Visual Attention Analysis for Critical Operations in Maritime Collision Avoidance

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***Abstract*—The research on how to provide effective onboard decision support for surface ships, especially in critical operational scenes such as collision avoidance, has been triggered as a goal in recent years. From the authors' perspective, to achieve this goal, it is crucial to comprehensively understand the operational logic and mechanism of the human navigators. In this paper, we use wearable eye tracker glasses to collect visual attention data from the navigators. The scene is established as a collision avoidance task in a strait water channel on a maritime simulator. By using the concept of critical operations, the whole sailing is divided into cruising and maneuvering time windows. The visual attention is analyzed in terms of the transition time/frequency and area of interest. It is the first time to exclusively analyze the navigators' visual attention in collision-avoidance tasks. The paper suggests a way to potentially predict the human-dominant onboard operations, which builds the basis for developing a better decision support system.**

***Index Terms*—Visual attention, eyetracker, human factor, collision avoidance, surface ships**

I. Introduction

As waterborne transportation dominates over 95 % of the cargo trade in the world [1], securing navigational safety and efficiency is one of the most attractive issues in both academia and industry. According to statistics of different caliber, 75 - 96 % of marine perils are caused by human-factor-induced errors [2]. So how to reduce the potential risk brought by human navigators becomes crucial to increase navigational safety. Engineers and researchers have been keen to equip the latest technologies onboard in the past decades, such as the electronic chart display and information system (ECDIS), automatic radar plotting aid (ARPA), satellite navigation systems, and many other onboard assisting systems, at the aim of providing decision supports to the navigators. As these tools are driven and oriented by the development of technologies, the navigators need to adjust themselves and their skills every time a new system is equipped onboard. As a reflection, a question is raised: does this workflow take the advantage of the navigators-in-the-loop to the largest extent? Is there a better solution to make the process being human-centered and explore the potential of the human?

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From the authors' perspective, the answer is positive. In recent years, onboard human factor analysis and human modeling are getting more attention [3] [4]. As there is still a long way to achieve the full-autonomous ships at level 4 according to the International Maritime Organization, human-in-the-loop maritime navigation will remain dominant in the next decade. The development of the artificial intelligence and sensor technology enable us to access to human data through multiple channels such as brain waves (electroencephalogram) [5], eye movement [6], gestures [7], body movement [8], and so on [9]. With the help of the sensors, we have the chance to know how human navigators respond to the situations, especially in critical scenes such as collision risks and avoidance which is one of the most concerning tasks in maritime operations [10]. In this paper, we use the wearable eye tracker glasses to record the eye movement of the navigators in a designed collision risky scenario to explore the mechanism of how navigators respond and act by statistical data processing and interpretation.

Before diving into the research objective of this paper, we take an outlook of the progress in the general transportaion industries. Visual attention and eye-movement-related research are not uncharted to this massive industry including land-based, airborne, and waterborne classes [11]. It has been used to monitor the fatigue status and mental workload [12] [13], test the usability of virtual reality equipments and simulators [14], improve the nautical training [15]. As for specific maritime operations, studies have been conducted on high-speed cruising [16] and heavy crane lifting [17]. Up to now, there is no specialized research that has been conducted exclusively on maritime collision avoidance. However, analysis and data processing methods can be referred from the aforementioned literature to assist the research target in this paper.

Different from the open sea and high sea sailing voyages where the main concern is the capricious meteorological and environmental conditions, the collision risk is almost the prime culprit in the busy and narrow water channels such as some straits. In this context, the navigators are demanded to be highly concentrated in handling the ship maneuvering with directing information coming from all channels. They cannot only rely on the electronic systems and system alarm but also be aware of the situation in their sense. For example, it is reported that about 40 % of vessels traveling in the busy strait are

Fig. 1. Navigator on a self-developed ship-bridge simulator.

not equipped with the automatic identification system (AIS), and even worse, the AIS contains wrong information which can mislead the navigator to wrong decisions [18]. Therefore, the navigators' experience, judgment, and awareness are more valuable in handling the collision risk in the narrow and busy water, where more information and clues are expected to be extracted from their visual attention and its transition [19].

In this paper, we look into the visual attention of the navigators when they operate in a designed collision avoidance task based on a commuter ferry route near Ålesund, Norway. The scene is designed and reproduced on a self-developed maritime simulator as shown in Fig. 1. Visual attention data are collected by using the wearable eye tracker glasses Tobii Pro 2. In this paper, we are inclined to emphasize the visual transition frequency and times, fixation duration in the time window before the critical operations. Exploring and understanding the pattern of navigators' vision ahead of the critical operations can enable us to predict the navigators' reflection and action in the future application.

The authors suggest a simple but practical approach to interpreting visual attention prior to critical maneuvering operations. Firstly, the data collected from the maritime simulator are synchronized with the eye tracker data. Next, the start/end points of critical operations are determined by significant changes of key features including speed and course of the ship. Then, time windows are split according to critical moments, and at the same time windows are applied to the eye tracker data. At last, the statistical features of visual attention are extracted to reflect the navigators' operational logic before taking action.

The paper is organized as following: Section II presents the proposed method in detail; Section III introduces the experimental setup including site, equipment, and scene selection; Section IV demonstrates a single trial case to introduce how the methodology is applied; Section V illustrates and discuss the results derived from the collected data; At last, a conclusion follows in Section VI.

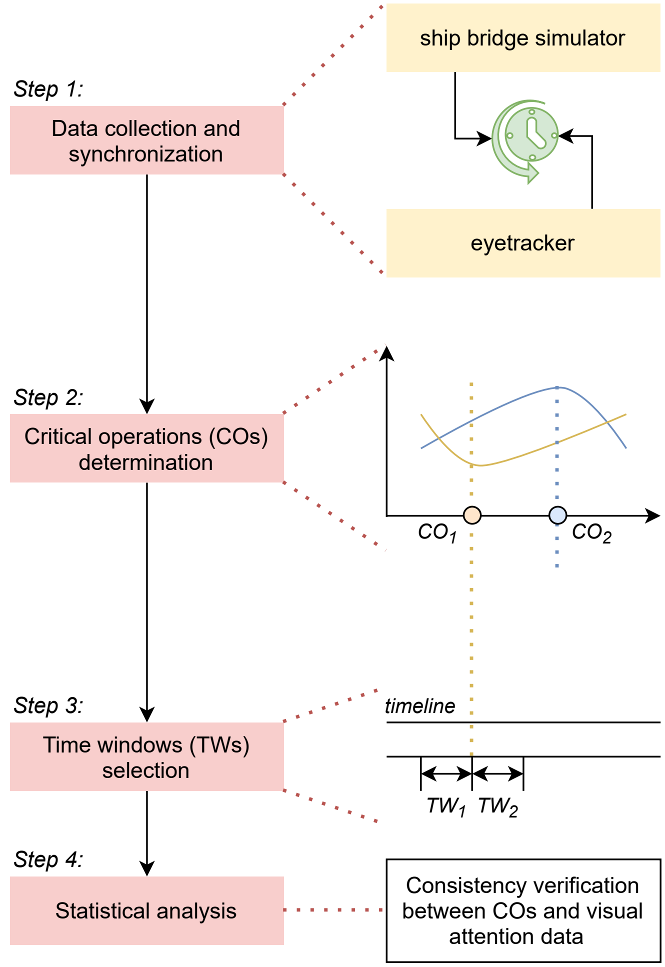

Fig. 2. Illustration of the workflow to this research.

II. Methodology

A. Workflow

The workflow in this paper contains 4 steps as shown in Fig. 2.

1) Step 1 - data collection and synchronization: Experimental data are collected in two ways: eye-tracker-based visual attention data collected from the participated navigators to the experiment; ship motion data including position, speed, and course are exported and collected through the simulator system. Since the eye-tracker system is independent of the ship-bridge simulator, data from the two portals need to be synchronized according to their timestamps.

2) Step 2 - critical operations (CO) determination: Critical operations (CO) are mainly determined by the change rate of speed and course to the ship, while also about the expertise (the participated navigators) recommendation. It means in this paper we do not use decisive criteria to make the assessment.

3) Step 3 - time window (TW) selection: Time windows (TW) are spells where the visual attention and transition are deemed to be closely relevant to assess how they relate to the COs. TVs can be prior, during, and post the COs.

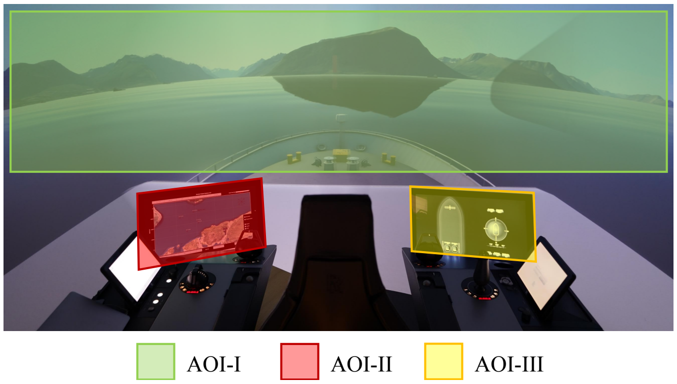

Fig. 3. Area of interest (AOI) on the simulator.

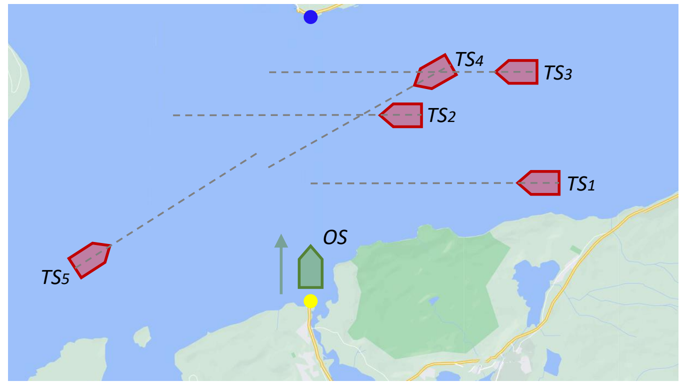

Fig. 4. Designed scenario on the map.

4) Step 4 - statistical analysis: After COs and TWs are settled, some features are counted for further analysis and comparison between different TWs. Before explaining the features, a commonly used concept - the area of interest (AOI) - should be clarified in advance:

- area of interest (AOI) is a manually selected region within the tracked map, and researchers can extract metrics to their need and interest specifically for this selected region.

The following features are counted based in terms of the different AOIs:

a) Transition times: how many times the AOI is transitted to from other AOI and/or area during a spell of TW;

b) Duration of fixation: the duration of the navigator's fixation on a specific AOI in an individual transition;

c) Total fixation time: the total time the navigator fixes on a specific AOI within a TW.

Results are discussed based on these defined features.

III. Experiment Design

A. Experimental Site & Equipment Setup

The experiment is conducted on a advanced ship-bridge simulator (Fig. 1) technically supported by Offshore Simulation Center AS and NTNU. The interface to the ship bridge simulator mainly contains three screens: the control panel where the maneuvering parameters (speed, course, propulsion, etc) are displayed, the customized ECDIS which provides the map-based navigational information, and the scene screen where the designed navigational scenario is displayed. These three screens are shown as Fig. 3 and their AOIs are framed accordingly: AOI-I, II, and III locate on respectively the scene screen, the ECDIS screen, and the control panel screen.

The eye tracker used in this experiment is Tobii Pro Glasses 2 which is a one-point calibrated and 3D-eye-modelling eye tracker. More specifications can be found in the official user's manual [20].

B. Scenario Design

The designed scenario to be implemented on the simulator is illustrated as in Fig. 4.

The scenario is designed to fulfill the requirement of the research objective - collision avoidance in a busy narrow water channel. In this context, we put 4 target ships (TS_1 - TS_4) coming from the starboard side of the own ship (OS) and 1 target ship (TS_5) coming from the portboard side of the OS.

According to the COLREGs [21], the OS shall give way to the TSs coming from its starboard. Therefore, in the designed scenario, the OS shall give ways to TS_1 - TS_4, however the regulation is not necessary to apply if the distance is far enough to guarantee traffic security. Though TS_5 which is from the OS's portboard side yields to give way, it still might attract the navigator's (on the OS) attention to synthetically analyze the traffic situation. It means the existence of TS_5 increase the complexity of the situation and requires more consideration and calculation from the navigator.

In a word, the designed scenario with sufficient complexity will require the navigator to pay more attention and choose a sophisticated routing solution, and we take the advantage of the eye tracker to reveal their attention and interest transition when they are aware and analyze the situation before making decisions.

IV. Look into a Trial Sailing

To make it easier to understand what happens at the spell around each COs and before selecting the TWs, we look into a specific trial from the collection. This trial is chosen randomly (without the inclination of the authors) from the collection to clarify the methodology. The visual assessment is provided individually for this case as well.

A. Scene Recurrence

First, Fig. 5 shows the speed and course which are the parameters to determine a CO according to Section II (step 2 in Fig. 2). Based on the speed changes in terms of deceleration and acceleration and the course alternation clockwise and anti-clockwise, COs are preliminarily selected as CO_1 where the ship starts to make a significant turn, CO_2 where the speed starts to decrease noticeably, CO_3 where the ship is back to accelerate, and CO_4 where the course turns back. We compare the selected COs and their happening moments to

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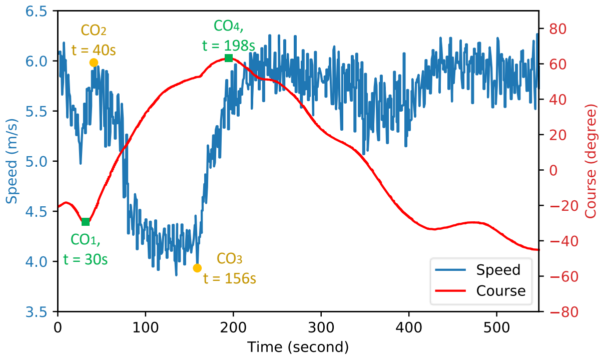


Fig. 5. Motion data of the illustrative trial.

the simulation's animation shown in Fig. 6 to find clues that evidence the COs are reasonably selected.

According to Fig. 6(a), before t = 35 s, the ship is towards a direction whose path is expected to pass the TSs from the front, which violates the COLREGs regulations and is potentially hazardous to the sailing. So at the moment, the ship starts to alter its course to yield to the evasive maneuver. As the navigator makes a significant turn at the time, the speed decelerates compliantly to secure the ship in a stable state. This operation is regarded as the most imperative operation for a collision avoidance task, so we confirm that CO_1 and CO_2 are correctly selected, while both are taken for a mutual aim, we combine the two COs as CO_o hereinafter.

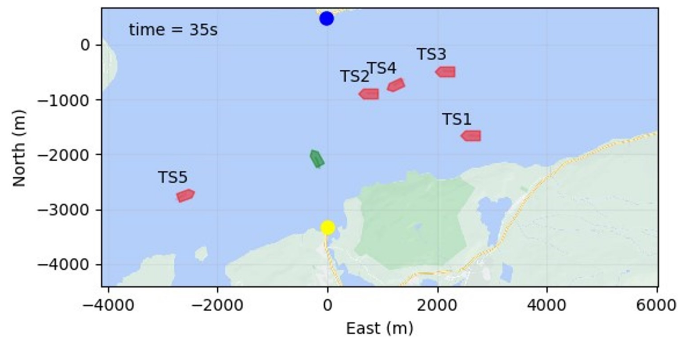
Fig. 6(b) shows the situation when CO_3 takes place at 156 s, at the moment the course alternation gradually becomes trivial, which means the ship has been maneuvered to a state that can pass the TSs safely. Therefore, the navigator starts to accelerate to increase the sailing efficiency. So CO_3 is confirmed as a correct selection.

At the moment when CO_4 takes place at 198 s, it shows the OS and TS4 are approaching each other soon, but before the moment that they pass by each other, the navigator has started to turn the course back to the destination, which implies that it is deemed that the parallel distance between OS and TS4 are sufficient to avoidance any collision. This operation is to finish the ultimate goal of the task: arrive at the destination, so CO_4 is also confirmed as critical.

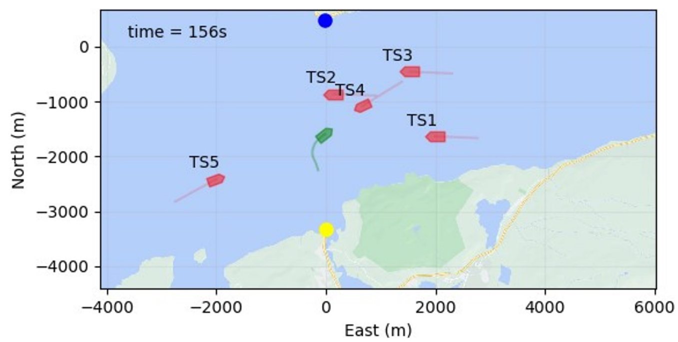
B. Attention Assessment

Due to the space limitation, comparisons among TWs with different lengths are not extensively demonstrated. We uniformly use the TW at the length of 30 s before and after the COs, and we use TW_1 (the spell from 5 s to 35 s) and TW_2 (the spell from 35 s to 65 s) which are prior and post CO_o for illustration in details.

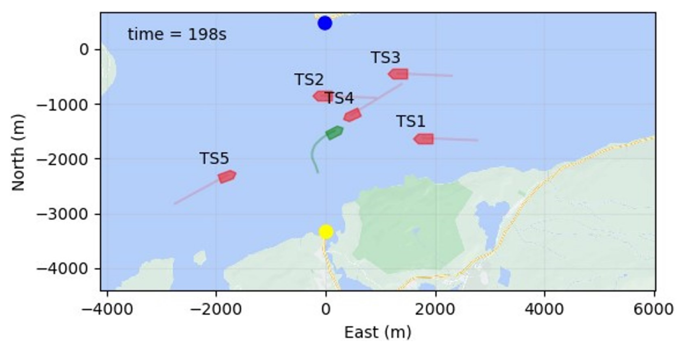
1) Transition times: As shown in Fig. 7, there are in total 9 times visual transitions between different AOIs. The transition between AOI-II and III are the most frequent. AOI-I, II, and III are visually visited 3, 3, and 3 times. The fixation is on AOI-III at the beginning of TW_1, so there are four times of duration of fixation in the following statistics. In TW_2 which



(a) Time t = 35 s, the mid-time between CO_1 and CO_2.



(b) Time t = 156 s, when CO_3 takes place.



(c) Time t = 198 s, when CO_4 takes place.

Fig. 6. Animation snapshots of the selected COs in the trial.

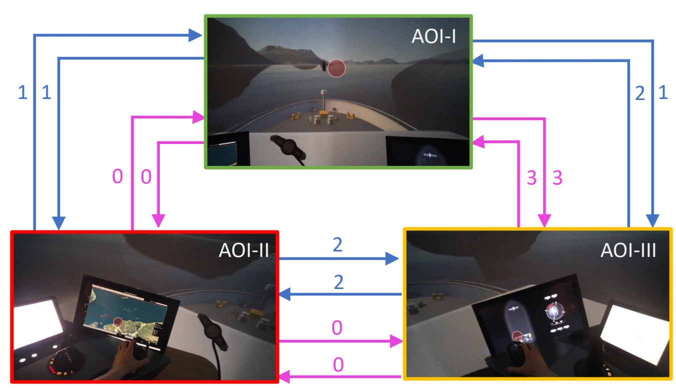


Fig. 7. Visual transition flows and counts at the TW_1 prior and TW_2 post to CO_o. The blue marks TW_1 and the pink marks TW_2.

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TABLE I
DURATION OF FIXATION STATISTICS IN TW_1 AND TW_2

AOI No.	Median (s)	Average (s)
TW_1		
AOI-I	**3.00**	3.33
AOI-II	1.00	1.67
AOI-III	**3.00**	**3.75**
TW_2		
AOI-I	**4.50**	**5.75**
AOI-II	N/A	N/A
AOI-III	2.00	2.33

Fig. 8. Visual attention heat map of the completed trial sailing.

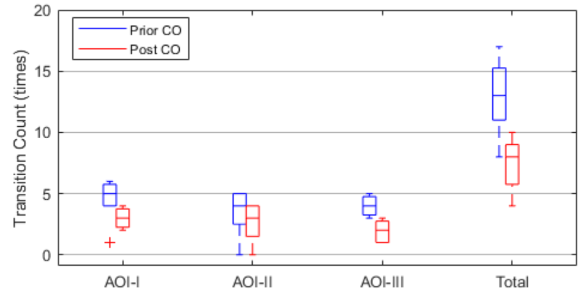

Fig. 9. Transition times of each AOI and the total count.

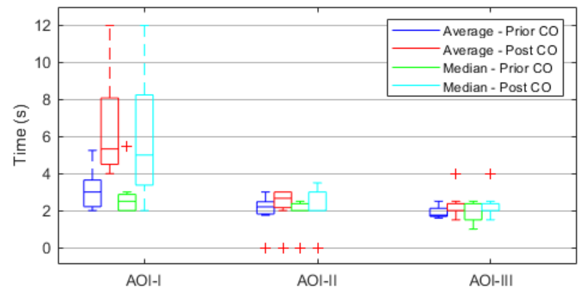

Fig. 10. Features to the duration of fixation for each AOI.

is post CO_o, the situation is significantly different compared to TW_1 as AOI-II is never visually visited and the visual attention transits between AOI-I and III repeatedly as shown in Fig. 7 (3 times for each). In general, the transition frequency also decreases from 9 times per TW to 7 times per TW.

2) Duration of fixation: The duration of TW_1 and TW_2 is given in Table I. It is noticeable that the most attractive region is changed from AOI-III to AOI-I in any terms of the metrics.

3) Total fixation time: The total fixation time for AOI-I, II, and III are 10, 5, 15 seconds in TW_1, while are 23, 0, 7 seconds in TW_2 respectively.

It can be inferred from the data that AOI-III which represents the control panel screen is most appealing to the navigator for maneuvering prior CO_o in the TW_1 as it is visually visited the most frequently with the highest average duration of fixation, and it is also leading in terms of the total fixation time (15s) than other two AOIs. While after CO_o takes place, the situation changes remarkably that AOI-I becomes the dominant region of the navigator's visual attention. Thus we can summarize the situation at the TWs around CO_o that the navigator's operational behaviors are different before and after the CO and the difference is clearly reflected by the eye-tracker data.

C. Overview of the Trial

Fig. 8 show the overall heat map of the trial sailing. It shows that AOI-I attracts the most visual attention during the whole sailing, and the AOI-II takes the second place. The overall demonstration seems to be unconsistent to the results analyzed in Section IV-B, while this confusion will be given an explanation in the following Section V.

V. STATISTICAL RESULTS AND DISCUSSION

Similar to the approach in Section IV, all collected trials' data are processed, while 16 COs are selected and 32 TWs are chosen accordingly. The derived statistical results are illustrated and discussed in this section.

A. Transition Times

Fig. 9 shows the counted transition times of each AOI. There is a clear trend that the visual transition is less active as all AOI are less frequently visited after the COs take place. AOI-I is visited more often by the navigator than the other two AOIs.

B. Duration of Fixation

The two data features, average and median values, are used to evaluate the duration of fixation shown in Fig. 10. Both features significantly increase in all AOIs. According to Section V-A, the visual transition frequency declines, which results in a great increment in the duration of fixation in every individual fixation.

C. Total Fixation Time

Fig. 11 reveals that after the CO takes place, the fixation time on AOI-I increases while incline to go down on AOI-II and III. Since the CO is defined as critical operations, it can be inferred that after CO happens, the navigator regards

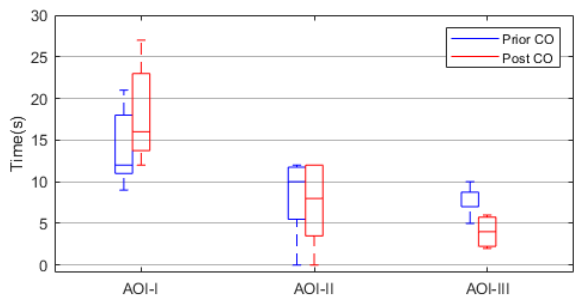

Fig. 11. Total fixation time for each AOI.

the ship in a safe state and is more relaxed than in the spell of prior-CO when the navigator is demanded to be aware of the situation from the ECDIS (AOI-II) and tightly from the control command (AOI-III), the navigator prefers to put more attention on the vivid scene screen (AOI-I) to visually explore new situations to be handled.

In summary, the statistical results show clear discrimination between the prior- and post- CO spells. In the spell prior to CO, the navigator visual attention transit fast between different AOIs to obtain information as completed as possible from every channel to make a synthetically optimal solution to handle the collision avoidance. After the CO, navigators prefer to keep visual outlook (AOI-I) than scrutinizing the information on the smaller screens (AOI-II and III).

VI. Conclusion

This paper suggests a new approach by applying eye-tracker-based visual attention assessment to evaluate the performance of how navigators handle the collision avoidance tasks in maritime traffic. The statistical results reveal that the visual activities change between different patterns during the whole process of handling collision avoidance. As it is the first attempt to analyze the navigators' behaviors in collision avoidance by visual assessment, more research details are expected in the future, and two of them are triggered and undergoing with the authors:

- analytical goal: as the result in this paper describe the visual attention with respect to transition frequency and fixation duration in general, the details in each AOI in terms of fixation points and distribution can be studied further to understand the navigators' logic more precisely.
- technically goal: as using a wearable eye tracker is not the most natural status to the navigator and is not applicable in real onboard operations, a solution without glasses is expected to be developed.

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