Evaluation on Effectiveness of Advanced ECDIS to Maritime Navigators

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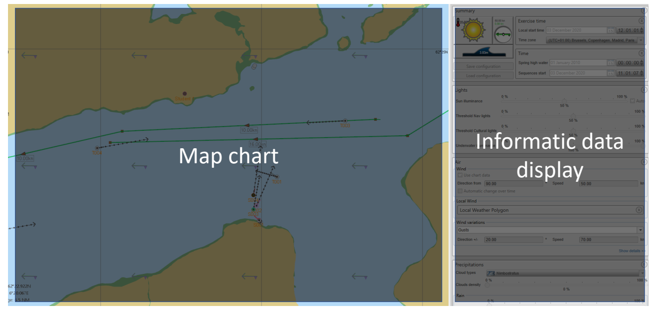
***Abstract*— With the development of new technologies, more updated tools are equipped onboard to help navigators make decisions and enhance sailing safety, among which the Electronic Chart Display and Information System (ECDIS) is one of the most pragmatic, general, mature, and also relentlessly advancing solutions. In this paper, the authors explore and evaluate the actual effectiveness of the ECDIS to maritime navigators by assessing the sailing performance. The analysis is conducted based on a collision avoidance task in a narrow and busy water channel. The assessment is realized by using a self-defined collision risk index, and meanwhile, the eye movement of navigators is tracked and recorded by wearable eye tracker glasses so that the visual attention is reflected and interpreted to understand the navigational process. The evaluation result shows that the ECDIS has a significant influence over the navigators' sailing performance and operating behavior. This research demonstrates the effectiveness of the ECDIS and indicates a way to study navigators' operational behaviors.**

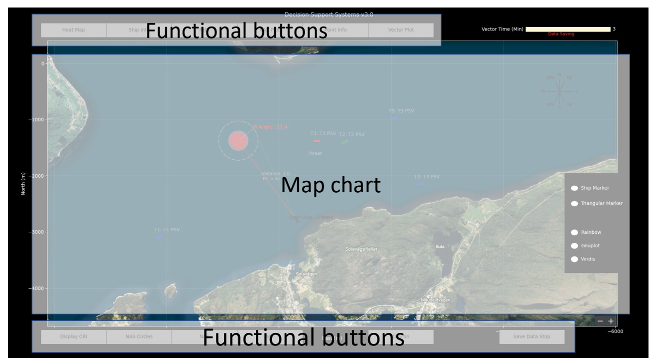
***Index Terms*—ECDIS; human-in-the-loop; eye tracking; maritime navigation; risk analysis.**

I. Introduction

Waterborne transportation plays an essential role in modern society, especially in the global trade sector, as over 95 % volume cargo is carried by assorted ships [1]. As the technological development over the decades, the human-machine interaction interface has been promoted, for example, from paper-based logbooks to the electronic archives, from nautical paper charts to electronic navigational charts (ENC), and in addition, there are other supplementary tools such as the automatic radar plotting aid [2]. It should be admitted that as the technological promotion improves the navigational environment and enhances sailing performance, navigators' operational logic and habits are also influenced to a certain extent [3]. As the operational interface gets complicated and data comes from multiple channels to navigators, navigating on such ship-bridge systems becomes complex. There are more visual areas of interest for navigators to pay attention to in order to select synthetically optimal maneuvering tactics. Therefore, we propose the study in this paper to explore how the ECDIS influences navigational performance based on a self-defined collision risk index and affects navigators' visual attention in terms of eye movement. This research is also within the research scope of maritime autonomous surface ships (MASS) at human-in-the-loop levels, which corresponds to MASS-I, II, and III [4] [5].



(a) Traditional ECDIS interface.



(b) Customized ECDIS interface (in this paper).

Fig. 1. Interfaces of different ECDISs.

The ECDIS, which displays information gathered from electronic navigational charts and real-time data from other signal channels, including the global navigation satellite system, automatic identification system, land-based and onboard radar, is one of the most crucial components of the modern ship-bridge system (illustrated in Fig. 1(a)) [6]. As the technical development on sensors and algorithms, the ECDIS can provide more calculated information, and elaborate functions based on the raw data input [7] [8]. In this study, a customized ECDIS (as shown in Fig. 1(b)) is engaged in the advanced ship-bridge simulator to provide informatic guidance and decision support to navigators. In this customized ECDIS, a collision-risk-index (CRI) based decision support system is graphically integrated to alert navigators on potential collision, which supports them to choose a proper way of evasion [9]. We compare navigators'

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sailing performance and behaviors in circumstances where the ECDIS system is enabled and disabled.

ECDIS-related research is conducted from multiple angles. From the technical development of ECDIS respect, there are studies with a specific target, for example, discussion on suitable ways of map projection for worldwide depiction in terms of distortion [10], integration of a fuzzy-theory based collision avoidance support system into the system [11], discussion the color scheme and symbols in the interface [12], using deep learning to fuse informatic graphs of ENC and radar images [13]. From the usability respect, there are studies on validation in terms of the position cross-checking on ECDIS according to conventional recommendations [14], discussion on the redundancy of positioning source on the system [15], and investigation on ECDIS-related marine accidents [16]. From the effectiveness respect, there are studies on comparing the performance difference on conventional and advanced bridges between navigators with different professional experience [17] and the performance difference between using ECDIS and paper-based charts [18]. The study in this paper focuses on validating the effectiveness of the advanced ECDIS system in comparison to the situation where only very fundamental functions are correctly working.

Using wearable eye tracker glasses to analyze navigators' behavioral logic and attention is a standard solution; there have been researchers working on analysis of visual attention features around the spell of critical operations [19], scanning patterns on a high-speed marine craft [20], using an eye tracker to compare navigators' and robotic solution on object detection [21], usability assessment of ECDIS [22] and integrated ship bridge [23], assessment of mental workload [24], and evaluation of maritime training process [25] [26]. In this paper, the authors use the eye tracker glasses to record and observe the visual attention difference in terms of advanced functions displayed on the ECDIS. This study also measures and compares navigational behaviors by using eye movement tracked data and relevant derived metrics.

In this paper, the authors design a specific collision avoidance operational task in the narrow and busy water channel and invite navigators to maneuver the ship. The experiments include two scenes according to the existence of advanced functions on the ECDIS. When the experiments are carried out, the navigators are asked to wear eye-tracker glasses to record their eye movement, which can reflect their visual attention. Next, collected sailing data are analyzed in terms of a collision risk index and with respect to the metrics of visual attention. Significant influence of the ECDIS is demonstrated in this study, and visual-attention-based navigator' behavioral analysis and performance evaluation methods can be referred to in further related studies.

The paper is organized as follows: Section II presents the proposed method in detail, including the over workflow, the experimental equipment, metrics to be used for risk analysis, and the experimental setup; Section III illustrates the results of the experiment and data collected, discusses the eye-movement based visual attention features, and analyzes the navigational performance in terms of the advanced ECDIS; At last, a conclusion, including summary, limitations, and future works, follows in Section IV.

II. Methodology

A. Workflow

The workflow of this paper is illustrated as shown in Fig. 2. The experiments are conducted in an advanced ship-bridge simulator which has a fixed seat configuration, a scene-projection wall, an ECDIS screen, a dashboard screen, and several control joysticks. Such configured ship-bridge system is often seen on high-speed catamarans. Navigators participating in the experiments are asked to wear a pair of eye-tracker glasses powered by Tobii Pro®. The eye-tracker glasses are equipped with a front camera to record the view of the wearer's sight and near-infrared illumination on the inner frame to model the wearer's eyes and track their movement, and then the eye movement is calibrated and synchronized to the view recorded by the front camera. The experiments have two channels of data output: one is from the eye tracker, and another is exported from the data interface of the ship-bridge simulator, which contains the own ship's (OS) sailing and maneuvering data and the traffic information, including target ships (TSs). Then two analyses, CRI-based sailing performance assessment and visual-attention-based behavioral analysis are implemented separately. While the CRI-based assessment helps to indicate some key time windows where collision risk is high, visual attention analysis can be implemented more specifically to those time windows. At last, a synthetical evaluation is given with respect to the fusion of the two channels.

B. Risk metric

In this study, a CRI is used as the risk metric, and it is calculated as:

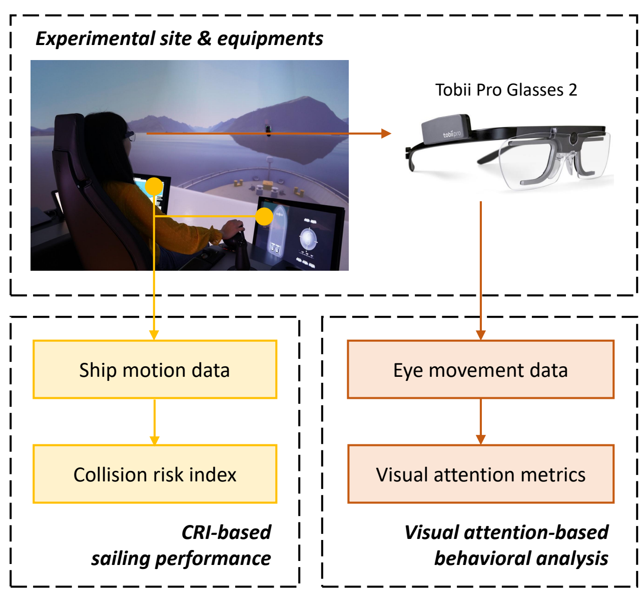


Fig. 2. Workflow of this work (Picture of Tobiipro glasses 2 is credtied to the official website to Tobii Pro®).

$$\mathrm{CRI} = \mathrm{W_{DIF}} \cdot \mathrm{DIF} + \mathrm{W_{dv}} \cdot \mathrm{d_v} + \mathrm{W_{rr}} \cdot \mathrm{rr}, \qquad (1)$$

where DIF, dv, and rr are denoted for the domain intersection factor, closest predicted distance, and Rick radius factor, while $\mathrm{W_k}$ represents the corresponding empirical weight. The details of the CRI explanation can be found in [9].

C. Visual attention assessment

1) Visual areas of interests (AOI): Visual AOI is a concept of a manually selected region with specific (research) interest. In this experimental configuration, three AOIs are selected according to the feature of collected data and expert recommendation as (also as shown in Fig. 3):

- AOI-I: scene-projection wall;
- AOI-II: the ECDIS screen;
- AOI-III: the dashboard screen.

2) Visual attention metrics: In this study, two visual attention metrics are used for assessment:

- Transition frequency f: the visual transition times between different AOIs in a specific time spell. The transition frequency reveals the activity level of the eye movement, i.e., a higher transition frequency implies that the navigator is fastly transitting his/her visual attention between different AOIs to closely monitor information from multiple channels so that the navigator gets aware of the situation in a big picture.
- Duration of fixation t: the gaze duration on a specific AOI. The length of the duration of fixation reflects how much the navigator is interested in an AOI at a specific gaze. The longer duration time means it takes longer time for the navigator to obtain information from the AOI and calculate the situation upon it. A derived term of duration of fixation is the total duration time, denoted as T, which is the total time the navigator keeps attention on a specific AOI during a complete experimental session. It can be calculated as $T_{\mathrm{AOI-j}} = \sum_{i=1}^{n} t_i$, where n represents the total times that AOI-j is visually visited in a complete experimental session.

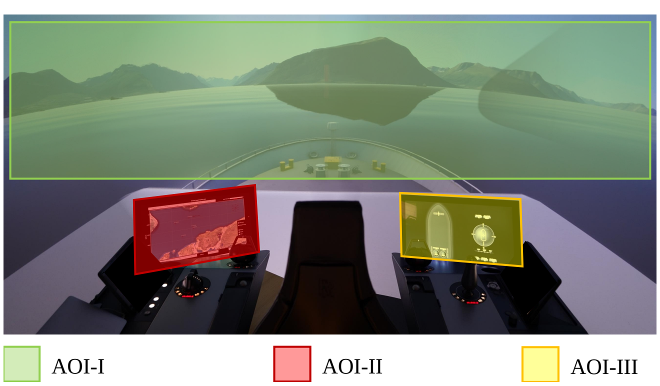


Fig. 3. Visual Areas of interests (AOIs) on the ship-bridge simulator.

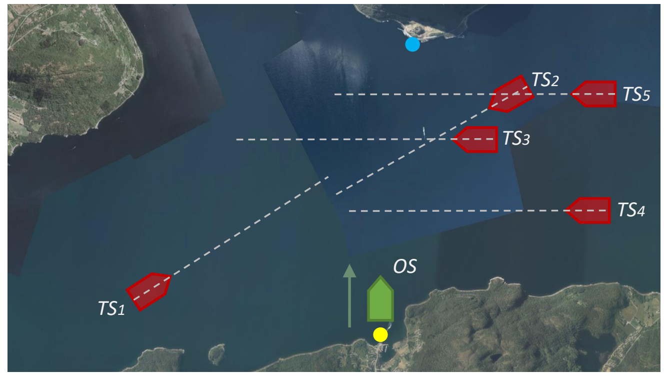


Fig. 4. Designed collision avoidance task scenario.

D. Experiment scenario & setup

The traffic layout of the designed collision avoidance task in the ship-bridge simulator is illustrated as shown in Fig. 5. There are four TSs are coming from the starboard side of the OS, while one TS comes from the portboard side of the OS. According to the International Regulations for Preventing Collisions at Sea (COLREGs), the OS shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the TS_{2-5}. While the TS_1 is added to distract the navigator's attention to assess the situation as a whole synthetically.

The scenario is implemented by navigators twice:

- the first trial is a partial ECDIS only with the ENC and the ships' positions, and without any additional information and calculated parameters;
- the second trial is a full ECDIS with distance at the closest point of approach (DCPA), time to the closest point of approach (TCPA), predicted route vector, CRI, and voyage information (speed and course) of the TSs in addition to the first trial.

This experiment setup expects to see how the ECDIS functionalities influence the navigational performance and navigators' attention.

III. Results & Discussion

A. Exampliary sailings illustration

First, we take an exemplary set of two trial sailings (as stated in Section II-D) for specific illustration to clarify the analysis process.

1) Collision risk analysis: The CRI curves along the two complete trial sailings are shown in Fig. 5. TS_1 which comes from the portboard side, remains its CRI at 0 with OS, which means there is no collision risk between these two ships, as they are at a far distance at their initial positions and the navigator chooses to sail in line with the COLREGs which will relentlessly enlarge the distance between two ships. For TSs coming from the starboard side of OS in this set,

- $\mathrm{TS}_{2,3,5}$: as advanced ECDIS functionalities are being enabled, it takes a longer time to handle the collision avoidance operation against these TSs. Moreover, it is clearly shown that the navigator inclines to take a higher

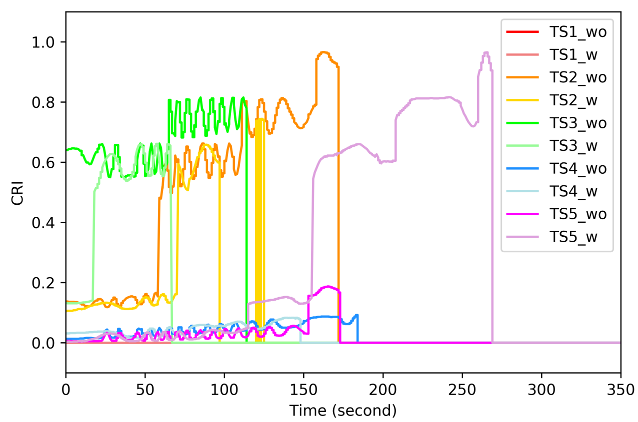


Fig. 5. CRI in a set of two trial sailings (TS_k_wo and TS_k_w respectively denote without and with advanced ECDIS functionalities enabled in the sailing).

risk of collision when maneuvering OS against TSs. In $TS_{2,3,5}$, the CRIs increases from 0.77, 0.66, and 0.19 to 0.96, 0.81, and 0.96 respectively. It suggests that the navigator is more confident in maneuvering when ECDIS provides necessary traffic information and calculated risk measurements.

- TS_4: since the initial distance between the two ships is long enough, the navigator chooses to pass from its front, which is not strictly compliant with COLREGs. However, the CRI shows that this tactic is a shallow risk.

It is comprehensible that the navigator inclines to choose a route with higher risk since it is assuredly calculated with complete ECDIS information. Nevertheless, why do durations of high-risk time against TSs become longer when using the full ECDIS? Clues can be found in the maneuvering details as shown in Fig. 6 in which the speed and course of OS are plotted. From Fig. 6, it shows that when ECDIS is enabled, the navigator is maneuvering in a milder way than without ECDIS. It can be inferred that with no ECDIS

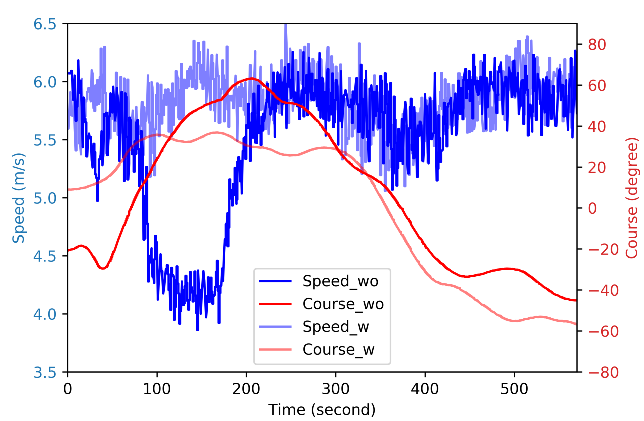


Fig. 6. Speed and course of OS in the set of two trial sailings (diluted lines are with ECDIS).

support, the navigator lacks the necessary information to calculate the route in advance and have to maneuver immediately as the situation occurs, and the excessive operational commands may help OS get over the collision risk very quickly at the cost of comfortability and stability. From another point of view, the navigator maneuvers more conservatively when there is no ECDIS by selecting a farther detour, which may also reduce the duration of high-risk time.

2) Visual attention analysis: As collision risk analysis distinguishes the maritime operations between the two trials and spells of high-risk time with respect to each TS can be located, we select these time spells as the time window to analyze the navigator's visual attention, including gaze and transition.

TABLE I

DURATION OF FIXATION FEATURES WHEN AGAINST TS_3

AOI No.	Scale (s)	Median (s)	Mean (s)	Total (s)
AOI-I				
wo.	[0.2, 7.8]	3.5	3.4	30.7
w.	[0.2, 12.5]	2.5	2.8	55.4
AOI-II				
wo.	[0.2, 0.8]	0.5	0.5	1.0
w.	[0.1, 5.5]	2.0	2.6	20.5
AOI-III				
wo.	[0.5, 4.2]	2.5	2.9	20.5
w.	[0.2, 6.5]	3.0	3.4	40.8

Table I shows the duration of fixation features in the spell of high-risk time against TS_3. The most conspicuous point is that when advanced ECDIS is disabled, the navigator rarely casts attention to AOI-II, which can be inferred that the ECDIS cannot provide the necessary information in this form. The mutual point between the two trials is that AOI-II always catches the most attention. The existence of advanced ECDIS does not significantly influence the proportion between AOI-I and III. From this time spell, we can conclude that advanced ECDIS has a noticeable impact on the navigator's visual attention during sailing and maneuvering.

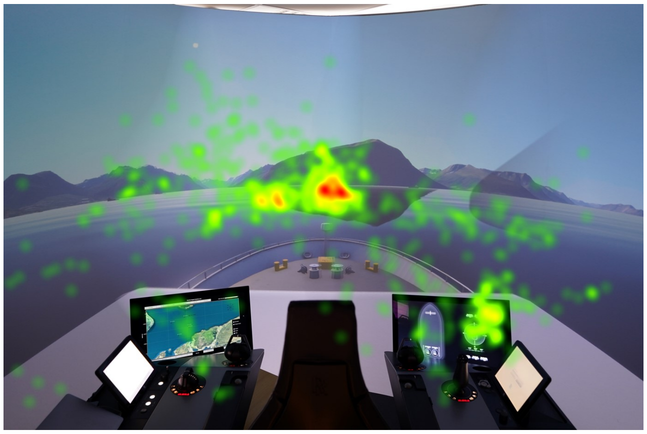
TABLE II

TRANSITION FREQUENCIES

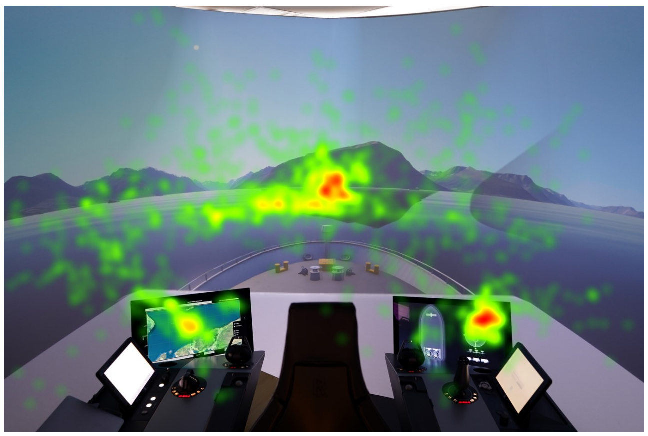
No.	I-II	I-III	II-III
TS_2			
wo.	4.0	16.0	-
w.	9.6	17.6	-
TS_3			
wo.	4.8	16.8	-
w.	7.2	12.8	0.5
TS_5			
wo.	-	6.0	-
w.	3.5	7.5	0.5

* times per minute

Table II shows the transition frequencies between every two AOIs regardless of transition directions (for example, from AOI-I to AOI-II and from AOI-II to AOI-I are counted



(a) Heatmap without advanced ECDIS functionalities.



(b) Heatmap with advanced ECDIS functionalities.

Fig. 7. Overall heatmaps of visual attention on AOIs in two trial sailings.

into I-II as a sum). It is remarkable that direct transition between AOI-II and III hardly happens, as the navigator prefers to even cast an eye on AOI-I for only 0.1-0.2 seconds instead of a direct transition. It may be due to the navigator wanting to fuse and calibrate the information obtained from AOI-II and III with AOI-I, where the navigator percepts the environment and traffic conditions on own visual sight. This particular behavior is worth further ergonomics research. Besides the transition II-III, it is found that the eye movement activity levels in the trial without advanced ECDIS are lower than the trial with the system. The transition happens the most frequently between AOI-I and III, which implies that the navigator monitors the maneuvering commands tightly, especially when dealing with the most critical collision avoidance task but without the advanced ECDIS (TS_3 wo).

Fig. 7 shows the heatmaps of visual attention without and with the advanced ECDIS. The heatmaps testify to the discoveries from Table I where AOI-II is rarely visually visited when advanced ECDIS is disabled. As the ECDIS is enabled, there is a re-distribution of the visual attention.

B. Statistics on visual attention

In total, we collected six sets of two-trial sailings, and the global statistical results are given as follows.

TABLE III
STATISTICS SCALES ON DURATION OF FIXATION FEATURES FOR COMPLETE SAILINGS

	Median (s)	Maximum (s)	Total (s)
AOI-I			
wo.	[4.3, 5.2]	[18.0, 24.0]	[278.0, 310.5]
w.	[4.4, 4.9]	[16.0, 23.5]	[240.7, 280.4]
AOI-II			
wo.	[0.5, 1.1]	[2.5, 5.5]	[5.0, 20.0]
w.	[2.8, 3.9]	[7.5, 9.0]	[98.5, 125.6]
AOI-III			
wo.	[3.7, 4.4]	[8.5, 10.2]	[225.8, 245.0]
w.	[3.8, 4.2]	[8.2, 12.0]	[196.8, 254.5]

In Table III, three featured values' scales, including median, maximum, and total duration, are listed. The statistics show a compliant result in line with the findings in the individual case: when advanced ECDIS is disabled, the navigator prefers to use visual sight to percept the environment directly, instead of getting the imperfect information from the partial ECDIS. The maximum in AOI-I can last very long, as the maximum usually happens at the tail of the sailing where the evasion of TSs has been addressed, and a distance remains to the destination; in this time spell, the navigator usually keeps the target their attention on AOI-I to percept the situation visually. An essential reason that may account for it is that not all types of ships are equipped with communication and positioning devices, which means the eye vision is the only reliable detector in this situation (for example, small fishing boats are usually not equipped with AIS, then it requires the navigator to detect, locate, and calculate it only rely on their own eye vision).

TABLE IV
STATISTICS ON TRANSITION FREQUENCIES IN COMPLETE SAILINGS

No.	I-II	I-III	II-III
wo.	3.5	10.4	-
w.	5.5	12.0	0.5

* times per minute

The values in Table IV are the overall average from all collected sailings in their classes. The overall trend corresponds to the individual case that the eye movement activity level is higher when advanced ECDIS is enabled. The transition between AOI-I and III is the most frequent, and direct transition between AOI-II and III rarely happens.

C. Summary

This section illustrates the CRI-based ECDIS effectiveness evaluation in an individual experiment set and how ECDIS influences navigators based on visual attention analysis. It is found that with the ECDIS, the navigators are more confident and willing to select a riskier route that is balanced with sailing efficiency. ECDIS also helps to plan the route early such that navigators do not have to take immediate actions upon situation occurrence, and in this way, the stability and comfortability are not diminished. From the visual attention patterns respect, according to the statistics, we can summarize that navigators' visual attention transition and distribution are in regularity, and the existence of advanced ECDIS does impact their visual attention distribution.

IV. Conclusion

In this study, we implement an evaluation of the effectiveness of advanced ECDIS to maritime navigators by utilizing collision risk analysis and visual attention assessment. Some interesting results from the eye-tracker glasses are presented, and some particular behaviors are demonstrated with respect to professional domain knowledge in nautical science. The content of the result and discussion is expected to enhance comprehending navigators' maritime operations and behavior, which can be used as the fundamental knowledge for developing specific intelligent decision support for MASS at human-in-the-loop levels. However, the data quantity and absence of a mathematical evaluation model prevent the exciting findings from being integrated into the current navigating pattern analysis studies. Therefore, in the further stage, we are expecting on developing a quantitative empirical mathematical model as the evaluation leverage; in addition, we plan to expand the database and open the advanced ship-bridge system to invite more experts and practitioners to test and utilize, which is believed to be beneficial to all parties.

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