Visualization in Maritime Navigation: A Critical Review

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Abstract. Innovations in navigation technologies are inducing subtle transformations in the navigator role and navigation processes. Thus, research on maritime navigation, entails the need to further study the designs of all technological artefacts that are or might be used in navigation, and specifically those that involve Human Computer Interaction. To the best of our knowledge, no systematic review about maritime navigation visualization has been carried out. The objective of this review is to fill this gap, by classifying new and innovative ways for the visualization of maritime navigation information. Recent findings on visual attention, offer new strategies and solutions for the representation of navigation information. Operators' visual attention can be largely improved through mitigation of cluttering effects or by guiding their attention. This review of visual attention also highlights the importance of systematic contextual research to understand all the interactions and processes that happen in the maritime navigation domain.

Keywords: Human-systems integration · Maritime navigation · Visual attention · Visualization

1 Introduction

As part of a research assessing navigational performance within the e-navigation concept, a review of the state of the art in information visualization was undertaken. Research over maritime navigation control processes, entails the need to study the developments or designs of all the technological artefacts that are or might be used, and specifically how humans interacts with them, as pointed out by Flach in [1]. Consequently, the main objective of this review is to identify innovative ways for the visualization of navigation information, within the ship domain.

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Among the theoretical views presented in the selected literature, this study takes into consideration the overarching elements, such as the navigation team, individuals and technologies, anticipated e-navigation solutions and the user's perspective. Therefore, it provides an important contribution to the existing research on technology-driven directions in the fields of visualization, computer graphics and cartography. Previous studies already addressed elements of this work, such as the comprehensive review on information visualization in the maritime domain, done by Davenport and Risley [2], listing suggestions about human factors, visualization requirements and collaborative visualization systems. They also identified new mapping solutions and display technologies, pointing out some issues such as lack of automation. Even though it reflects the use of similar data and information display, the study was not focused in maritime navigation, being mainly motivated by the requirements of maritime surveillance systems, without referencing specific design solutions. Another research applies spatial cognition in the design of a navigation system, but not in the maritime domain [3]. This work will then transfer the locus of attention to the shipborne systems supporting navigational functions.

Thus, the first part of this study focuses on the classification of pertinent topics drawn from the navigation processes and the context of maritime navigation. This conceptual analysis is followed by an explanation of the methodology and selection systematization criteria of the publications. Subsequently, the discussion embraces a synthesis of the findings related to visual attention and some reflections over their application in the light of the maritime navigation processes. Finally, we present derived conclusions, new research questions and some proposals for further exploration.

2 Conceptual Model of Maritime Navigation

Over the last two decades, the navigators have seen huge changes in the bridge settings, due to the extremely fast pace in the assimilation of new technologies. These changes are inducing silent transformations in the navigator role, which demands a review of the maritime navigation process [4–7]. More recently, automation, broad band communications and internet supported the probable operations of remote and unmanned vessels bringing additional challenges [8]. This trend in maritime navigation technology, highlighted in Fig. 1, has open-up a discussion on how to redefine the way ships are operated and designed. Despite the common acceptance of the advantages brought by digital information and computing technology, the overall complexity of technological support systems and regulatory framework for marine navigation emphasized the needs for new system design. This effect of amplification has been identified as an important driver of Cognitive System Engineering (CSE) development [9].

The role of the navigator is shifting to tasks more related with planning and monitoring, execution and surveillance are being undertaken by automated systems such as autopilot or automatic detection and tracking RADAR (ARPA - Automatic Radar Plotting Aid). Those functions fit into the second stage of human machine dependency (supervisory control) [12]. The third stage – fully automatic control – would correspond to unmanned vessels operations.

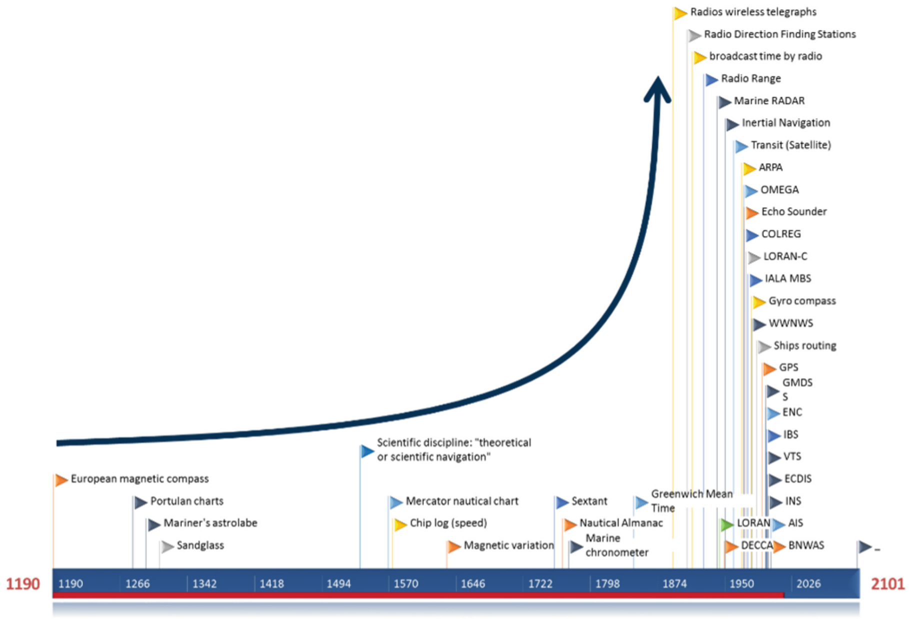

Fig. 1 Time line visualization of the trend in maritime navigation technologies and techniques

This alteration in the navigation tasks are stressed by the huge amount of data and information provided by on-board sensors, databases and shore based maritime services, leading to rising apprehensions about the workload and its effects on situation awareness and decision making [10–13]. Bainbridge [14] identified several automation glitches, such as over reliance, trust and feedback in human-machine collaborations, human drop of motivation and skills when engaged in monitoring tasks. The relevance of automation feedback and representations of its behaviour was highlighted in a ship the grounding study [15]. The same study points out the need for changes in the information systems to present new forms of highlighting changes and events, supporting the anticipation of changes, and facilitating the cognitive work engaged in the search and scanning in the displays.

Maritime navigation turned out to be a very complex and large-scale socio-technical system comprising human and man-made entities that interact with each other and operate in a rough environment [16, 17]. Improving the maritime navigation performance, requires the understanding of how the process works and its context. Therefore, we need to address this problem as a joint human-technological activity. Some challenges were identified by Klein *et al.* [18] for the success of human-agent team activities, comprising issues like mutual **predictability**, **common ground**, **visible status** and **intentions**, **attention management**, **collaboration** and **negotiation**. The thinking, computation and the decision-making processes are no longer only dependent of the operator himself, but are also socially distributed among the elements of the team, it is happening in the individuals and the cognitive tools of the sociotechnical systems [19]. To develop a collaborative spatial decision-making tool, Antunes et al.

[20] overviewed several decision models to derive six different requirements, the **support of perception**, **retention**, **knowledge externalization**, **divergent/convergent activities**, **recognition** and **task/pattern management**. The collaborative view of this human-technological system leads to the assumption of an ecological perspective, where the navigation function is directed by the joint human-agent system, in opposition to the traditional navigator egocentric design.

In the most common manual of maritime navigation [21, 22], we may identify the key navigation tasks: **setting objectives**, **planning**, **execution**, **monitoring**, and **revising or adapting the plan**. From a different view, Jul and Furnas [23] proposed a navigator model which considers the following nonlinear tasks: **setting a goal**, **selecting a strategy**, **collecting information**, **perception**, **assessing**, **creating a cognitive map** and **moving**. The last four tasks represent the wayfinding/motion loop. Darken and Peterson [24] defined wayfinding as the cognitive element of navigation, involving the **formation of strategies** and **tactic** that will guide the movements. The development and use of the cognitive map are an essential element of the wayfinding. In this view, they consider navigation as the aggregate task of wayfinding and motion. Bjerva and Sigurjónsson [25] proposed another concept of wayfinding and suggested that it comprises three steps: **cognitive mapping**, **wayfinding plan development**, and **physical movement**. Based on observations of pilots' mental workload, Westrenen [26] proposed a navigator model with a three-stage decision model, comprising **tracking**, **short-term planning** and **long-term planning** behaviour. In this view, long-term planning concerns mostly with the voyage planning, prior to sailing, and can be associated with the previous concept of goals setting and strategy selection. Short-term planning, comprises local observation and information collection necessary to make decisions over the control of the vessel. Tracking corresponds to the assessment of the movement and correlation with the initial plan.

In the view of control theory, distributed control emerge from the increased interaction between the agents, which supports self-organization and adaptability, when facing uncertainty or unpredicted constraints [27, 28]. Time and predictability are the major determinants of controlling system [9], thus in situations of low predictability and available time we will find a reactive decision type, where the operator responds without having foreseeing the events.

The conceptual navigation model adopted for this study may be visualized in Fig. 2 (a). It comprises the three-main functions, forming a goal, defining strategies and moving. Several nonlinear tasks are required in each stage and, all of them, have deliverables (goals, plan and control actions over ship). To support the categorization of visualization factors, the process of navigation is contextualized in the work space, Fig. 2(b), and available time, Fig. 2(c), together with expected control modes, Fig. 2(d), cognitive and decision making processes, Fig. 2(e). As an example, while sailing, the navigator tries to minimize reactive decision (i.), as they are not thought, they are usually linked to emergency situations and can only be reinforced thru experience and training. Since it is impossible to eliminate all the uncertainties, it might be worth to better prepare the ship for those events. Thus, a sound planning is the first mitigation measure (ii.), supported by cognitive process that helps to build a cognitive map of the physical voyage. At the same time, several alternatives are considered and tested. This process will further support the perception and understanding of the real world (iii.), and control is based on planned responses or projected events. Therefore, information systems, should be design to support the identified cognitive and decision-making processes, considering the navigation function, context and available time. For instance, observing Fig. 2, we can see that in the most front end stage, when acting in the conduction of the ship, events are occurring in the bridge and typical control modes are reactive and proactive. These control modes require continuous attention to stimulus and the operator must react in short time. From this case, we may argue that by enhancing attention abilities we strengthen the reaction possibilities. We may also focus on higher stages processes, such as enhancing the estimation and understanding cognitive processes, so the operator will use the proactive control mode, based on predictions that support better decisions.

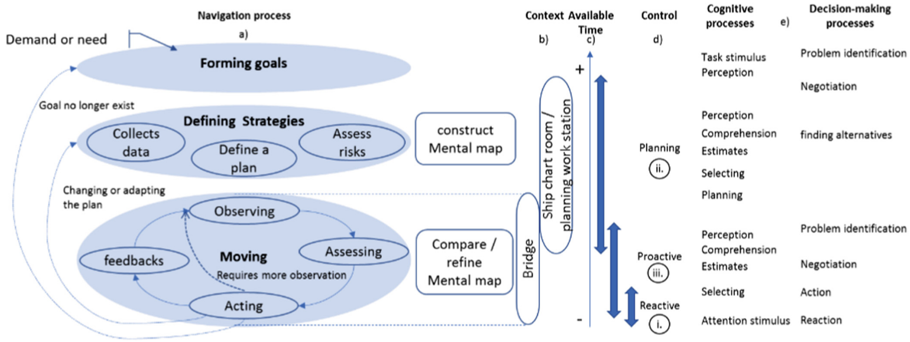

Fig. 2 Identifying the cognitive and decision-making processes within the navigation functions

3 Methodology

The literature research applied in this review was conducted in several databases, namely SCOPUS, Science Direct, Springer Link, EBESCOhost and ResearchGate. The articles were selected based on their relevance to visualization in the navigation and orientation domains. The following search terms were used: visualization, visual attention, visual perception, memory workload, cognitive workload, visual search, 3D visualization. Due to the large amount of results, additional keywords combinations were made with: wayfinding, navigation, orientation, map, decision-making, situation awareness. Studies in eNavigation domain and related with these areas were also retrieved. Finally, a comprehensive search was performed in a selection of conference proceedings over the last 5 years (Symposium on Information Visualisation - InfoVIS, International Conference Information Visualisation - IV).

Inclusion and exclusion criteria were driven by criteria such as: scientific Quality (theoretical basis, with empirical data set), scientific Context (references to related work), significance: originality, quality of presentation (clarity, illustrations); qualifications (credibility of authors and institutions), Studies addressing the relevant topics, published in English and in the recent years. To overcome the omission of significant studies, a selection of previous reviews that address the focus of the review question was made, providing not only a synthesis of the research already undertaken, but also an initial guidance for this follow up review.

Very few studies were conducted in the context of maritime domain, on other hand more were find in the field of air navigation. Apart from the above criteria, no review protocol was registered. The results were combined in the categories listed in Table 1, that were drawn from the navigation, cognitive and decision making processes illustrated in Fig. 2. This paper presents the analysis on the *Visual Attention* category.

Table 1. Categories and associated concepts used to guide de classification.

Cat ID	Category	Associated concepts
CAT1	Visual attention	Uncertainty, guided attention, visual search
CAT2	Visual memory	Information overload
CAT3	Visual perception	Strategies to predict and identify
CAT4	2D/3D	Space-time visualization, multi-attribute
CAT5	Wayfinding	Visualization in support of, strategies
CAT6	Planning	Creation mental map, learning, experience
CAT7	Multiple task	Support of, collaborative decision process

4 Results and Discussions

The results of the 24-selected sources, most of them published in journals (20), are summarized in Table 2. Publication years varies from 1980 to 2016, averaging 2008, and the majority are from the field of psychology and cognition, with some from computer vision and cartography. The dominant paradigm is experimental, together with four meta-analysis and few qualitative studies. Metrics are mostly associated with performance evaluation, measuring reaction times (RT), search times (ST) and target detection (TD). The author (first author) familiarity with maritime navigation helped in the identification and interpretation of the relevant consequences of the findings presented in the literature review. It is acknowledged that not all the theoretical and relevant publications may be presented, however we believe that this selection provides sufficient ground to support the claim of new design requirements in the visualization of navigational information and decision support for navigation control.

The viewers' role in his perception of visual information depends critically on where his attention is focused and what is already in his mind prior to viewing an image [29]. Additionally, human vision rapidly and automatically categorizes visual images into regions and properties (preattentive processing). Treisman's Feature Integration Theory [30], claims that if the target has a unique feature, one can simply access the given

Table 2. Integrated summary of the selected publications

Cit.	Year	Discipline, field	Methodology	Context
[28]	2012	Computer Vision & Pattern recognition	Meta-analysis	Attention and visual perception survey
[29]	1980	Psychology, cognition	Quant., 9 experiments Perfor. eval., ST + RT	Feature-integration theory hypothesis
[30]	1989	Psychology, cognition	Quant., 4 experiments Accuracy of TD & RT	Efficiency of visual selection, T-N similarity and N-N similarity
[31]	1994	Psychology, cognition	Computer simulation, literature review	Model of visual search, Guided search
[32]	2007	Psychology, cognition	Quant., 2 experiments Perfor. evaluation	Boolean map hypothesis
[33]	2001	Psychology, cognition	Quant., 3 experiments Perfor. evaluation	Visual attention, circular spots of various sizes
[34]	2016	Psychology, cognition	Quant., 5 experiments Perfor. evaluation	Visual search for target object in cluttered scenes
[35]	2012	Cognition, behaviour	Qualit., 1 experiments Perfor. Obs. + gaze	Ground traffic control decision support system
[36]	2004	Psychology, cognition	Meta-analysis	Review of guiding attributes for deployment of visual attention
[37]	2007	Computer vision & pattern recognition	Meta-analysis	Visual attention, Taxonomy of Clutter Reduction
[38]	2008	Psychology, cognition	Quant., 1 experiments Perfor. evaluation, RT	Color and location in a visual search
[39]	2015	Cartography	Descriptive - Quant.	Map Viewer Design for Seniors
[40]	2012	Cartography	Quant., modelling (computer science)	Map design, automatic symbolisation
[41]	2016	Cartography	Modelling (computer science)	Map design, distortion perception
[42]	2011	Visualization	Meta-analysis	Color use in visualization, survey
[43]	2010			

(*continued*)

Table 2. (*continued*)

Cit.	Year	Discipline, field	Methodology	Context
		Psychology, cognition	Quant., 3 experiments Perfor. evaluation	Visual search of low prevalence targets
[44]	2013	Psychology, cognition	Quant., 2 experiments Perfor. evaluation	Cognitive load, multiple displays
[45]	2012	Computer vision & pattern recognition	Quant., 3 experiments Perfor. simularion	Visual attention, feature type, layout impact on performance
[46]	2015	Computer Vision & Pattern recognition	Descriptive-Qualit., Metho. Case Study	Decision-making, uncertainty
[47]	2014	Computer vision & pattern recognition	Descriptive - Quant., Questionaire + 1 exper.	Visual attention, graphics analysis
[48]	2012	Cognition, behaviour	Quant., correlational analyses	Visual perception, spatial memory persuasive geocommunication
[49]	2016	Psychology, cognition	Quant., 2 experiments Perfor. evaluation	Visual attention, visual and semantic influences
[50]	2012	Psychology, cognition	Quant., 1 experiment Perfor. simulation	Visual attention assessment in HUD, methodology
[51]	2003	Psychology, cognition	Quant., 1 experiment Perfor. evaluation, RT	Visual attention, mapping spatial attention

feature map to see if any activity is occurring, it also suggests that the amount of difference between the target and the distractors will affect search time. Other studies revealed correlations of visual search with the type of task and the visualization settings [31], showing variations in search efficiency depending on the similarity of targets and non-targets. The Guided search theory [32] suggests that an activation map based on both bottom-up and top-down information is constructed during visual search, meaning that attention is drawn to peaks in the activation map that represent areas in the image with the largest combination of bottom-up and top-down influence. Based on this sights, the bottom-up activation depends on feature categorizations, whereas the top-down activation is driven by the viewer's goals when looking to an image in search for the required visual information. Boolean maps theory [33] considers that visual search comprises two stages: selection and access. In this view, the visual system selects some elements of a scheme, excluding the others, and proceeds for a deeper analysis by accessing additional details of the select elements. Finally, the ensemble coding theory [34] brings the idea that low-level vision can generate a quick summary of how simple visual features are distributed across the field of view. More recent experiments concluded that visual search of precisely known features are influenced by the presence of visually similar distractors due to limitations in selection and masking [35].

All these researches on visual processing, summarized in [29], gives us significant cues about how to govern the user's visual attention and the importance of task and contextual setting. Top-down approaches to guide operators' visual attention have been tested by a model based on heuristic decision making, to foreseen user's decision strategies [36]. The current navigational information displays (e.g. ARPA, AIS, ECDIS) provide a large collection of features, each with several and distinctive visual properties (e.g. colour, orientation, size), resulting in a complex visual representation. Hence, we should simplify the visualizations in regards to the users' task by minimizing visual confusion, this means for instance, adjusting the electronic charts symbols, depending on planning or monitoring tasks. While planning, the navigator has time to assess all the chart features, to set the route and safe boundaries in accordance with his risk assessment. On the other hand, while monitoring, he is firstly concerned on avoiding hazards and to follow the route plan, which suggest that we have two major sets of information: dangers and positioning/navigation features. Therefore, features belonging to each of this sets should share a coherent visualization structure, that would evolve as the operator moves for additional search to find a detailed target.

Among several object attributes, colour, motion, orientation and size are strong guides for the deployment of attention [37]. For many of them, the presence of a property is more readily detected than its absence, which might be relevant for the detection of moving target among stationary [37]. Additionally, visual search efficiency increases as a function of target–distractor difference and decreases as a function of distractor–distractor difference [31]. To address clutter in overcrowded displays, several mitigation strategies can be applied by manipulating the features' appearance, spatial distortion and animation [38]. The selection by colour in a multiple-item display, where location and colour information are independent from each other and equalized, is mediated by location information [39]. Yet, the attention to location seems to be equally influenced by colour and location cues. A study on maps colours, dark colours benefits the contrast of the map viewer content and elements, therefore improving the perception of the map contents. It also shown that long wave-lengths colours shortens the viewer's reaction times in colour perception [40].

Visualization of real time multidimensional data generates complex representations, as it may be found in ARPA radar displays, and it is critically increased when combined with other information layers (AIS or ECDIS). New properties of the guidance cues can emerge from the deliberate or unintended combination of attributes, inducing positive or negative variations in the operators' visual attention. On the bridge, most of the available information is geo-referenced, and the trends confirm that more data is becoming easily available, such as aerial photos, textual information, routing and passage plans, weather and oceanographic data. Integration of this data demands further considerations over the cluttering effects. The combination of several distinct objects in the same presentation must be reassessed differently from the traditional selection of different layers, each with its own visualization properties. Automatic symbolization methods were developed to address the needs for layer's integrations minimizing any data loss [41, 42]. All the features must be contextually and coherently merged to support and guide individual's visual attention. For instance, when supporting the perception of close situations, displays should provide a clear and prioritized view of all the hazards and dangers, blending features like depth contour, RADAR tracks and AIS information. Despite the different dimension of each feature, they are all hazards and this could drive the design of a common colour scales properties [43], to categorize their relative risk properties, e.g. time to closest danger.

One strategy to visualize large amount of information, has been using divided or several displays. This is more relevant when considering tasks involving search for low prevalence (LP) targets, i.e., that rarely occurs. Low target prevalence alters the behaviour of the operator and the implication of this phenomena are the viewer tendency to leave the search prematurely or to make motor or response errors. However it was found that no positive effect came by dividing up the display or by forcing the observer to slow down and correct errors [44]. In this view, it would be important to classify LP targets situations, like alarm cues, and study new designs to support their detection in time. Complementarily, it was demonstrated that simultaneous view is more appropriate than sequential view, further suggesting that the sequential view did not alleviate the divided attention problem, when we could suppose that sequential view would be more useful for monitoring tasks [45]. Viewers have an unconscious tendency to search for targets in novel locations in the display, as opposed to looking at locations that have already been examined [29]. Therefore, we could infer that this phenomenon could determine the size of displays used by operators.

Capacity limits of attention strongly affects the effectiveness of information visualizations, particularly the ability to detect unexpected information. Visual search experiments revealed that [46] search effectiveness can be increased by grouping, namely for oddball search, and reducing variety specially for demanding tasks. From these findings, we could again argue that same objects should be visualized differently depending on the user's task. It has profound implications in the way information is currently presented in bridge information's systems and subsequently in operator's effectiveness to extract information from them. Taking the example of ARPA displays, user's attention could be guided by grouping targets based on distinctive characteristics, like distance, CPA, TCPA or vessel type. Colour and flicker are attributes already used, but their effectiveness is reduced in congested displays, compelling operators to increase de RADAR scale and therefore losing the overall perspective. AIS data provides much more possibilities of manipulation due to the larger number of available dimensions, however the lowest integrity of this data recommends prudent evaluation of the integrated results, as they may cover-up erroneous data.

User's sense-making processes may induce cognitive biases in the process of visual perception, i.e., the type of representation may be subject to incorrect interpretations, particularly if the user is not familiar with the presented pattern [47]. Misinterpretations can emerge from clustering, completeness, anchoring and framing errors. One example that can be found in the bridge, is the representations of the same objects with different orientation schemes, such as AIS data in the ECDIS (north aligned) and in the radar display in head up mode. The mode error is found when the user unconsciously appropriates one of the visualisation schema, due to its greater perceived authority, to another which unwittingly does not fit. In what concerns the effects of interpretation of missing graphical data, it was found that higher degree of decision-confidence was achieved with the combination of emptiness and explanation [48]. Thus, rather than visualizing the last state or completing the data with some estimation form, it's better to provide a cue over the missing data. Additionally, map rhetorical styles influences the user trust in the data and confidence in answering questions about the data, which means that different rhetorical designs can help achieve different persuasive goals [49]. Moreover, it was demonstrated that visual attention is influenced by semantics, so among the visual qualifiers we need to ponder on the possible object meanings and how they might guide visual search [50].

Experiments have demonstrated that the locus of attention is symmetrically distributed around the viewer's point of fixation, leaving the peripheral area less observed [51, 52]. On-board, when observing the ECDIS or RADAR displays, the focus of attention is usually the own vessel, therefore noting that user's attention is around that point, we should think in means to represent prioritized targets near that area, so they get a higher chance to be spotted. Moreover, viewers can resume an interrupted search much faster than they can start a new search, due to the unconscious perceptual predictions they make about the target based on the partial information acquired during the initial glimpse of a display [29]. Additionally, based on the current display, users' domain knowledge may give expectations about where certain data might appear in future displays, improving viewer's ability to locate important data. Therefore, we should challenge the possibility to provide RADAR data representations with minimum necessity to change scales.

5 Conclusions and Future Work

This study is an important contribution to provide new insights in the analysis and understanding of cognitive processes involved in maritime navigation, opening new possibilities for human systems interactions. Regarding visual attention, several key issues were identified, both derived from both top-down and bottom-up visual processes. Displays sizes, sequenced windows, zooming tools and scale changes can impair visual attention. Guided attention effectiveness' depends mostly on the perceived user' task and contextualization of the represented objects. Finally, integration of several information layers raises the possibility of masking information, providing erroneous visual guidance or misperception, due to unrestricted cluttering effects or conflicting visual features' properties.

We recognize that many other factors affect the navigation process and not all issues remain in the visualization domain, thus these results should be integrated in a broader perspective when addressing the conceptualization and design of new maritime navigation systems. This perspective of visualization over the bridge systems, has shown that, among all the described constraints, it is essential to perform a systematic contextual research of the maritime navigation function, trying to understand all the interactions and processes that happen in this work domain. The other categories will be addressed in future publications and the concluding findings will be merged into a conceptual framework to assess vessels navigation performance.

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