, enabling designers to anticipate how behavior may change under specific conditions. Together, these capabilities lead to interfaces and systems that are more intuitive, efficient, and less prone to user error. Unsurprisingly, all studies focusing on human–machine interfaces identified this as the primary implication of their research findings [7, 10, 20, 26, 35]. Another study focusing on trust in automation reported the same [37].

3.4.4 Improved Decision-Making Processes

The ability of eye-trackers to effectively record gaze movement has motivated researchers to adopt the technology to investigate the decision-making processes of maritime professionals. Specifically, eye-tracking enables researchers to identify and confirm perceptual biases, such as over-reliance on certain information sources or neglect of critical cues. This allows researchers to evaluate the effectiveness of maritime decision-making support systems by revealing whether these systems successfully guide attention toward relevant information. These insights can lead to improved decision-making processes by improving the design of training, interfaces, and procedures that help seafarers avoid cognitive pitfalls and respond more effectively under pressure. Two studies noted this as the primary benefit of their research output [4, 36].

3.5 RQ5: Challenges in Applying Eye-tracking Technologies

The practical and methodological challenges in applying eye-tracking technologies in maritime research can be grouped into four categories: (1) Resource Intensive, (2) Limitations in Eye-Metric Interpretation, (3) Technical Limitations of Eye-Tracking Devices, and (4) Experimental and Environmental Challenges. Not all studies explicitly reported challenges; however, the following paragraphs summarise those that did.

3.5.1 Resource Intensive

Analyzing eye-tracking data in maritime research can be labor- and time-intensive, particularly when using mobile eye-trackers that lack clearly defined visual boundaries, which requires manually reviewing large numbers of frames to ensure accuracy [2, 7, 12, 24]. For instance, 12 minutes of recording can generate approximately 1,500 fixations, taking around 60 minutes to analyze [2, 7]. Time-consuming analysis can also occur with remote eye-trackers when metrics are not automatically generated by the accompanying software [23]. Eye-tracking studies can also be cost-intensive, as the high price of eye-trackers may limit their widespread adoption in maritime research [12, 13].

3.5.2 Challenges in Eye-Metric Interpretations

Interpreting eye-tracking data can be difficult due to the inherent ambiguity of eye metrics. Fixations may not accurately reflect cognitive processes, as attention can be directed elsewhere than the point of gaze [4]. Certain eye movements, particularly backtracks, are difficult to interpret because they can signal various cognitive states depending heavily on context [7]. Pupil dilation can be influenced by participants' expectations, complicating assessments of mental workload [11]. Similarly, fixation duration can be affected by the time of day, posing challenges for gaze-pattern analyses [14]. Current eye-tracking methods also struggle to distinguish between simultaneous mental processes such as stimulus perception and comprehension [23].

Although eye-tracking data can quantify mental workload, they may not always provide the most accurate measurement. Eye metrics are sensitive to changes caused by time pressure but less responsive to variations from task complexity [21]. Likewise, fixation counts and durations can be less sensitive than subjective assessments or heart-rate variability when evaluating workload [33].

Individual variability further complicates the interpretation of eye-tracking data. User-specific data may be necessary to ensure the accuracy of human fatigue models, likely due to inherent differences in eye metrics across individuals [15]. This variability also limits the reliability of average pupil area as an indicator of workload [30], and differences in behavior during simulations can introduce inconsistencies that challenge data interpretation [36].

3.5.3 Technical Limitations of Eye-tracking Devices

Eye-tracking devices may suffer from technical limitations that lead to data loss. Out-of-frame gazes and rapid eye movements can result in missing data, as current devices are not always sensitive enough to capture these quick actions [7, 22, 27, 29, 36]. Additionally, the use of eyeglasses can interfere with the recording process, producing poor data quality [38].

3.5.4 Experimental & Environmental Challenges

Eye-trackers can affect the ecological validity of maritime research by altering participants' natural behavior, causing discomfort, or influencing psychological states [7, 17, 25]. Limited battery life and the need for charging cables can exacerbate these issues, and the use of binoculars may become awkward for participants wearing eye-trackers [7]. Variations in light intensity, display lighting, and screen viewing distance can also reduce measurement accuracy and affect pupil-related metrics [7, 9, 17, 36].

4 Discussion

4.1 Overview of the Results

Table 12 shows the overview of the findings made by this review.

4.2 Limitations of Existing Studies

Two notable limitations should be considered when interpreting the findings of the reviewed studies. First, most of the studies were conducted with limited sample sizes, which may limit the generalisability of their conclusions. Second, the majority of the studies relied on either immersive or non-immersive simulation environments rather than real-world settings, which may influence the ecological validity of the results. The distribution of studies by sample sizes is presented in Table 13, and the distribution by environmental setups is presented in Table 14.

Table 12 Review's Overview

	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]	[29]	[30]	[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38]	Total
RQ1																																						
Mental Workload										○						○				○				○					○			○	○					7
Scan Strategies & Gaze Patterns		○			○		○	○					○														○								○		○	8
Training Improvement	○			○								○					○						○								○							6
Human-Machine Interfaces						○			○										○						○									○				5
Fatigue & Vigilance Assessment														○				○				○						○										4
Situation Awareness											○				○						○					○												4
Other			○																											○						○		3
RQ2																																						
Eye Trackers																																						
Mobile	○				○	○	○	○	○	○	○	○	○		○	○	○	○	○		○		○	○	○	○	○		○	○	○	○	○		○	○	○	29
Remote		○	○	○										○						○		○						○						○				8
Experimental Setups																																						
Operation-based	○				○	○	○	○		○	○		○		○		○	○			○		○			○	○		○	○	○	○	○		○	○	○	23
Screen-based		○	○	○								○		○		○			○	○		○		○	○			○						○				13
Hybrid									○																													1
RQ3																																						
Research Type																																						
Exploratory Research	○	○						○		○	○	○	○							○	○											○			○		○	12
Predictive Modeling					○									○		○		○				○		○		○		○	○	○			○					11
Usability Testing			○			○			○										○				○		○						○					○		8
Method Development				○			○								○		○										○							○				6
Eye Metrics																																						
Dwell			○			○	○	○	○																										○			6
Fixation	○	○	○		○		○				○	○	○		○	○	○		○	○	○	○	○	○	○	○		○	○	○		○	○	○		○		26
Saccade	○		○			○	○									○				○	○			○		○		○		○		○				○		13
Blink Rate/Duration	○							○								○				○				○					○									6
Pupil Dilation								○		○			○			○		○			○			○		○		○	○				○					7
Heatmap Interpretation											○	○							○		○				○	○										○		7
Scanmap Interpretation							○								○						○				○	○	○	○										7
Other		○	○	○										○																	○						○	6
RQ4																																						
Safety & Human Error					○		○	○					○	○		○		○				○		○		○	○	○	○				○				○	15
Training & Assessment	○	○		○						○	○	○			○		○			○	○		○							○	○	○						14
Interface & System Design						○			○										○						○									○		○		6
Decision Making			○																																○			2
RQ5																																						
Resource Intensive	○					○					○	○										○	○															6
Data Interpretation Challenges		○	○			○				○			○	○						○		○							○			○			○			11
Devices' Technical Limitations		○				○															○					○		○							○		○	7
Experiment & Environment Issues						○		○								○								○											○			5

Table 13 Studies and Their Corresponding Sample Sizes

Sample Sizes	Studies
1 – 29	[2], [7], [8], [10], [11], [13], [14], [15], [16], [17], [18], [19], [20], [22], [23], [24], [25], [26], [27], [29], [30], [32], [33], [38]
30 – 59	[3], [9], [12], [28], [34], [35], [36], [37]
60 – 99	[4], *[5], [31]
100+	[21]

* The total number of participants involved in five different experiments conducted by [5] is 69.

* [6] did not explicitly report the number of participants in their study; thus, excluded from the list.

Table 14 Studies and Their Corresponding Environmental Setups

Environmental Setups	Studies
Non-immersive Simulations	[3], [4], [5], [13], [15], [17], [20], [21], [23], [25], [26], [29], [35]
Immersive Simulations	[2], [6], [10], [11], [12], [16], [18], [19], [22], [24], [27], [28], [30], [31], [32], [33], [36], [37]
Actual Setups	[7], [8], [9], [14], [34], [38]

4.3 Limitations of Review Processes

This review has several limitations. First, the screening was conducted solely by the first author, ensuring methodological consistency but preventing assessment of inter-rater reliability. Second, only studies in English were considered, potentially excluding relevant findings in other languages. Third, the search terms and strategies may not have captured all relevant studies, particularly those using different terminology. Fourth, only peer-reviewed studies were included, which may have omitted useful insights from industry reports or grey literature, though this was done to maintain academic rigor. Finally, the review focused primarily on merchant shipping, excluding findings from adjacent fields deemed inapplicable to merchant shipping.

4.4 Research Gaps

Focusing on the major stakeholders (i.e., deck officers, engineers, VTS operators, and MASS operators), three notable research gaps were identified. First, while studies on deck officers have predominantly examined navigational tasks, none have addressed cargo operations. Second, no studies on engineering operations have employed immersive simulations or actual operational setups, nor have any involved practicing professionals. Third, no research on VTS and MASS operators has utilized actual operational setups.

4.5 Implications of the Results

The findings of this review have several practical and methodological implications for different stakeholders. For researchers, the results can inform the design of future eye-tracking–based studies by guiding the choice of appropriate eye-tracker types (e.g., remote vs. mobile), selection of relevant eye-tracking metrics, and identification of underexplored research areas. This review also enables researchers to anticipate potential benefits and limitations, thereby improving study validity and reliability.

For maritime educators, insights from studies focused on training improvements can be leveraged to design more effective training materials and assessment tools. For engineers and designers—such as nautical chart developers, navigational equipment interface designers, and bridge layout planners—findings from usability studies provide guidance on using eye-tracking data to optimize visual information placement, reduce cognitive workload, and create designs that are both intuitive and effective. Overall, eye-tracking technology holds significant potential to enhance the safety and efficiency of maritime operations.

5 Conclusion

Eye movement research has a history spanning more than a century, and the advent of video-based eye-trackers has significantly accelerated its application in maritime contexts. This technological advancement has enabled the exploration of diverse research themes through a wide range of eye-tracking metrics. Existing studies consistently demonstrate the strong potential of eye-tracking technologies to complement conventional research methods, particularly in assessing the cognitive states of maritime professionals and enhancing MET curricula. However, important limitations remain, especially regarding the interpretation of eye-metrics and the technical constraints of current devices. By synthesizing the existing body of work, this review aims to provide a valuable resource for maritime researchers, educators, and designers, supporting more informed and effective use of eye-tracking technologies in future studies and applications.

Funding: This paper did not receive any external funding.

Conflict of Interest: The authors declare no conflict of interest.

Author Contributions: Research/Writing/Data Collection/Data Curation/Methodology: Khairul Izzati bin Kamarumtham; Verification/Review and Editing: Thuta Kyaw Win; Verification/Review and Editing: Tatsuro Ishida Supervision/Final Approval: Koji Murai.

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Appendix

Paper	RQ1	RQ2	RQ3	RQ4	RQ5
[2]	Training Improvement	- Glasses-type - Operation-based	- Exploratory Research - Fixation, Saccade, Blink Rate	Enhanced Training and Assessment	Resource Intensive
[3]	Scan Strategies & Gaze Patterns	- Tower-mounted - Screen-based	- Exploratory Research - Fixation, Smooth Pursuit	Enhanced Training and Assessment	Challenges in Eye-Metric Interpretations, Technical Limitations of Eye-tracking Devices
[4]	Decision Making	- Table-mounted - Screen-based	- Usability Testing - Dwell, Fixation, Saccade, Number of Transitions	Improved Decision-Making Processes	Challenges in Eye-Metric Interpretations
[5]	Training Improvement	- Face Analysis Software - Screen-based	- Method Development - Gaze Vector	Enhanced Training and Assessment	(Not specified in the study)
[6]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Predictive Modeling - Fixation	Improved Safety and Prevention of Human Error	(Not specified in the study)
[7]	Human-Machine Interfaces	- Glasses-type - Operation-based	- Usability Testing - Dwell, Saccade	Improved Interface and System Design	Resource Intensive, Challenges in Eye-Metric Interpretations, Technical Limitations of Eye-tracking Devices, Experimental & Environmental Challenges
[8]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Method Development - Dwell, Fixation, Scanmap Interpretation, Saccade	Improved Safety and Prevention of Human Error	(Not specified in the study)
[9]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Exploratory Research - Pupil Dilation, Blink Rate, Dwell	Improved Safety and Prevention of Human Error	Experimental & Environmental Challenges
[10]	Human-Machine Interfaces	- Glasses-type - Hybrid	- Usability Testing - Dwell	Improved Interface and System Design	(Not specified in the study)
[11]	Mental Workload	- Glasses-type - Operation-based	- Exploratory Research - Pupil Dilation	Enhanced Training and Assessment	Challenges in Eye-Metric Interpretations
[12]	Situation Awareness	- Glasses-type - Operation-based	- Exploratory Research - Fixation, Heatmap Interpretation	Enhanced Training and Assessment	Resource Intensive
[13]	Training Improvement	- Glasses-type - Screen-based	- Exploratory Research - Fixation, Heatmap Interpretation	Enhanced Training and Assessment	Resource Intensive
[14]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Exploratory Research - Fixation, Pupil Dilation	Improved Safety and Prevention of Human Error	Challenges in Eye-Metric Interpretations
[15]	Fatigue & Vigilance Assessment	- Table-mounted - Screen-based	- Predictive Modeling - Gaze Velocity	Improved Safety and Prevention of Human Error	Challenges in Eye-Metric Interpretations
[16]	Situation Awareness	- Glasses-type - Operation-based	- Method Development - Fixation, Scanmap Interpretation	Enhanced Training and Assessment	(Not specified in the study)
[17]	Mental Workload	- Helmet-type - Screen-based	- Predictive Modeling - Pupil Dilation, Blink Rate, Fixation, Saccade	Improved Safety and Prevention of Human Error	Experimental & Environmental Challenges
[18]	Training Improvement	- Glasses-type - Operation-based	- Method Development - Fixation	Enhanced Training and Assessment	(Not specified in the study)
[19]	Fatigue & Vigilance Assessment	- Glasses-type - Operation-based	- Predictive Modeling - Pupil Dilation	Improved Safety and Prevention of Human Error	(Not specified in the study)
[20]	Human-Machine Interfaces	- Glasses-type - Screen-based	- Usability Testing - Fixation, Heatmap Interpretation	Improved Interface and System Design	(Not specified in the study)
[21]	Mental Workload	- Table-mounted - Screen-based	- Exploratory Research - Blink Rate, Fixation, Saccade	Enhanced Training and Assessment	Challenges in Eye-Metric Interpretations
[22]	Situation Awareness	- Glasses-type - Operation-based	- Exploratory Research - Fixation, Saccade, Pupil Dilation, Heatmap Interpretation, Scanmap Interpretation	Enhanced Training and Assessment	Technical Limitations of Eye-tracking Devices
[23]	Fatigue & Vigilance Assessment	- Table-mounted - Screen-based	- Predictive Modeling - Fixation	Improved Safety and Prevention of Human Error	Resource Intensive, Challenges in Eye-Metric Interpretations

Paper	RQ1	RQ2	RQ3	RQ4	RQ5
[24]	Training Improvement	- Glasses-type - Operation-based	- Usability Testing - Fixation	Enhanced Training and Assessment	Resource Intensive
[25]	Mental Workload	- Helmet-type - Screen-based	- Predictive Modeling - Pupil Dilation, Blink Rate, Saccade, Fixation	Improved Safety and Prevention of Human Error	Experimental & Environmental Challenges
[26]	Human-Machine Interfaces	- Glasses-type - Screen-based	- Usability Testing - Fixation, Heatmap Interpretation, Scanmap Interpretation	Improved Interface and System Design	(Not specified in the study)
[27]	Situation Awareness	- Glasses-type - Operation-based	- Predictive Modeling - Fixation, Saccade, Pupil Dilation, Heatmap Interpretation, Scanmap Interpretation	Improved Safety and Prevention of Human Error	Technical Limitations of Eye-tracking Devices
[28]	Scan Strategies & Gaze Patterns	- Helmet-type - Operation-based	- Method Development - Scanmap Interpretation	Improved Safety and Prevention of Human Error	(Not specified in the study)
[29]	Fatigue & Vigilance Assessment	- Table-mounted - Screen-based	- Predictive Modeling - Fixation, Saccade, Pupil Dilation, Scanmap Interpretation	Improved Safety and Prevention of Human Error	Technical Limitations of Eye-tracking Devices
[30]	Mental Workload	- Headband-type - Operation-based	- Predictive Modeling - Blink Rate, Fixation, Pupil Dilation	Improved Safety and Prevention of Human Error	Challenges in Eye-Metric Interpretations
[31]	Team Performance	- Glasses-type - Operation-based	- Predictive Modeling - Fixation, Saccade	Enhanced Training and Assessment	(Not specified in the study)
[32]	Training Improvement	- VR Headset - Operation-based	- Usability Testing - Gaze Pattern	Enhanced Training and Assessment	(Not specified in the study)
[33]	Mental Workload	- Glasses-type - Operation-based	- Exploratory Research - Fixation, Saccade	Enhanced Training and Assessment	Challenges in Eye-Metric Interpretations
[34]	Mental Workload	- Glasses-type - Operation-based	- Predictive Modeling - Pupil Dilation, Fixation	Improved Safety and Prevention of Human Error	(Not specified in the study)
[35]	Human-Machine Interfaces	- Table-mounted - Screen-based	- Method Development - Fixation	Improved Interface and System Design	(Not specified in the study)
[36]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Exploratory Research - Dwell	Improved Decision-Making Processes	Challenges in Eye-metric Interpretations, Technical Limitations of Eye-tracking Devices, Experimental & Environmental Challenges
[37]	Trust in Automation	- Glasses-typ - Operation-based	- Usability Testing - Fixation, Saccade, Heatmap Interpretation	Improved Interface and System Design	(Not specified in the study)
[38]	Scan Strategies & Gaze Patterns	- Glasses-type - Operation-based	- Exploratory Research - Gaze Pattern	Improved Safety and Prevention of Human Error	Technical Limitations of Eye-tracking Devices