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# Navigators' Errors in a Ship Collision via Simulation Experiment in South Korea

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Received: 28 February 2020; Accepted: 18 March 2020; Published: 3 April 2020



**Abstract:** A very significant number of marine accidents occur because of human errors. This study aimed to prevent ship collisions by identifying types of navigators' errors. Based on Reason's classification theory, the possible human errors are classified into skill-based slips (SBSs) (errors caused by the lack of skills), rule-based mistakes (RBMs) (errors caused by the misapplication of rules), and knowledge-based mistakes (KBMs) (errors caused by the lack of navigator's knowledge). For this study, a scenario-based experiment using a ship-handling simulator was conducted with 50 recruited student navigators. The results revealed two primary human errors of accidents, namely lack of knowledge and misapplication of rules. The results suggest that a collision can be minimized when a navigator has sufficient knowledge of an appropriate course of action and a deep understanding of safety rules. Accidents cannot be prevented by identifying errors, but steps can be taken to narrow the knowledge gap. Based on the results, we proposed a simulation training on navigator error in an unfamiliar situation. The results are expected to reduce errors in the maritime sector using a human-centric work system.

**Keywords:** human errors; marine safety; ship-handling simulator; collision

## 1. Introduction

The magnitude of marine accidents is considerable; therefore, their possible causes must be assessed [1]. Human errors must be considered the greatest risk [2] because they are related to a majority of marine accidents (75%–96%) [3]. Several researchers have investigated methods to reduce human errors, which requires a clear understanding of human behavior [4]. The US Navy's aircraft carriers, nuclear power plants, and organizations such as air traffic control centers have experienced difficulties in reducing human errors [5]. For example, research has been conducted to divide workers' behavior based on skills, rules, and knowledge to reduce human errors in nuclear power plants [6].

In the marine industry, the navigator's error causing a ship collision occurs during bridgework [7]. Bridgework includes rudder and wheel controls for maneuvering ships, circumference, avoiding ships, reflecting plans to destinations, and locating ships. In South Korea, 79% of maritime accidents that occurred over the last five years were related to navigators' errors [8]. Navigators' errors occur because of insufficient preparation for departure, poor management of voyage plan, negligence of evaluating ship location, inappropriate maneuvering, negligence of lookout, insufficient preparation and response to severe weather conditions and anchoring and mooring, misapplication of a navigation rule, negligence of duty, and non-compliance with safe working regulations on board. Similar to the case of aviation, human factor analysis and classification systems have been used to investigate human errors in the marine industry [9]. In the maritime sector, studies have been conducted to

classify situational awareness of seafarers via surveys [10] and classified bridgework as a criterion for situational awareness [11,12]. Recently, because of the use of augmented reality, there has been an improvement in avoiding collisions [13] and human behavior in intelligent systems [14]. However, because human errors have not been sufficiently investigated, studying human errors via education and training is important [4,15]. To avoid any unforeseen accidents, navigators' errors can be corrected using a ship-handling simulator by enhancing their relevant skills, rules, and knowledge required [16]. Therefore, Reason's human error classification was applied herein [17,18]. This study aimed to identify navigators' errors via ship-handling simulations. Using a simulator is an improved alternative method of training with relatively low cost and high safety [19,20]. Using a ship-handling simulator, Gould et al. tested human performance [21], but they did not intensively analyze human errors; therefore, in this study, we evaluated the navigator's errors. Evaluating navigators' errors can be used for human-machine evaluation studies and interface manipulation that are currently expanding into the human-oriented design of the maritime sector. Furthermore, specific training methods to reduce navigators' errors can be proposed for the safety of the vessel, which should include safety via human-technical interactions. The results of the simulation experiment can be used to detail the current comprehensive range of training and assess the bridgework, thus identifying the relationship between the navigational equipment interface and the navigators' work.

## 2. Classification of Navigators' Errors

Psychologists Reason and Norman developed a general classification of human errors, which were divided into two major categories, i.e., slips and mistakes [18,22,23]. According to them, slips occur because of skill-based errors or skill-based slips (SBSs), whereas mistakes are classified into rule-based mistakes (RBMs) and knowledge-based mistakes (KBMs). Slips are attributed to subconscious actions being set aside en route; they occur when the goal is correct, but the actions are not properly performed, i.e., the execution is flawed. For example, SBS can occur when a navigator manipulates the radar interface to a wrong target under the danger of collision in the open sea during bridgework [23]. For this study, the probability of SBS is between 1/200 and 1/20,000 [24].

Mistakes are attributed to inappropriate goals and plans. A person makes a poor decision, misclassifies a situation, or fails to consider relevant factors [22]. Rule-based mistakes (RBMs) perform actions consistent with their intentions but fail to achieve their intended results because of the incorrect application of rules [18]. Herein, the diagnosis of the situation is appropriate but the course of action is erroneous, i.e., the wrong rule is applied [22]. RBM is related to familiar situations or learned situations. For example, to avoid a collision, a veering behavior with the "port-to-port" principle from the Convention on the International Regulations for the Purposes of Collision at Sea should be applied [25]. Thus, RBM includes mistakes that can occur in action based on the established procedures that the navigator makes a decision in a familiar situation. For instance, while sailing on a designated course of the coastal voyage during bridgework, the navigator identified a vessel in immediate danger of collision. Note that the navigator must sail the ship in the route as per international rules, but RBM occurs when the navigator does not comply with the international navigation rules. The error probability for this study is between 1/20 and 1/2,000 [24].

Finally, owing to insufficient knowledge, the knowledge-based mistake (KBM) includes performing intended actions but not achieving the intended outcome [18]. The misdiagnosis of the problem is attributed to insufficient knowledge [22]. To avoid human errors, navigators must have clear action plans using conscious analytical processes and stored knowledge [26]. KBM occurs when the navigator has to navigate under a sudden change of visibility or weather conditions and needs to develop an action plan for collision avoidance [26]. At this point, KBM occurs when the navigator prepares an inappropriate action plan because of the lack of knowledge [6]. The error probability for these types of behaviors is between 1/2 and 1/200 [24]. Therefore, as shown in Figure 1, this study used the human error classification developed by Reason. Herein, we investigated a navigator's human errors based on the method used to investigate human error caused by a road traffic driver [27].

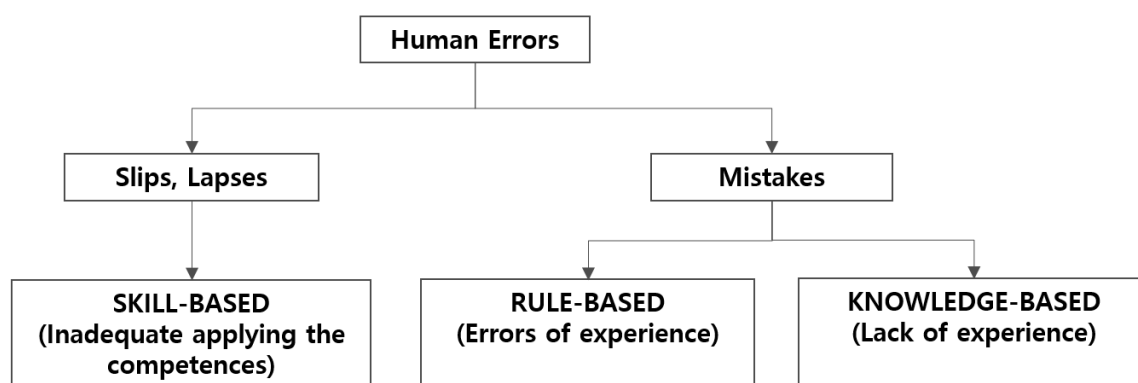


Figure 1. Classification of human errors (Reason, 1990).

### 3. Materials and Methods

Generally, a ship-handling simulator is used in the industry because it creates accurate and realistic scenarios to train students; therefore, to measure the participants' behavior according to Reason's human error classification, we used a ship-handling simulator. The participants executed the ship collision scenario via a ship-handling simulator and their errors were assessed via checklists, which comprised items to evaluate navigator errors according to the human error classification. The participants' errors according to the checklists were compared with video recording and participants' written action plans to avoid a collision.

#### 3.1. Participants

All participants were student navigators. For this study, 50 adults (45 men and 5 women) with an average age of 22.6 years (range between 22 and 25 years old) participated. These participants had taken maritime training courses for three and a half years at International Maritime Organization (IMO)-accredited maritime educational institutions. They had a third-class deck officer license and were in a merchant vessel as an intern for more than a year. All participants had at least 80 hours of experience with simulation training.

#### 3.2. Materials

Using a real environment experiment is difficult because of both time and cost. Therefore, the proposed simulator was used as an alternative [19,21]. The equipment used herein was a ship-handling simulator from Kongsberg, Norway; it was installed by Kongsberg Korea as an experimental equipment at Mokpo Maritime University. Its configuration is shown in Figure 2. For this study, a telegraph to control the speed of the ship, a wheel to change the direction of the ship, a radar for navigational aid, and an electronic chart display and information system (ECDIS) were included. We implemented a large-screen virtual reality training session and displayed navigation information on speed and rate of turn. The visual monitor was displayed at 160° ahead, thus allowing the user to control the visible background. Moreover, a video recorder was installed to record the operation of the interface, such as participants' behaviors and navigation devices, to reevaluate participants' behaviors using the recorded screen in the event of any doubt on their behavior evaluation. Mokpo Port in South Korea was selected as a simulation site because most participants have visited it at least ten times; therefore, they were familiar with the place. For this study, all the dynamic data of the ship during navigation were stored by the instructor.



**Figure 2.** Configuration of Kongsberg's typical ship-handling simulator.

### 3.3. Procedure and Scenarios

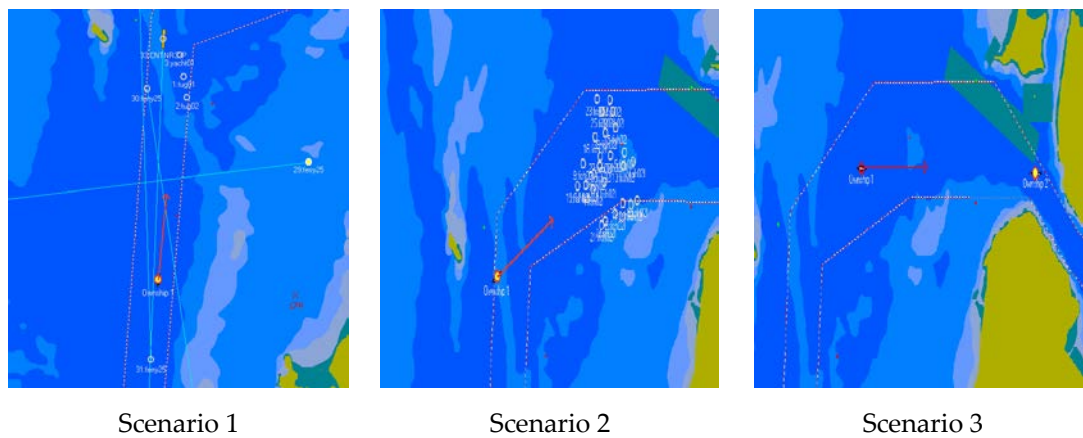
For this study, the autopilot mode was used; therefore, the bridge team comprised a navigator solo watch. Because the ship-handling simulator was separately installed, the experiment was repeated for three consecutive weeks owing to the number of participants and individually observing the progress over three weeks. Furthermore, the bridge team normally consists of skillful captain and navigator, but in this experiment, a solo watch was used to measure the errors of navigators. The participants were trained on the core of the experiment and scenario. Then, the familiarization process with the ship-handling simulator was conducted and they became familiar with the maneuvering and various interfaces of the simulators. Because familiarization with ship-handling simulators was important for measuring SBS [6], 15 min were allowed for familiarization with the interface, radar, ECDIS, and navigation equipment despite their prior 80-hour simulation experience. After the familiarization process was completed, the experiment was conducted by applying three collision scenarios, as shown in Table 1 and Figure 3. The participants were asked to write their action plan to avoid a collision for each scenario. Because planning is a crucial factor for measuring their KBMs [28], the plan had to be prepared in detail. The results of the written action plan were then used to evaluate the KBMs.

**Table 1.** Measurement of the navigator errors using a ship-handling simulator in the collision scenario.

No.	Selected Scenarios	Duration
1	The situation where multiple ships cross the ship's route	10 min
2	The situation of meeting with many fishing boats under restricted visibility	8 min
3	In a head-on situation, sudden turn of a not-under-command vessel	8 min

To identify the navigator errors more clearly in the research design stage, only the environments related to the scenarios were adjusted and designed. The first scenario was the crossing of multiple vessels in the ship's route. The second scenario was the sudden approach of multiple fishing vessels under limited visibility, whereas the last scenario was the situation where a not-under-command ship made an unexpected turn that was highly likely to lead to a collision. After the experiment was completed, the action plans to avoid a collision, which was submitted by participants, were evaluated by a group of experts. The experts comprised eight people, including captains, shipping company representatives, coast guards, navigators, professors, and researchers. The action plans written by the

participants were assessed in various ways, e.g., whether or not they could be applied to the actual voyage exposed to other risks. Figure 4 shows the participants' handling of the ship in the simulator.



**Figure 3.** A ship-handling simulator is used to perform three scenarios for measuring navigator errors. It is an instruction program from Kongsberg and the ship is controlled by participants.



**Figure 4.** Participant handling the ship in the simulator from the video being recorded.

### 3.4. Navigator Error Measurement Checklist

As shown in Table 2, the checklists comprised three steps; they were developed using three major distinctions listed in Tables 3–5. Human error classification, such as SBS, RBM, and KBM, was repeatedly evaluated for each scenario. SBS, RBM, and KBM were evaluated in steps 1, 2, and 3, respectively. Finally, the result for collision was verified. Evaluation in steps was based on the decision-making model presented by Embrey [29]. The checklist was constructed as per the stage of the study. Responses were evaluated as Yes/No, with Yes indicating an appropriate action (binary code one) and No for a non-appropriate action (code zero). For example, if the number of responses with Yes (code 1) was five for SBS in the checklist, it was rated as five points. If the number of responses with Yes was four for RBM, it was rated as four points. The number of checklists for the SBS and the RBM was five per scenario, whereas the number for KBM was one because knowledge is a behavior that includes planning for unfamiliar situations [17]. This indicates that one KBM can be measured with one scenario.



**Table 2.** Number of measurement items and questions in the checklist.

Observation		Number of Questions in Each Checklist			
Step	Factor	Checklist 1	Checklist 2	Checklist 3	Sum
1	SBS	5	5	5	15
2	RBM	5	5	5	15
3	KBM	1	1	1	3
	Sum	11	11	11	33
Result	Collision	1	1	1	3

**Table 3.** Checklist to observe the participants' continuous behaviors (questions on the appropriateness of the action plan for the collision situation of multiple ships).

Step	Number	Human Error Classification	Questions in Checklists	Response = Yes/No (1/0)
Step 1	1	SBS	Did the participant check the course and speed of other ships on the radar?	
	2	SBS	Was the rudder operation appropriate?	
	3	SBS	Was the telegraph operation appropriate?	
	4	SBS	Was the visual lookout appropriate?	
	5	SBS	Was the radar lookout appropriate?	
Step 2	1	RBM	Did the participant take the avoidance action following the procedure applied to the crossing situation?	
	2	RBM	Did the participant take the collision-avoidance action according to international regulations for preventing a collision at sea?	
	3	RBM	Did the participant follow the route?	
	4	RBM	Did the participant use navigation information such as the bow crossing range?	
	5	RBM	Were the acceptable ranges such as the closest point approach appropriate?	
Step 3	1	KBM	Was the action plan set in a situation where multiple ships cross the ship's route appropriate?	

**Table 4.** Checklist 2 for observing continuous behaviors (multiple fishing vessels and encounters with limited visibility).

Step	Number	Human Error Classification	Questions in Checklists	Response = Yes/No (1/0)
			Steps 1 and 2 are similar to those listed in Table 3	
Step 3	1	KBM	Was the plan set in the situation of meeting with many fishing boats under restricted visibility appropriate?	

**Table 5.** Checklist 3 for observing the participants' continuous behavior (inquiry about the plan of not-under-command in a head-on situation).

Step	Number	Human Error Classification	Questions in Checklists	Response = Yes/No (1/0)
			Steps 1 and 2 are similar to those listed in Table 3	
Step 3	1	KBM	Was the plan set in a head-on situation, the sudden turn of the not-under-command vessel appropriate?	

Furthermore, the participants were asked to describe their plans to avoid a collision using the evaluation sheet as the plan had to be evaluated after the experiment was completed. Therefore, the experiment was tested for three scenarios for one participant and 150 checklists were measured for all

50 participants. The progress of all the participants was recorded via video-based equipment. The characteristics of these checklists were then summarized as follows. The checklists were separately performed for the three scenarios. In step 1, the SBS with five checklists was evaluated. In step 2, the RBM with five checklists was evaluated. In step three, the KBM with one checklist was assessed. After the scenario was implemented, the cases of collision and non-collision were recorded. Because the experiment was to measure the behavior before the collision, the ship in the simulation stopped if a participant led to a collision in the experiment. In such a case, the instructor intervened in the simulation to prevent any subsequent errors and then resumed the experiment.

#### 4. Results

Results were derived via the checklist for 150 cases, wherein 50 participants were evaluated based on three collision scenarios using a ship-handling simulator. The results were then analyzed by calculating frequencies and percentages. Moreover, Pearson's correlation analysis was used to analyze the correlation between navigator errors and ship collisions.

##### 4.1. Frequency Calculation for Navigator Errors

The results of the navigators' error checklist were analyzed after being divided into two types, namely collision and non-collision events. Collisions occurred for 64 cases out of 150 cases (43%), and their frequency calculation results are listed in Table 6. The frequency calculation results for 86 cases (57%) without any collision are listed in Table 7. First, the frequency calculation results for collisions listed in Table 6 indicated the frequency of Yes and No for appropriateness of the action in three scenarios and expressed them with percentages. A total of 64 frequencies were then measured, i.e., 30, 6, and 28 cases in scenario one, two, and three, respectively. Yes was twice as much as No in step one. In step two, Yes was measured to be more than 15% of No. However, in step three, No was the majority of the evaluation (96.87%). The result of step three is noticeable because collisions occurred at a rate of 96.87% when navigators made KBMs.

**Table 6.** Frequency calculation when a collision occurs ( $n = 64$ ).

Step		Scenario 1 ( $n = 30$ )		Scenario 2 ( $n = 6$ )		Scenario 3 ( $n = 28$ )		Sum ( $n = 64$ )	
		Yes (1)	No (0)	Yes (1)	No (0)	Yes (1)	No (0)	Yes (1)	No (0)
1	Fr.	95	55	21	9	98	42	214	106
	%	63.33	36.67	70.00	30.00	70.00	30.00	66.88	33.12
2	Fr.	81	69	14	16	86	54	181	139
	%	54.00	46.00	46.67	53.33	61.43	38.57	56.56	43.44
3	Fr.	0	30	0	6	2	26	2	62
	%	0.00	100.00	0.00	100.00	7.14	92.86	3.13	96.87
Sum	Fr.	176	154	35	31	186	122	397	307
	%	53.33	46.67	53.03	46.97	60.39	39.61	56.39	43.61

Fr.: Frequency; %: percentile, n: number of cases.

Second, the frequency of Yes and No for the three scenarios wherein no collision occurred is listed in Table 7. A total of 86 frequencies were measured, i.e., 19, 44, and 23 cases in scenario one, two, and three, respectively. In step one, Yes was thrice as much as No; in step two, Yes was twice as high as No; and in step three, Yes was 81.40%. For non-collision cases, the frequency of Yes is much higher than that of No in all the three steps. In particular, 81.40% of cases did not result in collisions in the absence of KBM in step three. These results suggest that there are significant differences in human errors for both collision and non-collision.

The results are summarized as follows. First, among the total of 62 collision cases, 96.87% of them were related to KBM. However, the other two types of errors were also responsible for collisions; 33.12% and 43.44% of collisions occurred when SBSs and RBMs were made.

**Table 7.** Frequency calculation when a collision does not occur ( $n = 86$ ).

Step		Scenario 1 ( $n = 19$ )		Scenario 2 ( $n = 44$ )		Scenario 3 ( $n = 23$ )		Sum ( $n = 86$ )	
		Yes (1)	No (0)	Yes (1)	No (0)	Yes (1)	No (0)	Yes (1)	No (0)
1	Fr.	69	26	149	71	90	25	308	122
	%	72.63	27.37	67.73	32.27	78.26	21.74	71.63	28.37
2	Fr.	67	28	130	90	88	27	285	145
	%	70.53	29.47	59.09	40.91	76.52	23.48	66.28	33.72
3	Fr.	16	3	33	11	21	2	70	16
	%	84.21	15.79	75.00	25.00	91.30	8.70	81.40	18.60
Sum	Fr.	152	57	312	172	199	54	663	283
	%	72.73	27.27	64.46	35.54	78.66	21.34	70.08	29.92

Fr.: Frequency; %: percentile, n: number of cases.

#### 4.2. Correlation Analysis Between Navigator Errors and Ship Collision

To test the relation between navigator errors and ship collision, Pearson's correlation analysis was conducted. The data used for correlation analysis were divided into 1 and 0 by experimenters. Binary code, which is the experimental result of the checklists from 50 participants, was used. The correlations between the four variables, namely SBS, RBM, KBM, and collision, were analyzed using the percentage of Yes for the questions in the checklists. The results are listed in Table 8.

**Table 8.** Pearson's correlation analysis among SBSs, RBMs, and KBMs and ship collision variables.

	SBS	RBM	KBM	Collision
SBS	1.000			
RBM	0.620**	1.000		
KBM	0.430**	0.568**	1.000	
Collision	0.308**	0.545**	0.686**	1.000

\*\* $p < 0.01$ 

The correlation coefficient between SBS and RBM was 0.620, showing a statistically significant positive correlation. A significant and positive correlation was then identified between SBS and KBM with the correlation coefficient of 0.430, whereas the correlation coefficient between SBS and collision was 0.308, also showing a significant and positive correlation. The correlation between SBS and KBM ( $r = 0.568$ ) was significant, and the correlation between RBM and collision was significant and positive with a correlation coefficient of 0.545. Among the three types of human errors, the correlation coefficient between KBM and collision was 0.686 and KBM was most highly correlated to collision.

## 5. Discussion

KBM was most closely related to ship collisions. The correlation analysis to understand the behavior of navigators causing the ship collision showed strong relationships between KBM and collision. Although training to improve relevant skills, rules, and knowledge is important for the reduction of ship collisions, providing training for sufficient knowledge of navigation is more necessary compared to training for skills and rules. Because KBM has been shown to be mostly related to ship collisions, a method to reduce errors is required [30]. Various scenarios can be implemented via ship maneuvering simulators to reduce the navigator's knowledge-based errors through education and training, thereby increasing the safety of ships. For participants who did not cause a collision, the error in the operation of the radar interface was common, whereas the error of the wheel operation rarely occurred. The results of these studies were similar to previous studies [8], which suggest that student navigators made errors although they had been well familiarized with handling navigational equipment interfaces. Accidents cannot be prevented by identifying errors, but steps can be taken to narrow the knowledge gap. Therefore, further research is required on the training program that



enhances novice navigators' ability to handle navigation equipment interfaces. Moreover, ship collision is attributed to the misapplication of rules [9]. However, as per the results of this study, KBM and SBS are more strongly related to ship collision accidents than RBM. Therefore, detailed education and training to reduce KBM and SBS via simulation is necessary for the safety of vessels. However, here again, KBM was measured only once, so the importance can be overemphasized due to the lack of symmetry of the parameters compared to RBM and SBS. This part needs further study. We propose policy implications based on the findings of this study. Measuring the navigator errors on a real ship is tedious and expensive [16]. Therefore, alternatives to control human errors using such a virtual reality experiment are desirable. For example, it can provide effective ways of training for student navigators, who are not ready for independently controlling a real ship, by showing their human errors.

A few limitations of the present study deserve a brief discussion. Participants were student navigators; therefore, they were more likely to make errors compared to navigators who work independently. Thus, a large number of collisions in the experiment may be related to the use of student navigators. Furthermore, errors may occur owing to the difference between the virtual environment and the actual one. Additionally, since the captain forming the bridge team was excluded in this experiment, there is a difference from the probability that an accident may actually occur. Next, there are technical limitations in implementing all real environments through the ship-handling simulator; it is thus desirable to consider developing and using other virtual reality equipment [19,31]. Moreover, the precision and diversity of experimental scenarios are important, but the present scenarios were more directly related to KBMs compared to SBSs and RBMs.

## 6. Conclusions

The results of the experiment demonstrated that among all the collision cases, a navigator's insufficient knowledge is responsible for 96.87% of collisions. Moreover, a strong correlation among collision, RBM, and KBM exists. A collision can be minimized when a navigator has sufficient knowledge of an appropriate course of action, the skills to navigate, and an understanding and application of navigation rules. The results of this experiment demonstrated that navigator errors can be classified into the SBSs, the RBMs, and the KBMs, and that the RBMs and the KBMs are strongly related to ship collision. Based on the experimental results, we proposed a method of education and training of navigators using simulation to enhance the safety of ship navigation. Therefore, navigators should be trained repeatedly in scenarios of unfamiliar situations using simulators to improve their ability to respond to risk. In the future, researchers must continue to examine how to evaluate navigator errors to reduce them. In addition, to minimize navigator errors, human-centered automation methods should be studied, and the relationship between the sensor and the ship-controlling machine should be included.

**Author Contributions:** Conceptualization, J.-B.Y. and C.-k.L.; Investigation, J.-B.Y.; methodology, D.-J.P. and H.-S.Y.; validation, D.-J.P.; data curation, H.-S.Y. and D.-J.P.; Formal analysis, D.-J.P. and H.-S.Y.; writing—original draft preparation, D.-J.P.; writing—review and editing, J.-B.Y. and C.-k.L.; supervision and funding acquisition, J.-B.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** The contents of this paper are the results of the research project funded by the Ministry of Oceans and Fisheries of Korea (fundamental research on maritime accident prevention—phase 2).

**Conflicts of Interest:** The authors declare no conflict of interest.

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