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Ship navigators' situation awareness analysis using heart rate variability under simulated environment

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Abstract:

In Korea, it is observed that increased frequency of ship accidents. Numerous research has been carried out to identify the cause of the collision and prevent recurrences. Marine navigation focuses on the process of monitoring and controlling the movement of ship or vessel from one destination to another. This study focused on studying the relationship between physiological loads to the navigators and their behavior on situation awareness and collision. In this study, a total of 10 navigators participated and they were grouped in to two groups as expert and novice based on their experience in navigation. To measure physiological load, heart rate variability's were measured using wearable sensors. The heart rate variability measures considered were heart rate, the power of LF, the power of HF, and LF/HF ratio. Ship Maneuvering Simulator containing radar, ECDIS, auto-steerer, and other essential nautical instruments and screen to confirm the environment outside the bridge was utilized. In the simulator more realistic scenario was created including various events. The experimental results confirms that the experts' navigators were more aware about situation than the novice, which reduce the risk of accidents / collision.

Keywords: Heart rate variability, maneuvering simulator, situation awareness.

I. INTRODUCTION

Ship navigation involves various physical and mental workloads to the navigator. The mental loads include signal detection, recognition, and the overall judgment, ability to identify target ships approaching their ship either through the radar or the naked eye. Also, the helmsman's ability to remember commands from the captain and acting wisely to avoid collision with the target ship, etc. These cognitive tasks cannot be guaranteed to occur intermittently or sequentially [1].

The helmsmen acquire various information from the onboard instrument (ARPA: Automatic Radar Plotting Aids, ECDIS: Electronic Chart Display & Information System, etc.) and process that information to make judgments for future action. There are various ship navigation instruments around the world due to technological advancement. However, in recent times, ARPA radar is the most widely used navigation equipment in ships. The helmsmen operate the ship mainly with radar information and also by observing by his own eyes. These attention switching increases cognitive loads to the helmsmen and increases the chances for errors. These errors might lead to accidents/collision.

In Korea, ship accidents are frequently happening. According to the marine accident statistics of the Maritime Tribunal, the marine accident rate increased from 2.01% in 2014 to 3.35% in 2016 by 1.34%. In 2014, the number of ships registered was 77,730 in that 1,565 ships met with accidents out of which 1,330 were marine accidents. In 2016, the ship registered was 76,152 in that 2,549 ships met with accidents out of which 2,307 were marine accidents. As per the types of accidents, the highest rate was a collision, stranding, and abalone order, and collision and stranding accidents. These types of accidents were increased from 266 cases in 2013 to 346 cases in 2016, with an increase of 30.1% [2]. Hence, numerous research has been carried out to identify the cause of the collision and prevent recurrence [3-5].

Helmsmen inexpertness, including judgmental error, lack of situation awareness and wrong strategies, causes about 80% of crashes. Also, navigators subjected to various stresses due to the isolated environment and uncertain weather conditions at sea. Notably, the unsettled weather conditions like typhoons and turbulence burden the navigators. These conditions increase the unexpected behavior of other ships and enhance the navigation traffic volume. This increased workload also one of the reasons for the accident. Technical limitations of control devices and complexity to using them also contributing factor to increasing disasters.

Studying the autonomic nervous system is one of the methods of measuring psychological stress [6]. Stress accelerates the sympathetic nerves and causes increased heart rate, blood pressure, sweating, and stress hormone. Sympathetic nerves and parasympathetic nerves activities evaluated using Heart rate variability test, where changes in heartbeat rhythm patterns analyzed. Total frequency domain of the heart variability is between 0.04 to 0.40 Hz, where the low-frequency is 0.04 to 0.15 Hz, and the high frequency is between 0.15 to 0.40 Hz. The low-frequency (LF) domain represents the baroreflex associated with the activities (blood pressure control) of the sympathetic nervous system. The high-frequency (HF) domain represents the activities (vagus nerve and breathing activity) of the parasympathetic nervous system. Individual feel uncomfortable once the sympathetic nerve activity is dominant when the increased value of the LF/HF ratio. In the case of decreased LF/HF ratio, it indicates the dominant parasympathetic nerve activities [7-11], when the individual feels comfortable or unstressed.

In recent years, the importance of recognition, i.e., situation awareness of helmsmen being studied in the marine field [11, 12]. Attention is the cognitive process or cognitive ability of a human being, which means that perceiving the environment that the person is currently facing through the sensory system and understands the unstable environment precisely. How well humans perform recognition has a profound effect on job performance. Therefore, research on recognition has become a subject of interest and research in various fields such as aviation, automobile, nuclear power plant, and the medical field.

In this study, we investigated navigators' situation awareness on the navigation system, control equipment, and surrounding environment while they were operating the ship by measuring their heart variability's. It is difficult to measure and also challenging to investigate recognition errors and assess recognition in the actual field. Hence, we have used ship navigator simulators, which can simulate the practical situations. The ship navigation simulation includes complex scenarios that can occur in the real environment. It is better to study/research on mental fatigue, to understand and to minimize it further. Hence, this work studied psychological behaviors of less experienced navigators and relatively skilled navigators in a simulated environment. This study results/outcome could be used to prepare countermeasures to minimize the stress on navigators and to minimize the accidents caused due to stressed navigators.

II. RESEARCH METHODOLOGY

II. I. Subject/participants of this study

Ten male subjects participated in the experiment to determine the mental stress level. There were two groups: an expert group with eight years of voyage experience and novice group with less than three years of voyage experience. Purpose and experimental procedure communicated to the participants. Participants demographics details presented in Table 1.

Table 1. Physical Characteristics

Group	Age (years)	Height (cm)	Weight (kg)	Career (years)
	(Mean ± SD)			
Expert (5 no's)	41.60 ± 9.45	172.60 ± 5.41	80.00 ± 10.37	13.80 ± 5.54
Novice (5 no's)	23.60 ± 2.19	174.00 ± 4.36	67.60 ± 10.01	1.40 ± 0.89

II. II. Equipment's used for measurements

A wireless T-sens ECG equipment was used to measure heart variability. The devices details summarized in Table 2.

Table 2. Experimental measuring devices

Name of Equipment	ITEM	Specification
Wireless T-sens ECG	Over sampling Resolution Range	x4 (1024Hz) 16Bits 4.4mV, ± 2.2mV, ±1.46mV
Wireless T-sens Heart rate (CFM)	Measuring range BPM Frequency Accuracy	10 - 220 16Hz 1 BPM
Analysis software		CAPTIV-L7000 premier
Digital to analog converter	Recommended range Bandwidth	20m (max. 150m for T-Belt) 512 Hz

II. III. Ship Maneuvering Simulator

This study utilized the ship maneuvering simulator (TRANSAS) owned by Kunsan National University. This simulator is composed of radar, ECDIS, auto-steerer, and other essential nautical instruments and screen to confirm the environment outside the bridge (Fig. 1).

Fig. 1. Ship maneuvering simulator

II. IV. Navigation Scenario

Figure 2 shows the navigation scenario utilized in this study. This study considered a trawler ship carrying 1000 ton and traveling with a maximum speed of 15 knots. A situation in which this ship entered the port of Pusan was about 3.5 miles southeast of the Oryukdo breakwater. The sea environment is set to be good weather, with wind direction being north, wind speed being 0 knots and waves being 0.1 meters. The scenario configured as the navigator ship enters the port of Pusan (Fig. 2), encountering (3 targets) with target ships, and the failure of steering gear after passing the Oryukdo breakwater. The first encounter was crossing relation; the navigator's ship is the stand-on-vessel; the Target ship 1 is the give-way-vessel. The second encounter was also passing relation; the navigator's ship is the stand-on-vessel; the Target ship 2 is the give-way-vessel. The third encounter was a situation where both ships face almost directly; here, both ships are give-way-vessel. During the last case, a failure of steering gear situated. Here, the control room check that the navigator's vessel passed the breakwater and proceeded to give the failure situation. During this situation, the participants required to act as a navigator, perform the instruction given by the helmsman and handle the situation.

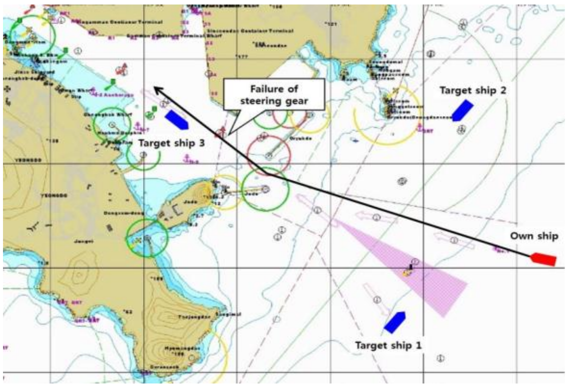

Fig. 2. Navigation scenario

Table 3. Input event and other details in the simulator

Event	Speed (kn)	Tons (ton)	Encountering Angle (°)	Time (min)
Event 1	15.5	240	80	17
Event 2	13.7	35	90	22
Event 3	4.5	8286	20	28
Own ship	14	1087		

II. V. Experimental Procedure

The participants had enough experience in the simulator environment. They have not informed about the details of the scenarios to produce a realistic situation. In the bridge, two participants engaged one act as a navigator and another as helmsman. Overall test procedure explained to the participants. Participants' heart rate variability were measured for 40 minutes (5 min before task, 30 during the task, and 5 min after the mission). Speed and direction of operating the ship various between participants. Hence, speed and direction differ the environment; the relative position of the vessel also changed. Therefore, the experimenter challenge was to create a situation where the navigator could be nervous. The ship's angle of encountering different for each event (Table 3). The participants were instructed to navigate the vessel at a speed of 14 knots while maintaining the direction of the ship, simultaneously to control the ship to avoid a collision if there was a risk of accident and reminded that collision avoidance was a more critical task in this training. The second task was to monitor the secondary display on the left side of the radar, which response to the radar warning by pressing the 'ALARM' button located next to the 'GYRO' button as soon as subject detect the flashes with the alarm in the 'GYRO' button. Participants contacted the central control center via VHF communication after all preparations in the bridge for the experiments completed. Then the experimenter initiated the investigation in the control room. The scenario continued for 30 minutes whether a collision or not.

II. VI. Analysis of the Heart Rate Variability (HRV)

To measure heart rate variability 2 sets of electrocardiogram (CAPTIV T-Sens ECG, EC-0092, EC-0096, Group TEA, France) measuring sensors and 2 sets of heart rate measuring sensors (CAPTIV T-Sens CFM, CF-0096, CF-0097 Group TEA, France) were used. The total frequency domain set as 0.04 to 0.40 Hz. Normalized heart rate variability only used for comparison between subjects. Fig. 3 explains the sensor attachment and simulator cabin environment. In HRV, we have estimated LF, HF, and LF/HF ratio.

Fig. 3. Scene of HRV and CFM measurement during ship 3D simulation recognition training

II. VII. Analysis of Data

We have used a statistical program (SPSS v24.0) to test the statistical significance in the results. To test the difference in HRV frequency-domain measures depends on events were tested through One-way ANOVA and Scheffe post-hoc test with significance level of $p < 0.05$.

III. RESULTS

III. I. CHANGE IN HEART RATE

The changes in the heart rate in beat per min (BPM) for expert and novice group for various events presented in Table 4. There was statistically significant difference found in the heart rate in event 2 and event 3.

Table 4. Change in heart rate variability in beats per minute

Characteristic	Event	Expert (n=5) (Mean ± SD)	Novice (n=5) (Mean ± SD)
Heart rate (BPM)	Pre	95.39±2.16	73.03±14.80
	Event1	115.40±11.15	77.11±15.14
	Event2	128.29±15.67*	76.78±10.26
	Event3	126.04±7.21*	75.51±11.84

*: $p < 0.05$

III. II. Change in low frequency (LF)

The changes in the absolute power of low frequency (LF) band in ms2 for expert and novice group for various events presented in Table 5. The low-frequency (LF) domain represents the baroreflex associated with the activities (blood pressure control) of the sympathetic nervous system. Overall, the power of LF for expert group was greater than novice group. There was no statistically significant difference found in the power of LF between events and between groups.

Table 5. Change in power of low frequency (LF) in ms^2

Variable	Event	Expert (n=5) (Mean ± SD)	Novice (n=5) (Mean ± SD)
Lower frequency (LF) in ms^2	Pre	147.84±13.35	160.87±18.23
	Event1	151.44±11.33	150.74±24.61
	Event2	152.73±13.84	153.19±22.20
	Event3	148.94±5.40	151.41±22.45

III. III. Change in high frequency (HF)

The changes in the absolute power of high frequency (HF) band in ms2 for expert and novice group for various events presented in Table 6. The high-frequency (HF) domain represents the activities (vagus nerve and breathing activity) of the parasympathetic nervous system. Overall, the power of HF for novice group was greater than expert group. There was no statistically significant difference found in the power of HF between events and between groups.

Table 6. Change in power of high frequency (HF) in ms^2

Variable	Event	Expert (n=5) (Mean ± SD)	Novice (n=5) (Mean ± SD)
High frequency (HF) in ms^2	Pre	63.94±6.15	112.63±9.16
	Event1	56.32±11.91	116.77±7.00
	Event2	49.70±18.13	118.54±7.99
	Event3	48.99±15.31	121.28±14.82

III. IV. Change in LF/HF ratio

The changes in the LF/HF ratio for expert and novice group for various events presented in Table 7. The ratio of LF to HF power (LF/HF ratio) may estimate the ratio between sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) activity under controlled conditions. As mentioned earlier, individual feel uncomfortable once the sympathetic nerve activity is dominant when the increased value of the LF/HF ratio. In the case of decreased LF/HF ratio, it indicates the dominant parasympathetic nerve activities, when the individual feels comfortable or unstressed. There was no statistically significant difference found in the LF/HF ratio between events and between groups.

Table 7. Change in LF/HF ratio

Variable	Event	Expert (n=5) (Mean ± SD)	Novice (n=5) (Mean ± SD)
LF/HF ratio	Pre	2.31±0.02	1.43±0.09
	Event1	2.75±0.43	1.29±0.13
	Event2	3.35±1.13	1.29±0.10
	Event3	3.22±0.87	1.24±0.03

IV. DISCUSSIONS

In this study, we investigated navigators' situation awareness on the navigation system, control equipment, and surrounding environment while they were operating the ship. We have used ship navigator simulators, which can simulate the practical situations. Through this experiment we could estimate the degree of stress caused by navigation situation on experienced and less experienced navigators. The outcome of this research would allow us to prepare countermeasures to minimize the stress, increase the situation awareness for the navigators and to minimize the accidents caused due to stressed navigators. The degree of stress estimated by measuring heart rate variability and its measures of experienced and less experienced navigators and compared. The autonomic nervous system is directly involved in maintaining internal balance in response to changes in the internal and external environment, which has led to many studies trying to find a connection between autonomic nervous system and disease. It was observed that increased heart rate for the expert group compared to novice group in event 2 and event 3, that too significant increase ($p < 0.05$). This increase represents the expert group more attentive and recognizing the situation i.e., increased situation awareness for the expert group compared to the novice group. This increased situation awareness minimized the risk of collision at event 2 and event 3 for the expert group then the novice group. In terms of the novice group, there was no significant difference in their heart rate for event 2 and event 3. It proves, they were less aware about the situation. Similar trend observed in the results of power of LF and the power of HF. In terms of LF/HF ratio, increased ratio found in the expert group, which confirms the expert group felt stress. The result of LF/HF ratio also convey that the expert

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group more attentive to the situation than the novice group. Hence, the expert group act positively to the accident situation and maintain sufficient gap/distance between ship to avoid collision, which lead to reduced accident risk. However, the novice group unaware of situation and make wrong decision, which lead to increased risk for accident. To conclude, it is understandable that heart rate variability is one of the parameters can be used to know whether the navigators attentive to the situation or not. Also, we could make countermeasures like providing additional or special training for the novice ship navigators in the simulator to minimize the risk of collision.

V. CONCLUSION

This simulator based study investigated navigators situation awareness on the navigation system, control equipment, and surrounding environment while they were operating the ship. Heart rate variability measured from novice and expert navigators using wearable sensors. From both expert and novice group, the heart rate variability measures including power of LF, power of HF, LF/HF ratio and heart rate were measured and compared. The experimental results confirms the experts' group navigators were more aware about situation than the novice group navigators. This study also proves that using heart rate variability as one of the parameters to understand the navigators' situation awareness. In future, proper evaluation system should be constructed by developing a more reliable ship 3D simulation recognition training system that reflects the stress evaluation criterion.

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