



Article

Identification of the Relationship between Maritime Autonomous Surface Ships and the Operator's Mental Workload

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Abstract: Shipping is an indispensable tool for the sustainable global supply chain, and seafarers play a key role in safe navigation. Maritime autonomous surface ships (MASS) have been expected to reduce marine accidents by human error of the seafarers. On the other hand, MASS may have adverse effects on operators' mental workload (MWL) and increase safety risks in some cases. This research aims to provide a scheme for identifying the relationship between MWL and MASS in the maritime that can be utilised for rulemaking and technological development. The provided scheme identifies the factors that affect the MWL of operators and sub-elements of MWL through gap analysis. Five factors related to MASS operation were defined, in addition to general factors. The case study was carried out by utilising the scheme on typical cases focusing on the normal navigational situation. The NASA task load index method was used to measure MWL. Ten deck officers with various ranks, including the third officer and captain, participated in the case study. The results suggested that various causes such as conflicted situations, machine–human interfaces, mechanical-style movements of the ship, reliability of MASS, and visibility constraints affect the MWL of operators. It also confirmed the verification of the identification scheme.

Keywords: maritime autonomous surface ships (MASS); mental workload; identification scheme; navigation; regulation; stress



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1. Introduction

Shipping is an essential tool for maintaining the supply chain. World seaborne trade has become more than 60 trillion ton-miles internationally, by utilising over 50 thousand commercial vessels [1]. The stability and safety of shipping could not be achieved without skilled and experienced seafarers. They are currently more than 1.6 million, including 774 thousand officers [1]. The turmoil of shipping by the constraints of crew changes due to the restriction of international and domestic transport by the COVID-19 pandemic has reiterated these facts. The International Maritime Organization (IMO) stresses the necessity of seafarers and encourages governments to recognise them as “key workers” who conduct an “essential service” [2].

One of the critical issues for seafarers is human error that causes maritime accidents. According to Coraddu et al. [3], multiple studies indicate that over 80% of marine accidents are caused by human-related failures. One of the crucial factors that induce human error is mental workload (MWL). When MWL exceeds the upper limit, the level of performance decreases [4]. Then, the failure of decision-making and human error are induced [5], and safety may not be maintained [6]. Excessive MWL, similarly referred to as excessive “stress” [7], also causes fatigue that has a significant influence on ship safety, while fatigue is caused by a wide range of elements, such as the lack and poor quality of sleep and rest [8]. The level of influence is enormous, especially for the officers responsible for ships'

safety and security. Crews are exposed to significant stress from work pressure compared to land-based work [9]; therefore, controlling MWL is vital for ship safety.

One useful solution to overcome the issue is ship automation, autonomy, and remoteness. The contemporary development of information and communication technology, including computation and artificial intelligence (AI), has enabled these ships' emergence. IMO defines these ships as maritime autonomous surface ships (MASS). The broad level of autonomous ships has been demonstrated and developed technologically. Examples are international voyages using a navigation support system [10], a fully autonomous project demonstrated in coastal water [11], and an unmanned commercial ship planned in Norway [12].

On the other hand, automation and autonomy will not always decrease mental stress, but rather heighten the risk of human error in some cases. For example, a remote control system needs a higher level of cognition for operators [4] and might lead to higher mental stress. Remote operators' stress at the remote control centre (RCC) might sometimes increase due to information overload by receiving enormous amounts of visual data to compensate for the lack of the feeling of the environment inside or outside a ship [13]. According to Endsley [14], the workload generally increases at the decision-making stage in automation despite decreasing the situation awareness at the implementation stage. This implies that seafarers' stress navigating MASS might be higher at the decision-making stage than traditional ships, depending on the automation level. Wróbel et al. [15] suggested a relationship between keeping psychological conditions and operating remotely controlled ships safely. Taking into account ship safety and the mental health of operators navigating MASS (from now on called "operators"), the MWL of operators should be retained at an appropriate level [4].

The activities to ensure the safety of MASS through international regulation have been carried out at the IMO. It adopted the interim guidelines for a trial in 2019 [16]. It has also conducted regulatory scoping exercises (RSE) of international regulations, including 13 conventions related to maritime safety [17], since 99 sessions of the Maritime Safety Committee (MSC). In the RSE discussions, the IMO [17] shows four regulatory ways to achieve safe operation of MASS, including "amending existing instruments" and "developing new instruments". Some industrial associations and classification societies have also prepared non-mandatory standards and guidance. For example, Maritime U.K. has developed industrial guidance for MASS less than 24 m in length [18]. DNV GL, a classification society, also sets guidelines on technical rule and acceptance criteria, etc., based on a goal-based approach [19]. These guidelines suggest the necessity of the linkage between human elements including stress and technical requirements. While these activities are expected to accelerate, the inclusion of the detailed elements of MWL in the rules is indispensable for establishing an effective regulatory framework.

On the other hand, little research has focused on the relationship between MWL and MASS. Wulvik et al. [20] measured the MWL of engineering students on two scenarios by using bridge simulators to investigate the relationship between the subjective and physiological change of remote operators. Ramos et al. [21] suggested factors that have effects on shore control operators' decisions, such as boredom, by using human reliability analysis. Porathe et al. [22] discussed the human-machine interaction of operators from a human factors perspective. Nevertheless, no research comprehensively discusses a model for identifying the factors that influence operators' MWL in the MASS related systems.

Based on the above background, this paper aims to construct a scheme for identifying the relationship between MWL and MASS in the maritime domain. The scheme can be utilised for not only rulemaking, but also technology development, focusing on the navigation of a ship (Figure 1). It focuses on a normal navigational condition and excludes emergencies such as fire, collision, and search and rescue to simplify the assumption and eliminate complicated cases, considering that MWL is likely to drastically change in these cases.

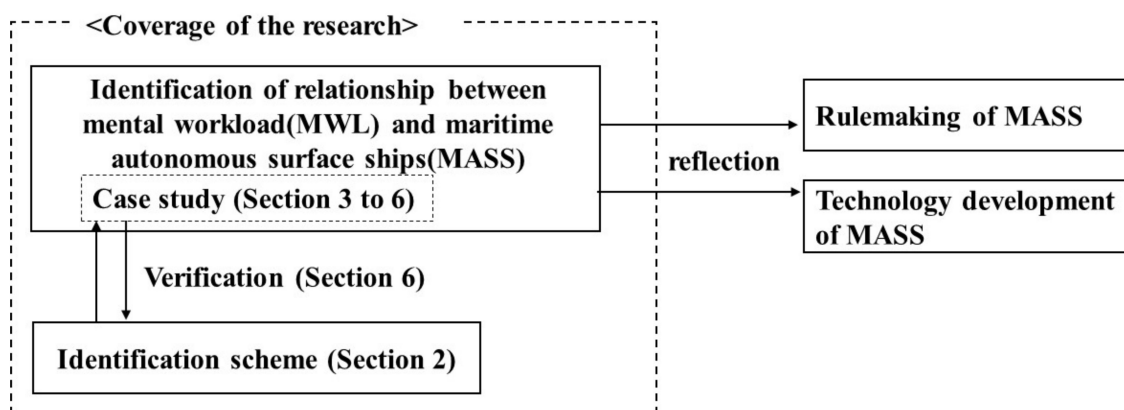


Figure 1. Flow diagram of the research.

The remaining parts are as follows. Section 2 explains the mental workload model that is adopted in this research. This section also builds the identification scheme of the relationship between MWL and MASS based on the adopted model. Sections 3–5 carry out the case study on the typical patterns and show the results. Section 6 discusses the results, including verification of the scheme. Section 7 concludes the research.

2. Relationship between MWL and MASS

This section provides the scheme that identifies the relationship between MWL and MASS, after explaining the concept of MWL.

2.1. Mental Workload and Safety

Hart and Staveland [23] defined the workload as not task-centred, but human-centred. MWL is a widely utilised concept in ergonomics and is used in various ways, including analysis of the effects of additional tasks such as the new automated design [24]. MWL can also measure the effects on elements of the safety of transportation, such as drivers' reaction time [25]. The commonly used MWL concept comprises three domains: the input of load outside the human factor, the effects inside the human factor, and performance (data output) caused by a human operator [7]. Pickup et al. [24] developed Johansson's model [7] by adding the concept of physical and cognitive demand, elements of goals and strategies to discuss the MWL of railway signalling operators. As a partly similar model, Wong and Hang [6] show a unique mental process on road safety, including the MWL model, to analyse contribution factors that influence MWL and discuss the optimal situation. According to them, "task activities" are generated from external conditions such as roadway conditions and traffic situations. Then, the task activities connect to "task demand" through situation awareness. "Motivated capability" originating from physical capacity and psychological condition also influences MWL. When it comes to shipping, there are some differences from land transport. For instance, ships do not have fixed routes except in some areas such as traffic separation schemes, (TSSs), narrow channels, and in ports. Sudden crossing by small boats often happens even in fixed traffic areas. Moreover, some weather conditions (e.g., waves and wind) have effects on ships' manoeuvring. Nevertheless, the mental process is similar between ships and automobiles.

The MWL can measure the safety level. Jex [26] suggests that MWL is the "operator's evaluation of the attentional load margin (between their motivated capacity and the current task demands) while achieving adequate task performance in a mission-relevant context". MWL would have a potential safety risk of navigation when task demand exceeds motivated capacity and the workload margin becomes negative [6]. In this case, MWL is too high. On the other hand, the too-much margin becomes the too-low MWL that also leads to a safety risk due to a careless attitude. They suggested that adjusting these two items was necessary to keep MWL at an optimal level and drive safely. This could apply to the

navigation of a ship. The too-high MWL leads to excess task demand beyond motivated capacity (negative load margin). A potential safety risk of navigation emerges in this situation. Too-low MWL leads to far less task demand than motivated capacity (too much positive load margin), where a potential safety risk of navigation also emerges (Figure 2).

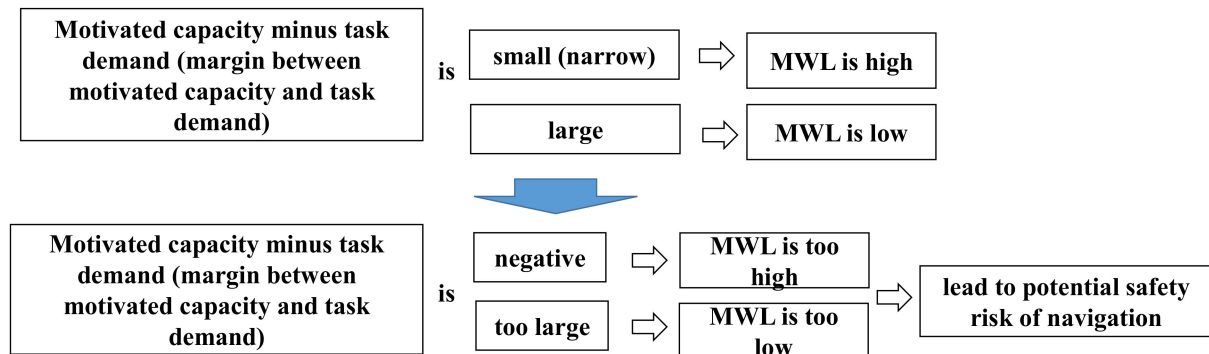


Figure 2. Image of relationship between MWL and navigation safety.

2.2. MWL–MASS Identification Scheme

Figure 3 shows the process for identifying the relationship between MWL and MASS. The scheme finally identifies factors that affect the MWL of operators in the MASS related systems, and sub-elements of MWL that significantly change (step 5 in Figure 3). The first step is to define the candidate factors and set options and levels of each factor (step 1 in Figure 3). Wong and Huang (2009) specify the factors related to driving task demand and drivers' motivated capabilities in the MWL model. Figure 3 lists five key factors for this scheme based on their specification. In addition, it also specifies five factors that should be added, according to the introduction of MASS. A detailed explanation is shown in the next section. Once MWL is measured in each factor (step 2 in Figure 3), the next step is to confirm that the increase and radical decrease in MWL corresponds to the potential safety risks described in Section 2.1 (step 3 in Figure 3). Then, the gap of MWL among levels and options of each factor is measured (step 4 in Figure 3). Finally, factors and sub-elements are identified (step 5 in Figure 3).

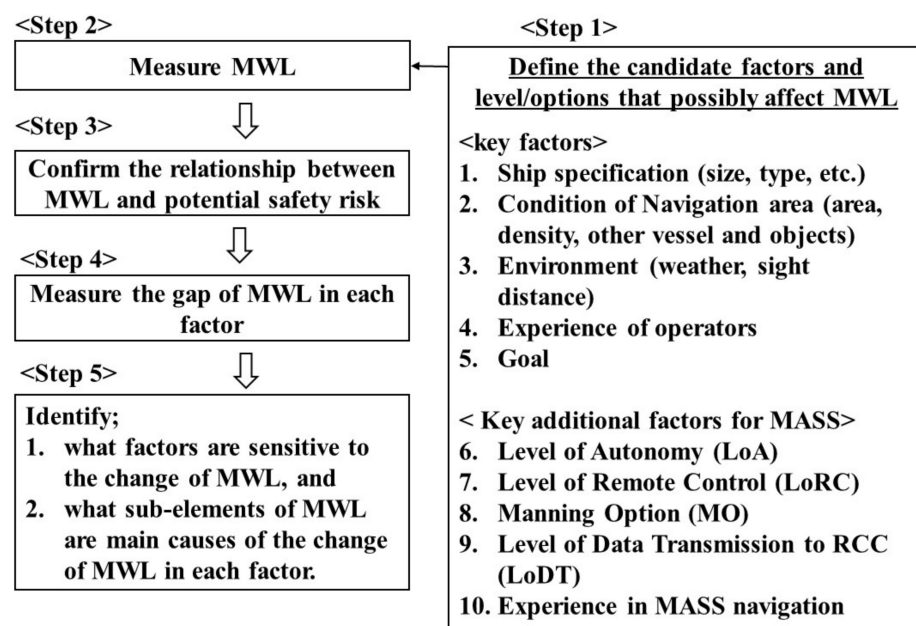


Figure 3. Outline of the scheme for identifying the relationship between MWL and MASS.

2.3. Key Additional Factors for MASS

One of the critical factors is the autonomy level of MASS. Various articles and documents define the level. Zhou et al. [27] separated the process for MASS development into four stages; “system decision support”, “shore-based remote control with seafarers onboard”, “shore-based remote control without seafarers onboard”, and “fully autonomous”. This stage is almost the same as the degree of MASS used in the IMO [17]. These stages can be categorised into two dimensions: level of autonomy (LoA) and level of remote control (LoRC). Maritime U.K. [18] provides six autonomous levels. These categories are defined depending on to what extent the human (operator) is involved in the navigation. DNV GL’s degree [19] is almost the same as Maritime U.K. Ringbom uses two key functions, LoA and manning level on board (MLoB) [28]. MLoB is classified into three levels: fully manned, periodically unmanned, and unmanned. The periodically unmanned level can apply to a wide range of situations, according to LoA. For instance, an unmanned situation onboard might be possible in the open sea and under low congestion, then a watch officer will rush to the bridge in the emergent situation by noticing a false alarm. The Norwegian Forum for Autonomous Ships (NFAS) adopts a similar approach [29]. It divides the level into two axes: “Operational autonomy level” and “Bridge manning level”. Combining four levels of the operational autonomy level and three bridge manning levels, it also defines the type of autonomy (e.g., automatic ship by the combination of automatic levels, and unmanned bridge with crew onboard).

From a human-centred point of view, some issues should be considered to define the autonomy level. Firstly, because multiple crews who are engaged in special duties are onboard a ship unless it is just a one-crew small boat, the manning formation and relationship should be carefully considered. From a fatigue perspective, effective management of the manning level contributes to its reduction [30]. Appropriate manning will be one of the factors to reduce stress and fatigue. “Appropriate” means not only the number of crews but also the tasks given to each crew.

Ships provide a bridge manning matrix that describes who will be on the bridge and what tasks they should do during navigational watch. Based on the matrix, they work together as the bridge team [31]. Bridge resource management is vital for safe navigation. For instance, double manning during navigation causes ambiguous command and enhances collision risk [32]. The responsibility of seafarers is also a critical point. For instance, while the captain has a final and ultimate responsibility for the ship’s safety, remote operators might be responsible for navigational watch on behalf of a captain and manage the bridge team [31]. These differences in the responsibility between seafarers are reflected in the stress. According to Liu et al. [33], a captain shows the highest mental stress in the four levels of navigation staff (captain, officer on watch (OOW), steersman, and pilot), probably due to the difference in responsibility; the steersman’s stress is the lowest due to them having the most straightforward tasks. The MASS related systems drastically change the bridge management team’s formation including their tasks, and formation of the MASS navigation team should be elaborated. Who takes the ultimate responsibility and in which position the person is engaged in duty on the bridge or at the RCC are especially important.

The second key factor is the information that operators acquire. The appropriate information positively affects MWL [6] and contributes to keeping the MWL at an optimal level. Conversely, according to Svensson et al. [34], improper information such as a lack, complexity, and overload of information would deteriorate air pilots’ performance and face the risk. Seafarers are the same; the lack of information as well as information overload induces the issue of MWL and ship navigation in many cases. The complexity of information also influences MWL. MASS operators should manage the information under different conditions from conventional ships. In particular, due to the possible limitation of data transmission between the bridge and RCC, the quality and quantity of the information that the operators at the RCC can receive would change a lot.

The final factor is the experience of navigating MASS as an operator. Wong and Huang [6] suggest that experiences affect motivated capacity in the mental model. This also applies to MASS.

To sum up, the key additional factors for the MASS related systems are: (i) level of autonomy (LoA); (ii) level of remote control (LoRC); (iii) manning option (MO), including formation and responsibility; (iv) level of data transmission to RCC (LoDT); and (v) experience of MASS navigation (EoM).

3. Case Study (Levels and Options of Factors (Step 1 in Figure 3))

The case study was carried out using the identification scheme described in Section 2 to confirm the scheme's verification, find the trend in typical cases, and identify the limitation of the scheme.

3.1. Levels and Options of Candidate Factors That May Affect the MWL of Operators (Step 1 in Figure 3)

This case study sets the levels and options of factors in Table 1. There are many factors (variables); therefore, some of them had only one fixed option, to decrease the number of scenarios that interviewees should answer. At first, the ship type and size were set as a general type of vessel of 3000 gross tonnages (GT). This is because the highest rank in the competencies for seafarers that International Convention on Standards of Training, Certification and Watchkeeping of seafarers (STCW Convention) requires is a master (captain) and a chief mate of a ship of "3000 gross tonnages (GT) and more" (Regulation II/2). The goal to be achieved by operators was to navigate safely to the next port without a long delay. The study set only one option of operator's experience (deck officer), considering the number of interviewees. Operators were assumed to have no experience of navigating MASS because all interviewees had not yet experienced it. Finally, it was assumed that operators at the RCC could acquire the same information displayed on the bridge equipment (e.g., ECDIS and Radar/ARPA) without any delay. The next sections explain the detail of other factors.

Table 1. Outline of factors that may affect MWL of operators in this study.

Factor	Option/Level
Ship size	Approximately 3000 gross tonnages (GT)
Ship type	General type of ship (ocean-going ship)
Goal of operators	Navigate safely to the next port without a long delay
Weather	Clear, Rain, Heavy rain, and Fog (Section 3.2.1)
Navigation area	Open sea, Coastal water, and Channel (Section 3.2.1)
Traffic density	One vessel every four hours, Two vessels every one hour, and Five vessels every one hour. These vessels approached own ship at the same time (Section 3.2.1)
Visibility	Visibility of 1 mile, 3 miles and 7 miles ahead from own ship (Section 3.2.1)
Experience of operators	Deck officer
<Additional factors for MASS>	
Level of Autonomy (LoA)	No autonomy, Navigation support system, Autonomous navigation system with monitoring and Autonomous navigation system without monitoring (Section 3.3.1)
Level of Remote Control (LoRC)	No remote control, Support of navigation, and Navigation (Section 3.3.1)
Manning Option (MO)	Combination of responsible officer and support officer between the bridge of a ship and remote-control centre (RCC) (Section 3.3.2)
Level of Data Transmission to RCC (LoDT) (visibility on screen and sound at RCC)	Static image (one picture/10 s), rough video and clear video (Section 3.3.3)
Level of Data Transmission to RCC (LoDT) (data of navigation equipment (e.g., ARPA/Radar and ECDIS))	Same between the bridge and RCC (i.e., operators can acquire the same data without delay and trouble)
Experience of MASS navigation (EoM)	No experience

3.2. Factors on General Matters (1–5 of Step 1 in Figure 3)

3.2.1. Navigational Condition

Detailed navigational conditions used in this case study, including weather, navigation area, traffic density and visibility, are shown in Table 2. Each option in the table was set based on scenarios that happen in the actual navigation area. It excludes the port area because the operators' task in this area is complicated. They sometimes navigate the ship with the help and advice of a pilot [35] in the pilot area. The main difference between Option 2 and 3 is visibility and average wave height, and the difference between Option 3 and 4 is the navigation area (density).

Table 2. Navigational condition in the case study.

Option	Navigation Area	Expected Area	Frequency of Approaching Ship(s)	Non-AIS-Equipped Ships	Visibility (Weather)	Average Wave Height
NC-1	Open Sea	Pacific Ocean	A vessel every 4 h	No	Visibility of 3 miles ahead (Rain)	3 m
NC-2	Coastal water	Coast of Boso Peninsula	Two vessels every one hour at the same time	Small fishing vessels Leisure crafts	Visibility of 7 miles ahead (Clear)	1 m
NC-3					Visibility of 1 mile ahead (Heavy rain)	3 m
NC-4	Channel	Uraga Channel	Five vessels every one hour at the same time		Visibility of 1 mile ahead (Fog)	1 m

AIS: Automatic Identification System.

3.3. Additional Factors for MASS (6–10 of Step 1 in Figure 3)

3.3.1. Level of Autonomy (LoA) and Level of Remote Control (LoRC)

LoA and LoRC were categorised into four and three levels, respectively, based on the function of autonomy and remote-control systems (see Table 3). LoA4 was eliminated in this case study because this level does not involve any operators. The autonomy functions of LoA-2 and LoA-3 are as follows:

- LoA-2: The system can identify non-AIS ships (e.g., small boats) and objects (e.g., driftwoods), make some warning on the existence of these objects, and advise on appropriate collision avoidance routes;
- LoA-3: The system can make autonomous collision avoidance in addition to LoA2. The system takes preventive action for collision avoidance before the target ships enter the obstacle zone by the target;
- Both systems are highly reliable, although there is a slight chance of failure.

Table 3. LoA and LoRC in the case study.

LoA	Detail	LoRC	Detail
LoA-1	No Autonomy	LoRC-1	No remote control
LoA-2	Navigation Support System (NSS)	LoRC-2	Support of Navigation
	The system can identify non-AIS ships (e.g., small boats) and objects (e.g., driftwood), make a warning, and advise appropriate collision avoidance routes.		
LoA-3	Autonomous Navigation System (ANS) with monitoring	LoRC-3	Navigation
	The system can make autonomous collision avoidance in addition to LoA-2, and is monitored by responsible officers (ROs) defined in Section 3.3.2.		
LoA-4	Autonomous Navigation System (ANS) without monitoring		
	This system is totally autonomous without any human monitoring (not applicable in the case study).		

3.3.2. Manning Option (MO)

Table 4 shows the manning options in this study. Navigational manning comprises a captain, OOW, remote operator, lookout, and a helmsperson. A helmsperson steers a ship by order of responsible officers on the bridge. This position might be omitted if the autonomy level is high, because responsible officers can easily steer a ship independently. The lookout has the task to “look out” around the ship on the bridge and reports every important sight and hearing signal to watchkeeping officers [31]. This study divides the manning into two groups:

- Group 1 (responsible officer: RO): remote operators, OOWs or captain and helmsperson (total of two persons) who have the responsibility for navigation;
- Group 2 (support operator: SO): lookout for supporting watchkeeping.

Table 4. Manning options in the case study.

Option	MO-1	MO-2	MO-3	MO-4	MO-5	MO-6
	LoRC-1	LoRC-2	LoRC-1	LoRC-3	LoRC-3	LoRC-3
Bridge of a ship	RO + SO	RO	RO	-	SO	-
Remote control centre (RCC)	-	SO	-	RO + SO	RO	RO

3.3.3. Level of Data Transmission to RCC (LoDT) (Visibility on Screen and Sound at RCC)

The speed of network connection between a ship and shore directly affects the level of data transfer and information that operators can receive at the RCC. The current satellite system commonly used for ships is L-band, and its bandwidth is low (e.g., 432 Kbps of the Inmarsat Fleet Broadband Service [36]). In this case, it is not easy to continuously and simultaneously send large amounts of data such as video data to shore. On the other hand, recent IT development has led to improved commercial satellite systems [37]. For example, StarLink plans to service 1 Gbps per user by utilising low earth orbit satellites [38]. In some sea areas close to land, ships can connect to 3G or LTE, whose maximum bandwidths are, e.g., from 2–3 Mbp to 40–50 Mbp of upstream speed in Japan, from a base station on the land. Rødseth et al. [39] suggest that around 4 Mbps should be required for a sufficient remote control system.

Nevertheless, the necessary bandwidth depends on the required resolution and level of redundancy, etc. Taking these into account, this study defines three levels of information level between a bridge and RCC, shown in Table 5. Level 2 utilises a similar situation to the demonstration project on remote control navigation that was carried out by using “Shioji-maru” of the Tokyo University of Marine Science and Technology in 2018.

Table 5. Level of visibility on screen and sound at the RCC.

Visibility	LoDT-1: Static image with one picture/10 s	
	- Identify vessel of a length of 45 m in 1 mile under the clear weather condition in the daytime.	
	LoDT-2: (rough) Video	
	- Identify vessel of a length of 45 m in 1 mile under the clear weather condition in the daytime.	
	LoDT-3: (clear) Video	
	- Identify vessel of a length of 45 m in 6 miles under the clear weather condition in the daytime.	
	- Recognise the mast of a vessel in 10 miles.	
Time delay	<0.1 s	
Failure of data transmission	Redundancy by another internet connection Recover in 1 min	
Sound	Clear and no delay	

4. Case Study (Method)

4.1. Participants

The study selected the participants based on the following criteria:

- They were active seafarers, because they should accurately grasp the real situation from recorded video during the interview;
- They were qualified officers in charge of a navigational watch, chief mates (officers) or masters (captains) in accordance with regulation II/1 and II/2 of the STCW Convention, because they answered questions as a responsible officer (RO);
- They had an experience of international ocean-going service on a ship of more than 3000 GT; scenarios in the case study included the option of navigating this size of ships in the ocean;
- Participants should have a variation of ranks and experiences to acquire balanced results.

As a result, a total of ten (10) seafarers participated in the study. Their average experience of sea-going service as an officer was 9.5 years, with a maximum of 20 years and a minimum of 3 years. Their experience of sea-going service included very large crude carriers (VLCCs) of over 150,000 GT, container ships, roll-on/roll-off ships (ferries) and ocean-going training ships of over 4000 GT. Their latest ranks in the ship are shown in Table 6.

Table 6. Participant's latest rank in the ship.

Level	Rank	Number of Interviewees
Management level	Captain (Master)	2
	Chief officer (Chief mate)	3
Operational level	2nd officer	2
	3rd officer	3

4.2. Scenario Setting

Table 7 shows the number of scenarios that were used in the interview. The number was scrutinised to 25 (28 with duplication) for the participants to be able to concentrate on the interview. Thus, in addition to Table 1, the study fixed some variable factors in the scenarios to one option or level, as described in the note (assumption) of Table 7. At first, coastal navigation (NC-2) was used in factors 1, 2 and 4 of Table 7 as an assumption, considering that MASS have been developed for navigating coastal water. In addition, clear visibility (good weather) in NC-2 was adopted to avoid the complexity of analysis. LoDT-2 (rough movie on the screen of RCC) was also used in factors 1, 2, and 3 of Table 7 as an assumption, considering the current communication level. LoA-3 (autonomous navigation system) was used in factors 3 and 4 of Table 7 as an assumption of autonomy level to recognise the direct change of mental stress under the autonomous conditions. Finally, MO-4 (every navigational staff at RCC) was adopted in factor 4 of Table 7 as an assumption to exclude the effects of support operators onboard a ship on MWL.

4.3. Methodology

The study adopted an interview that utilised the NASA task load index (NASA-TLX) [23]. NASA-TLX is a commonly used subjective MWL measurement tool. It measures the weighted average of MWL based on six subscales: mental demands (MD); physical demands (PD); temporal demands (TD); frustration level (FR); effort (EF); and own performance (OP). These ratings can lead to many “theories that equate workload with the magnitude of the demands imposed on the operator, physical, mental, and emotional responses to those demands” [40]. This study also adopted the six subscales as the sub-elements of MWL in step 5 of Figure 3. In order to obtain the results of step 3 in Figure 3,

the following closed question was added in each answer sheet; “Is your MWL in the given scenario as high as you feel a potential safety risk?”

Table 7. Number of scenarios.

Variable Factors in Section 3.2	Number of Scenarios	Note (Assumption)
1. Level of Autonomy (LoA)	17 scenarios	
2. Manning Option (MO)	Three LoAs in Table 3 and six MOs in Table 4 are combined. One scenario (LoA-1 (no autonomy) and MO-3 (only RO onboard ship without support)) is excluded from the study because this scenario just makes current manning more severe without technological development and would be unlikely to happen.	NC-2 (coastal water in clear visibility) and LoDT-2 (rough movie on the screen of RCC) are applied as an assumption.
3. Navigational Condition (NC)	8 scenarios (*) Four NC options in Table 2 and two MOs (MO-1 and MO-4)) in Table 4 are combined. (*) Two scenarios are duplicated with the scenarios used in LoA and MO.	LoA-3 (autonomous navigation system) and LoDT-2 (rough movie on the screen of RCC) are applied as an assumption.
4. Level of Data Transmission to RCC (LoDT) (visibility of screen and sound at RCC)	3 scenarios (*) Three LoDTs in Table 5 are used. (*) One scenario is duplicated with the scenario used in LoA and MO.	LoA-3 (autonomous navigation system), MO-4 (every navigational staff at RCC) and NC-2 (coastal water in clear visibility) are applied as an assumption.
Total	28 scenarios (25 scenarios without duplication)	

4.4. Process of Interview

Figure 4 shows the process of the interview. The interview was on a one-to-one basis through a social network service (SNS) or face-to-face. Prior to the interview, the interviewees received information on the research’s objective and outline and consented to take the interview. The interviewer explained the detail of each scenario before interviewees filled the answer in each of them. The interviewees answered the questions under the assumption that they navigated ships as responsible officers (ROs). The average length of each interview was 2.5 h.

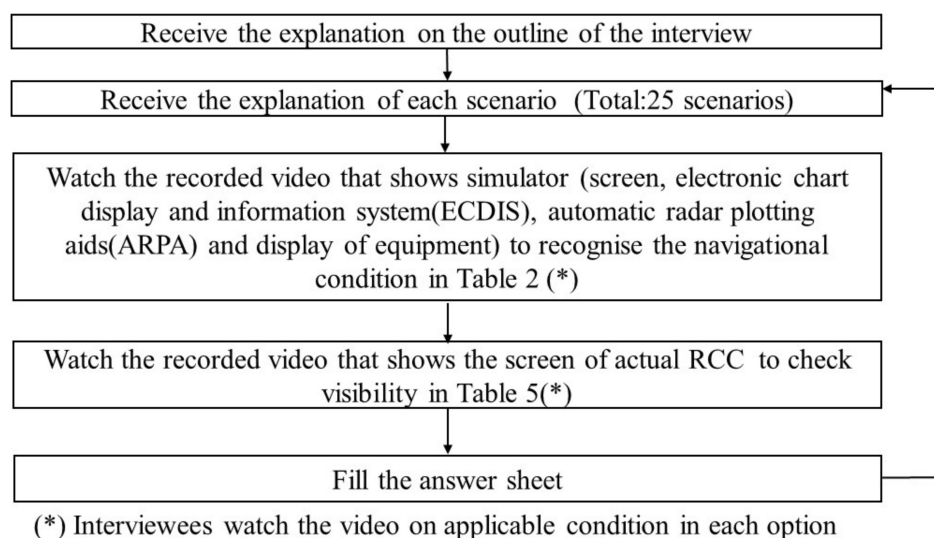


Figure 4. Outline of interview process.

5. Case Study (Results (Step 2 to 5 in Figure 3))

After measuring MWL by using the NASA-TLX (step 2 in Figure 3), steps 3 to 5 were analysed.

5.1. Relationship Between MWL and Potential Safety Risk (Step 3 in Figure 3)

Figure 5 shows the number of interviewees who answered that their MWL was so high as to feel a potential safety risk of navigation. The horizontal axis shows the average MWL of interviewees in terms of each scenario. The number of interviewees in the vertical axis indicates the level of potential safety risk of navigation. The level of potential safety risk is higher when the number of interviewees in the vertical axis increases.

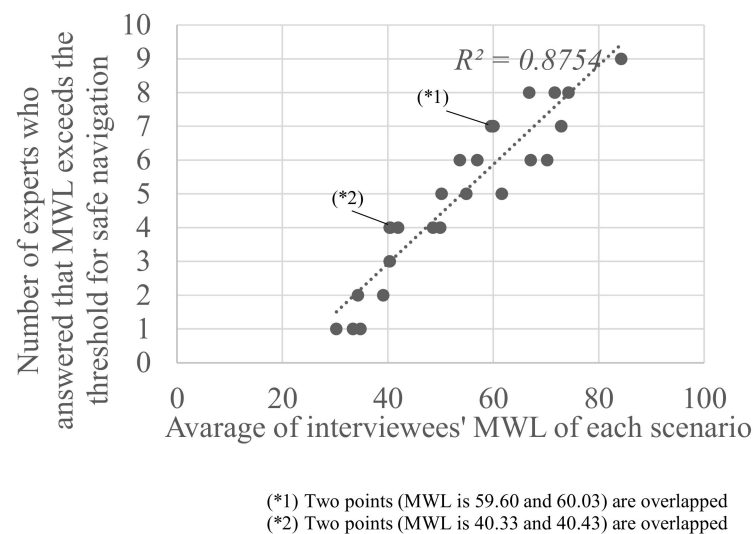


Figure 5. Relationship between the average weighted MWL and potential safety risk of navigation.

The results suggest a strong positive correlation between the two variables. The number of interviewees in the vertical axis increases approximately linearly with the increase in the average of interviewees' MWL in the horizontal axis. This means that the potential safety risk of navigation (vertical axis) increases when MWL (horizontal axis) increases. This can verify the theory on the relationship between the potential safety risk of navigation and MWL in Section 2.1 from one side. When MWL increases and becomes too high, a navigational safety risk emerges. Thus, this case study can identify the relationship between MWL and MASS in the context of minimising the navigational safety risk by decreasing the MWL.

On the other hand, Section 2.1 also indicates another theory on the relationship between navigation safety risk and MWL. The potential safety risk of navigation emerges when MWL is too low due to careless attitude, etc. If this theory could be verified, the number of experts in the vertical axis would increase when MWL in the horizontal axis was very small (negative correlation). However, the results do not show a negative correlation. Thus, the case study can neither justify the theory nor identify the relationship between MWL and MASS in the context of minimising the navigational safety risk by avoiding a too-low MWL.

5.2. Gap of MWL in Each Factor (Step 4 in Figure 3)

5.2.1. Ship Autonomy Level

Table 8 shows the average weighted MWL of interviewees ($n = 10$) with the matrix of the navigation manning and level of autonomy. As described in Section 4.2, the option of a combination of MO-3 and LoA-1 (grey-coloured cell in Table 8: a responsible operator (RO) onboard navigates the ship alone without any autonomous system and support by lookout) was not applied in this study. Rough video was displayed on the screen at RCC (LoDT-2 in

Table 5). The ship was assumed to navigate the coastal water in clear visibility (NC-2 in Table 2). Figure 6 shows the scenarios considered to have a significant difference between the level of autonomy in the same manning options ($p < 0.05$ of t -test (two-tailed)). Cells (scenarios) at a start point and an endpoint of an arrow line in the figure are significantly different. Table 9 shows the difference of MWL in the scenarios extracted in Figure 6. Table 10 breaks down the differences into six sub-elements and describes the sub-elements considered to have a significant difference between them ($p < 0.05$ of t -test). These suggest the following findings:

- Installation of navigation support systems (LoA-2) and autonomous navigation systems (LoA-3) do not show apparent positive effects on the MWL of responsible operators (ROs) when they are onboard a ship (MO-1, MO-2 and MO-3). The autonomous system rather negatively affected MWL in one case ((1) in Figure 6 and Table 9);
- Installation of navigation support systems (LoA-2) and autonomous navigation systems (LoA-3) show apparent positive effects on the MWL when ROs are at the RCC (MO-4, MO-5 and MO-6);
- MWL of ROs does not clearly change between navigation support (LoA-2) and autonomous navigation (LoA-3) when they are at RCC and lookouts support them (MO-4 and MO-5). Positive effects emerge when they navigate alone at the RCC (MO-6: (7) in Figure 6 and Table 9);
- Mental demands are the key sub-elements to decrease the MWL of ROs at RCC when autonomous navigation systems are installed in the case of (3), (5) and (6) in Figure 6 (Table 10). Mental demands were also the key sub-elements which increased the MWL of ROs on the bridge when autonomous navigation systems were installed in the case of (1) of Figure 6 (Table 10);
- Effort was the key sub-element to decrease the MWL of ROs at RCC when autonomous navigation systems were added to the navigation support systems in the case of (7) of Figure 6 (Table 10).

Table 8. Average rating of MWL (matrix of navigation manning and level of autonomy).

Manning Option and Level of Remote Control				Level of Autonomy		
Manning Option	Level of Remote Control	Bridge	RCC	LoA-1	LoA-2	LoA-3
				No Autonomy	Navigation Support System	Autonomous Navigation System with Monitoring
MO-1	LoRC-1	RO + SO	-	33.37(22.30)	30.23 (18.20)	39.13 (19.30)
MO-2	LoRC-2	RO	SO	41.93(23.12)	40.33 (22.97)	40.43 (22.21)
MO-3	LoRC-1	RO	-		34.83 (18.55)	34.33 (14.38)
MO-4	LoRC-3	-	RO + SO	66.80(15.80)	59.60 (16.21)	56.97 (14.33)
MO-5	LoRC-3	SO	RO	54.87(17.99)	50.20 (19.23)	48.53 (18.84)
MO-6	LoRC-3	-	RO	72.87(16.80)	67.10 (14.98)	60.03 (16.19)

Numbers in parentheses are standard deviations. RO, responsible operator; SO, support operator.

Table 9. Difference of MWL in scenarios extracted in Figure 6.

In Manning Option	MWL of RO in LoA-Endpoint of Arrow Line in Figure 6	Increase or Decrease	Comparison to MWL of RO in LoA-Start Point of Arrow Lines in Figure 6 (Parentheses Are Numbers in Figure 6) [Square Brackets Are Difference of MLW]
MO-1	LoA-3	increase	(1) LoA-2 [+8.9]
MO-4	LoA-2	decrease	(2) LoA-1 [−7.20]
	LoA-3	decrease	(3) LoA-1 [−9.83]
MO-5	LoA-2	decrease	(4) LoA-1 [−4.67]
	LoA-3	decrease	(5) LoA-1 [−6.34]
MO-6	LoA-3	decrease	(6) LoA-1 [−12.84], (7) LoA-2 [−7.07]

Level of Autonomy (LoA)				LoA-1	LoA-2	LoA-3
Manning Option	Level of Remote Control	Bridge	RCC	No Autonomy	Navigation Support System	Autonomous Navigation System with monitoring
MO-1	LoRC-1	RO + SO		33.37 22.30	30.23 18.20	39.13 19.30
MO-2	LoRC-2	RO	SO	41.93 23.12	40.33 22.97	40.43 22.21
MO-3	LoRC-1	RO			34.83 18.55	34.33 14.38
MO-4	LoRC-3		RO + SO	66.80 15.30	59.60 16.21	56.97 14.33
MO-5	LoRC-3	SO	RO	54.87 17.99	40.20 19.23	48.53 18.84
MO-6	LoRC-3		RO	62.87 16.80	42.97 14.98	60.03 16.19

Figure 6. Scenarios that have a significant difference between LoA in the same MO according to t -test ($p < 0.05$) (described by arrow lines).

Table 10. Sub-elements of MWL that have a significant difference on each number in Figure 6 ($p < 0.05$ of t -test).

No	$p < 0.05$	No	$p < 0.05$	No	$p < 0.05$	No	$p < 0.05$	No	$p < 0.05$	No	$p < 0.05$	No	$p < 0.05$
(1)	MD	(2)	-	(3)	MD/TD	(4)	EF	(5)	MD	(6)	MD/FR	(7)	EF

MD, mental demands; TD, temporal demands; EF, effort; FR, frustration level.

5.2.2. Manning Option

Figure 7 shows the scenarios considered to have a significant difference between manning options in the same level of autonomy ($p < 0.05$ of t -test) in Table 8. Cells (scenarios) at the start point and endpoint of an arrow line in the figure have a significant difference. Table 11 shows the difference of MWL in the scenarios extracted in Figure 7. Table 12 breaks down the difference into six sub-elements and describes the sub-elements considered to have a significant difference between them ($p < 0.05$ of t -test). These suggest the following findings:

- Formation changes between the onboard bridge and RCC (MO-1 and MO-2) and the decrease in lookouts (MO-3) generally do not have apparent effects on MWL of the responsible operators (ROs), regardless of the level of autonomy when they are onboard a ship;
- MWL of the ROs significantly worsens when they are at RCC (MO-4, MO-5, and MO-6) compared to when they are on the bridge of a ship (MO-1, MO-2, and MO-3). The effects especially emerge when ROs operate alone at RCC (MO-6: (1), (2), (9)–(11), (21)–(23) in Figure 7 and Table 11). Negative effects on MWL are much smaller when an autonomous navigation system has been installed (LoA-3) compared to no autonomy (LoA-1) and navigation support (LoA-2). In other words, an autonomous navigation system works well to alleviate the mental stress of ROs at RCC (Figure 7);
- MWL of ROs at RCC decrease when a lookout onboard a ship supports them (MO-5), compared to the other cases (MO-4 and MO-6) when they are at RCC ((3), (6), (13), (16) and (24) in Figure 7 and Table 11);
- The set of mental demands and frustration are the overwhelming sub-elements that show the clear effects according to the change of navigation manning ((1), (2), (4), (7)–(11), (14), (15), (17)–(26) of Table 12);

- Time pressure, effort, and own performance emerged in two cases as significant sub-elements that increase MWL. Both cases are related to the situation where the lookout supports RO navigating at RCC ((6) and (13) in Table 12).

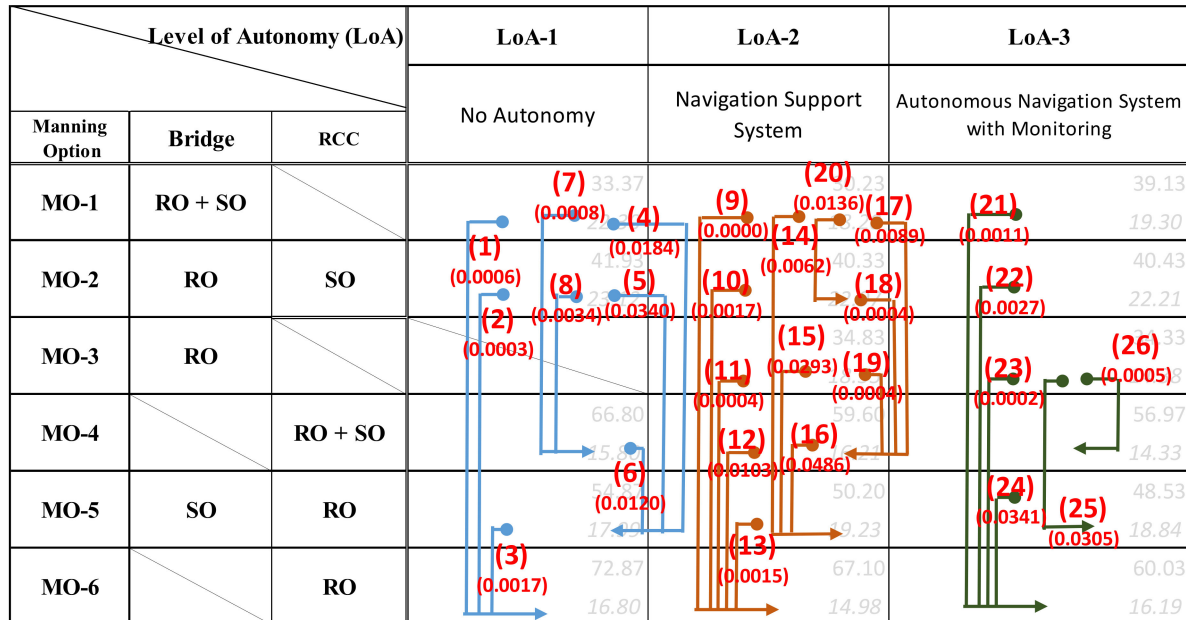


Figure 7. Scenarios that have a significant difference between MO in the same LoA according to *t*-test ($p < 0.05$) (described by arrow lines). Numbers in parentheses are *p*-values of the *t*-tests.

Table 11. Difference of MWL in scenarios extracted in Figure 7.

In LoA	MWL of RO in MO-Endpoint of Arrow Line in Figure 7	Increase or Decrease	Comparison to MWL of RO in MO-Start Point of Arrow Lines in Figure 7 (Parentheses Are Numbers in Figure 7) [Square Brackets Are Difference of MWL]
LoA-1	MO-6	increase	(1) MO-1 [+39.5], (2) MO-2 [+30.94], (3) MO-5 [+18.00]
	MO-5	increase	(4) MO-1 [+21.5], (5) MO-2 [+12.94]
		decrease	(7) MO-4 [−11.93]
	MO-4	increase	(7) MO-1 [+33.43], (8) MO-2 [+24.87]
LoA-2	MO-6	increase	(9) MO-1 [+36.87], (10) MO-2 [+26.77], (11) MO-3 [+32.27], (12) MO-4 [+7.5], (13) MO-5 [+16.90]
	MO-5	increase	(14) MO-1 [+19.97], (15) MO-3 [+15.37]
		decrease	(16) MO-4 [−9.40]
	MO-4	increase	(17) MO-1 [+29.37], (18) MO-2 [+19.27], (19) MO-3 [+24.77]
LoA-3	MO-2	increase	(20) MO-1 [+10.1]
	MO-6	increase	(21) MO-1 [+20.90], (22) MO-2 [+19.60], (23) MO-3 [+25.70], (24) MO-5 [+11.50]
	MO-5	increase	(25) MO-3 [+14.20]
	MO-4	increase	(26) MO-3 [+22.64]

Table 12. Sub-elements of MWL that have a significant difference on each number in Figure 7 ($p < 0.05$ of t -test).

No.	$p < 0.05$	No.	$p < 0.05$	No.	$p < 0.05$	No.	$p < 0.05$
(1)	MD/FR	(2)	MD/FR	(3)	MD	(4)	MD/FR
(5)	FR	(6)	MD/TD	(7)	MD/FR	(8)	MD/FR
(9)	MD/FR	(10)	MD/FR	(11)	MD/FR	(12)	-
(13)	OP/EF/FR	(14)	MD/FR	(15)	MD/FR	(16)	-
(17)	MD/FR	(18)	MD/FR	(19)	MD/FR	(20)	MD/FR
(21)	MD/FR	(22)	MD/FR	(23)	MD/FR	(24)	MD/FR
(25)	MD/FR	(26)	MD/FR				

MD, mental demands; TD, temporal demands; EF, effort; FR, frustration level; OP, own performance.

5.2.3. Navigational Condition

Table 13 shows the average weighted MWL of interviewees ($n = 10$) depending on navigational condition. As described in Section 4.2, two typical manning cases are applied; every navigation staff is on board a ship (MO-1) and at RCC (MO-4). Rough video is displayed on the screen at RCC (LoDT-2 in Table 5). The ship is assumed to have an autonomous navigation system (LoA-3). Figure 8 shows the scenarios considered to have a significant difference between navigational conditions in the same manning option ($p < 0.05$ of t -test). Cells (Scenarios) at a start point and an endpoint of an arrow line in the figure have a significant difference. Table 14 shows the difference of MWL in the scenarios extracted in Figure 8. Table 15 breaks down the difference into six sub-elements and describes the sub-elements considered to have a significant difference between them ($p < 0.05$ of t -test). These suggest the following findings:

- MWL significantly increases when the visibility is restricted due to weather conditions (NC-3 and NC-4) compared to the clear visibility (NC-1 and NC-2), even if the ships have an autonomous navigation system (LoA-3) ((1) to (6), (8) and (9) in Figure 8 and Table 14).
- MWL is quite high when traffic condition is severest in the channel in bad weather (NC-4). The responsible operators (ROs) especially feel the highest mental stress in all 25 scenarios of the study when they are at RCC (Table 13).
- Responsible operators feel more time pressure in the congested channel (NC-4) than navigating in the other areas when they are at RCC (MO-4) ((5)–(7) in Table 15). Notwithstanding, mental demands and frustration are also the primary sources of a significant increase in MWL in general (Table 15).

Table 13. Average rating of MWL (navigational area).

Manning Option and Level of Remote Control				Navigational Condition			
Manning Option	Level of Remote Control	Bridge	RCC	NC-1	NC-2	NC-3	NC-4
				Ocean: relatively clear visibility	Coastal: clear visibility	Coastal: restricted visibility	Channel: restricted visibility
MO-1	LoRC-1	RO + SO	-	40.37 (20.37)	39.13 (19.30)	61.60 (18.55)	70.23 (19.77)
MO-4	LoRC-3	-	RO + SO	53.67 (14.87)	56.97 (14.38)	71.67 (20.95)	84.27 (14.45)

Numbers in parentheses are Standard Deviation. RO: Responsible operator, SO: Support operator.

Navigational Condition (NC)			NC-1	NC-2	NC-3	NC-4
Manning Option	Onboard Bridge	RCC	Ocean sea: Relatively clear visibility	Coastal: Clear visibility	Coastal: Restricted visibility	Channel: Restricted visibility
MO-1	RO + SO		(3) (0.0153) 40.37	(1) (0.0008) 39.13	(2) (0.0003) 61.60	70.23
MO-4		RO + SO	(5) (0.0000) 53.67	(6) (0.0004) 56.97	(7) (0.0119) 71.67	84.27
			(8) (0.0011) 14.78	(9) (0.0189) 14.33	20.95	14.45

Figure 8. Scenarios that have a significant difference between navigational conditions in the same MO according to *t*-test ($p < 0.05$) (described by arrow line) (Number in parentheses is *p*-value of *t*-test).

Table 14. Difference of MWL in scenarios extracted in Figure 8.

In Manning Option	MWL of RO in NC-Endpoint of Arrow Line in Figure 8	Increase or Decrease	Comparison to MWL of RO in NC-Start Point of Arrow Lines in Figure 8 (Parentheses Are Numbers in Figure 8) [Square Brackets Are Difference of MLW]
MO-1	NC-4	increase	(1) NC-1 [+29.86], (2) NC-2 [+31.1]
	NC-3	increase	(3) NC-1 [+21.23], (4) NC-2 [+22.47]
MO-4	NC-4	increase	(5) NC-1 [+30.6], (6) NC-2 [+27.30], (7) NC-3 [+12.6]
	NC-3	increase	(8) NC-1 [+18.00], (9) NC-2 [+14.70]

Table 15. Sub-elements of MWL that have a significant difference on each number in Figure 8 ($p < 0.05$ of *t*-test).

No.	$p < 0.05$	No.	$p < 0.05$	No.	$p < 0.05$	No.	$p < 0.05$
(1)	MD/FR	(2)	MD/FR	(3)	MD/FR	(4)	MD/FR
(5)	MD/TD/FR	(6)	MD/TD	(7)	TD	(8)	MD/FR
(9)	-						

5.2.4. Level of Data Transmission to RCC (LoDT) (Visibility on the Screen)

Table 16 shows the average weighted MWL of interviewees ($n = 10$) depending on the screen's visibility. Every operator was at RCC (MO-4) in the coastal water in clear visibility (NC-2). The ship was assumed to have an autonomous navigation system (LoA-3). Figure 9 shows the scenarios considered to have a significant difference between data transmission levels ($p < 0.05$ of *t*-test). Cells (scenarios) at a start point and at an endpoint of an arrow line in the figure have a significant difference. Table 17 shows the difference of MWL in the scenarios extracted in Figure 9. Table 18 breaks down the difference into six sub-elements and describes the sub-elements considered to have a significant difference between them ($p < 0.05$ of *t*-test). These suggest the following findings:

- MWL significantly increased when the responsible officers (ROs) could see only a static image on the screen at RCC (LoDT-1: (1) and (2) in Figure 9 and Table 17). On the other hand, a significant difference between rough video (LoDT-2) and clear video (LoDT-3) was not found;

- Time pressure and frustration were the main critical sub-elements in a significant change (Table 18).

Table 16. Average rating of MWL (visibility on the screen).

Manning Option and Level of Remote Control				Level of Data Transmission to RCC		
Manning Option	Level of Remote Control	Bridge	RCC	LoDT-1	LoDT-2	LoA-3 LoDT-3
				Static image: 1 picture/10 s	Rough video	Clear video
MO-4	LoRC-3	-	RO + SO	74.27 (12.29)	56.97 (14.33)	49.93 (13.86)

Numbers in parentheses are standard Deviations. RO, responsible operator; SO, support operator.

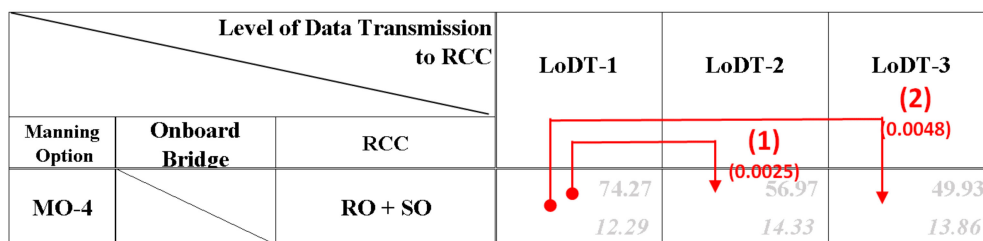


Figure 9. Scenarios that have a significant difference between level of data transmission to RCC according to *t*-test ($p < 0.05$) (described by arrow lines). Numbers in parentheses are *p*-values of *t*-tests.

Table 17. Difference of MWL in scenarios extracted in Figure 9.

In Manning Option	MWL of RO in LoDT-Endpoint of Arrow Line in Figure 9	Increase or Decrease	Comparison to MWL of RO in LoDT-Start Point of Arrow Lines in Figure 9 (Parentheses Are Numbers in Figure 9) [Square Brackets Are Difference of MLW]
MO-4	LoDT-2	decrease	(1) LoDT-1 [−17.30]
	LoDT-3	decrease	(2) LoDT-1 [−24.34]

Table 18. Sub-elements of MWL that have a significant difference on each number in Figure 9 ($p < 0.05$ of *t*-test).

No.	$p < 0.05$	No.	$p < 0.05$
(1)	TD/FR	(2)	MD/TD/EF/FR

MD, mental demands; TD, temporal demands; EF, effort; FR, frustration level.

5.3. Summary of the Results

Table 19 sums up key points of the results in Section 5.2. The table also suggests the main linkages between the factors and the findings described in Section 6.1.

Table 19. Summary of the results in Section 5.2.

Factor	Key Sub-Elements of MWL That Mainly Cause MWL Change	Note (Effects on MWL)	Main Linkage with Findings in Section 6.1 (Section Number)
Level of Autonomy (LoA)	MD	RO is on the bridge - No significant effect (negative effects in one case) RO is at RCC	- Reliability of the autonomous system (Section 6.1.4) - Mechanical-style movement of the system (Section 6.1.5)
	EF	- Positive effects by installing autonomous systems - No significant effect between NSS and ANS (except when RO is alone)	
Manning Option (MO)	MD	RO is on the bridge - No significant effect by manning change RO is at RCC	- Reliability of the autonomous system (Section 6.1.4) - Conflicted situation (Section 6.1.1) - Physical restriction (Section 6.1.2) - Human–human and human–machine interface (Section 6.1.3)
	FR	- Significant negative effects compared when RO is on the bridge - Decrease in MWL when lookout is on the bridge	
Navigational Condition (NC) (area, traffic density, weather, visibility)	TD	- Negative effects under high traffic density	- Conflicted situation (Section 6.1.1) - Visibility constraint (Section 6.1.6)
	MD	- Significant negative effects in restricted visibility in bad weather	
	FR		
Level of Data Transmission to RCC (LoDT) (visibility on the screen)	TD	- Significant negative effects by using a static image	- Visibility constraint (Section 6.1.6)
	FR	- No significant effect between rough and clear movie	

MD, mental demands; TD, temporal demands; EF, effort; FR, frustration level; NSS, navigation support system; ANS, autonomous navigation system.

6. Discussion

6.1. Imprecation of Results

The results in the last chapter and discussions with interviewees imply some findings on factors that affect the MWL of ROs.

6.1.1. Conflicted Situation

The first is the conflicted feeling between the safety and effectiveness of navigation. Crews navigate ships utilising personal capabilities including “spatial awareness” [41]. However, ROs navigate the ship at the RCC under restricted conditions, including limited information. In this situation, they express a desire to largely deviate from the planned route to secure safety. Nevertheless, they also face the pressure to maintain a “cost-effective” route to ensure that the ship arrives at the next destination on time. This situation induces severe ROs mental pressure. Congested situations and the existence of other appearing ships also challenge them to deviate routes for keeping safe. These conditions cause an increase in mental demands and frustration.

6.1.2. Physical Restriction

Physical restriction leads to the increment of frustration. An interviewee expressed self-confidence that he could deal with various situations and make decisions with his responsibility even if the condition is harsh when navigating a ship on the bridge. Ac-

According to Hanton and Connaughton [42], self-confidence is closely related to anxiety and performance. When the RO could navigate a ship at a physically different and restricted place, such as the RCC, these situations influence self-confidence. This leads to anxiety about the performance and impatience.

6.1.3. Human–Human and Human–Machine Communication

Support of ROs at the RCC by lookouts at the bridge of a ship decreased MWL compared to the other options provided to ROs at the RCC. Interviewees stated that they communicate with lookouts onboard, suggesting that they gather the necessary information. In other words, they utilise the lookouts as part of their “eyes.” They pointed out that human–human communication is mentally more comfortable than using autonomous support and navigation system in this situation. These comments coincide with the suggestion by Guzman and Lewis [43]. According to them, the communication theory between humans and AI, which would be mainly used in the autonomous system, is different from traditional human-based communication. On the contrary, the support from a lookout at the RCC to RO at the bridge did not work well for decreasing the MWL of RO. Interviewees were sceptical of the information which the lookout acquired from the limited visibility of the screen at the RCC. Conflict of information between the lookout and the autonomous system was also a point of concern from an interviewee. The mistake of support by lookouts based on the autonomous system’s wrong information is also a high risk for ROs.

6.1.4. Reliability of the Autonomous System

Navigation support and autonomous navigation systems alleviate the high MWL to some extent if ROs remotely operate ships at an RCC. The addition of the ways to support ROs helps them make decisions under limited information, which corresponds to the decrease in mental demands. Nevertheless, these autonomy systems far from completely address the difficult situation, even in comparably clear weather. Innovative technologies should be to “overcome perceptions of risk and uncertainty” by users to improve their reliability [44]. The maritime autonomous system is also the same. Interviewees stressed that they could not wholly rely on the systems even if they were highly reliable and autonomous. An interviewee exemplified that autonomous navigation might misdirect based on the mismeasured information from a defective gyrocompass. Another interviewee pointed out that the stress would be kept high unless ROs could completely confirm that the system makes correct decisions based on appropriate information.

6.1.5. Mechanical-Style Movement of the System

Systematic and impersonal movement of the system would increase the stress. An interviewee suggested the complicated intention of ROs. For instance, ROs sometimes oversteer greatly, then ease to the appropriate position to encourage other ships to be aware of their ship. On the other hand, because human behaviour is quite complicated, the current situation far from completely understands human actions in the technological domain [45]. Therefore, the autonomous navigation system tends to take “mechanical-style” action. When it conducts such unexpected and “mechanical-style” navigations and supports, ROs should consider their meanings. This type of stress emerges even when ROs are at the ship’s bridge.

6.1.6. Visibility Constraint

Visibility constraints owing to bad weather such as heavy rain and fog make the MWL much higher than good weather conditions, especially in high-congested areas. Visibility is the main tool for recognising the situation outside the bridge [46]. Multiple interviewees confessed that the limited visibility within one mile with many crossing ships feels so severe as to affect safe navigation in many cases, even when the RO and lookout are onboard. The prompt decision-making in a very short time is inevitable under these

situations; thus, the time pressure of ROs rises significantly in addition to mental demands and frustration. All interviewees expressed that they could not imagine remote navigation without the crew's support onboard with maintaining safety and stable mental conditions, even if highly reliable autonomous navigation systems were installed. An interviewee suggested that he could not judge whether the information from autonomous systems was accurate under the limited data transform condition, because the situation outside a ship changes rapidly. Another interviewee commented that he would turn off the autonomous navigation system under these situations if he was onboard. The most reliable tool is his "eye", and unexpected intervention by autonomous systems would induce confusion. According to him, this feeling does not change as far as the RO has final responsibility for navigation.

The interruption of visual information that ROs acquire during remote navigation significantly increases the stress. This trend is outstanding in the congested area. ROs should manage a ship by the information of only navigation equipment during the interruption that changes the situation around a ship a lot. For instance, ROs cannot confirm the movement of small fishing boats that do not have AIS on the screen during the interruption, even though the delay of decision-making for a few seconds would directly lead to an accident. According to interviewees, autonomous systems will not be alternated with visibility information, even if they are highly reliable. The case study used visual data that supplied static images every 10 s. All interviewees were surprised at the time length and stressed the irritated feeling and time pressure due to the lack of visual information while waiting for the next visual image. One unique comment was that 10 s of interruption under non-congested (e.g., ocean) and clear weather conditions would not lead to a significant rise of MWL because ROs can easily predict future situations.

6.2. *Validity of the Identification Scheme and Limitation of the Case Study*

Through the case study, the identification scheme can be verified as a useful tool to specify the factors that affect MWL and sub-elements of MWL that cause the main difference of MWL. These results could largely contribute to the consultation of the development of regulations and technological development from a mental health perspective of ROs.

On the other hand, the case study also suggests the matters to be addressed for further studies utilising this scheme. Firstly, this case study scrutinises scenarios for the interview on each sub-element due to the time constraint. The result can indicate some trend of change in MWL. Nevertheless, the results would change according to the change of the assumption, such as the experience of operators and MASS navigation. The second is the number of interviewees. As described in Section 4.1, participants were carefully selected based on the criteria. Although the case study worked well, expanding the set of participants for future work would contribute to acquiring more stable results. Thirdly, the study used a recorded video for interviewees to recognise each option because they were to consider many scenarios. They could identify well and did not claim any restraint to filling in the answers. Notwithstanding, a study based on actual navigation using a simulator or actual MASS could produce more reliable data. The fourth issue is how to define the autonomy level. There are various types and levels of autonomy, and they change according to technological development. Even focusing on collision avoidance, many methods have been studied and developed [47]. The case study relatively defined the autonomy level including the system's reliability in Section 3.3.1, in order for each participant to be able to grasp the image according to their experiences. This approach worked well to some extent without any significant problem. However, a detailed and more objective definition should be considered in future micro-level studies. The last thing is the relationship between MWL and the navigational safety risk (step 3 of Figure 3). As described in Section 5.1, the case study could not discuss the relationship between MWL and MASS in the context of minimising the navigation safety risk by avoiding a too-low MWL. The main reason is that MWL of the interviewees did not decrease until they became

careless in the given scenarios. Future studies are expected to deal with this issue by increasing the factors and options.

7. Conclusions

Shipping is an essential tool for keeping the supply chain, and sustainable shipping is maintained by skilled and experienced seafarers. Ship autonomy is expected as a useful solution to reduce the stress of the seafarers and marine accidents owing to human error. Despite the recent technological development of autonomous ships, the autonomous systems should also be carefully considered because they might increase MWL. This research firstly explained the relationship between motivated capacity and task demand in the MWL model. Secondly, it defined the factors that possibly affect the MWL of seafarers engaged in the duty of watching MASS navigation, developed a scheme that identifies the sensitive factors to the change of MWL, and detailed MWL sub-elements mainly causing the change of MWL. Then, a case study with a typical scenario focusing on watchkeeping duty in a normal situation was carried out. The case study was performed through the interview of ten (10) officers with various sea-going experiences. MWL was measured using NASA-TLX methods.

The results implied that operators' MWL is considerably affected due to the conflicted situation, physical situation, the lack of human-machine communication, impersonal movement, and visibility constraints. The study can also confirm the validity of the scheme. At the same time, this study has some limitations, such as the interview's limited scenarios and the use of recorded video because of the physical constraints. Nevertheless, the identification scheme (Figure 3) and the additional key factors for MASS (step 1 in Figure 3) are beneficial to the maritime sector.

It is expected that this research will be the trigger for further considerations of the development of international and national regulations and technological innovation from seafarers' mental and health perspectives.

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