Causal Factors and Symptoms of Task-related Human Fatigue in Vessel Traffic Service: A Task-driven Approach

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Abstract:

Human fatigue is a major risk factor in transportation that contributes, directly or indirectly, to a large number of traffic accidents. Though many studies have investigated fatigue-inducing factors in transportation to efficiently manage human fatigue, limited studies related to vessel traffic service (VTS). To fill this gap, this work aims at determining the key causal factors and symptoms of human fatigue with a focus on VTS operations. Achieving this aim is hindered by the problem of no standard task-related fatigue definition and limited data source. To solve these problems, this paper proposes a novel definition of task-related human fatigue, a task-driven approach for identifying causal factors and a causal network-based approach for selecting key causal factors. Twelve key causal factors of human fatigue in VTS were identified and analyzed. In addition, it was found that VTS operators suffered from multidimensional fatigue, especially physical fatigue. The results provide a foundation and future directions for designing interventions to manage human fatigue.

1. Introduction

Vessel Traffic Service (VTS) refers to an integrated shore-side service provided to vessels navigating in territorial waters (Hughes, 1998). As early as 1948, the first radar chain, the predecessor of VTS, was established to minimize the delay of vessels at Douglas (Praetorius, 2012). It was found that the VTS can promote efficient, safe navigation in areas with high traffic density. Hence, more VTS centres have been established with advanced techniques, such as automatic identification system (AIS), marine geographic information system, meteorological/ hydrological system, and closed-circuit television (Li et al., 2016, Xu et al., 2015). Nowadays, there are more than 500 VTS centres around the world. According to the International Convention for the Safety of Life at Sea (SOLAS), Chapter V, Regulation 12, there are two types of VTS operations: port and coastal operations. Port operations focus on providing services to vessels entering or leaving ports, while coastal operations mainly provide services to vessels passing through a sea area. For both port and coastal operations, VTS operators (VTSOs) monitor the traffic situation through VTS console and directly communicate with vessels to provide three types of services, including information service (INS), navigational assistance service (NAS), and traffic organization service (TOS), through broadcasts on very high frequency (VHF) radio.

VTS operation is complex and dynamic in nature thereby resulting in a high degree of task-related human fatigue (Akhtar and Utne, 2014, Michalaki et al., 2015, Li et al., 2019), which causes an increase in response time and undermines the capacity of human operators. Thus, human fatigue is increasingly being considered as the primary cause of most traffic accidents (Bye and Aalberg, 2018, Herlambang et al., 2019, Renata et al., 2018). More recently, several maritime casualties were caused by watchkeepers falling asleep while on duty (Jepsen et al., 2017). Hence, it is imperative and critical to manage task-related human fatigue in VTS.

Recognizing causal factors and fatigue symptoms is generally considered as the first step in managing human fatigue (Ji et al., 2006). It helps in understanding human fatigue as well as in developing fatigue countermeasures (May and Baldwin, 2009). Ji et al. (2006) found that human fatigue could be modeled based on a set of fatigue-inducing factors. Thus, causal factors analysis has received interests from various fields, such as road transportation (Sallinen and Hublin, 2015), hospital (Paterson et al., 2014), and maritime transportation (Bal et al., 2015).

Owing to a similar target of maintaining safety and traffic smooth, VTS operations are often compared with air traffic control (ATC) (Praetorius et al., 2012). Recent studies indicated that human fatigue of ATC operators is mainly caused by inadequate sleep, 24-hour operations, the length of the duty period, and the pattern of workload (Gander, 2001). Though there are some similarities between VTS operations and air traffic management, the pattern of workload is greatly different. Specifically, VTS operators currently only provide information service and advisory instead of instructions to pilots, while air traffic controllers provide instructions to aircraft pilots (Praetorius, 2012, Chen et al., 2019, Chang et al., 2019). Moreover, VTS operators monitor 2-dimension traffic space, while air traffic controllers monitor 3-dimension traffic space (Liu et al., 2019). Due to these significant differences, the causal factors of human fatigue in VTS might be different from air traffic management and therefore are worthy of an investigation.

The specific aim of this work is to determine the key causal factors and symptoms of human fatigue with a focus on VTS operations and the workspace environment. Several challenges are waiting to be addressed to achieve this aim: first, there is no clear and widely acknowledged definition of human fatigue (Trejo et al., 2015). It is always used as a synonym for tiredness and drowsiness (Trejo et al., 2015). Nevertheless, some researchers indicated that there are significant differences between drowsiness and human fatigue (Phillips, 2015, Wolf et al., 2017). Hence, it is

necessary to clearly define human fatigue before identifying causal factors. Second, human fatigues were usually underestimated and not reported in maritime accidents (Alonso et al., 2016). Objectively assessing the importance of causal factors of human fatigue is difficult due to the limited accident reports related to human fatigue in VTS. Third, there are too many interacted factors that induce human fatigues (Sallinen and Hublin, 2015). Considering the complex inter-relations, it is very challenging to determine the key causal factors.

To reach the target of identifying the critical causal factors of human fatigue in VTS and addressing the abovementioned challenges, the authors proposed a novel definition of human fatigue, developed a task-driven approach for causal factor identification and presented a fatigue causal network for evaluation. The remainder of this paper is organized as follows. Section 2 provides a review on human fatigue definitions and the methods of evaluating fatigue-inducing factors. Based on the analysis of existing studies, a novel definition of human fatigue is provided. Sections 3 and 4, respectively, describe the research methodology, including task-driven identification and causal network-based evaluation, and discuss the results of the vital causal factors and symptoms of human fatigue in VTS. Section 5 summarizes the main conclusions reached in this work.

2. Literature review

Defining human fatigues can help determine the scope of this work and reduce the misunderstandings of people in subjectively identifying causal factors (Phillips, 2015). Hence, human fatigue definitions are reviewed below. In addition, the commonly used approaches to evaluate the importance of fatigue-inducing factors are analyzed.

2.1 Definitions of human fatigue

Human fatigue is normally defined as a suboptimal state caused by exertion/inadequate rest. For the suboptimal state, several definitions describe human fatigue, especially mental fatigue, as a feeling (Phillips, 2015, Trejo et al., 2015). For example, fatigue was defined as an overwhelming sense of tiredness, a lack of energy, and a feeling of exhaustion. These experiential definitions of human fatigue heavily depend on subjective sense and individual understanding. Besides, the links of perceived fatigue to human performance are not straightforward (Phillips, 2015). Hence, other researchers define human fatigue from the perspective of objective measurements, including psychophysiological depletion and performance decrement (Alonso et al., 2016).

The causes of human fatigue are normally varied with different definitions. Some researchers suggested that fatigue was caused by inadequate rest (Gander, 2001, Job and Dalziel, 2001). However, this kind of definition is used in a limited manner because it can easily be confused with drowsiness. Most studies agree that fatigue is caused by demanding physical or mental activities (Van Cutsem et al., 2017, Charbonnier et al., 2016). Nevertheless, it has been found that both high-demand and low-demand work can induce human fatigue (Desmond and Hancock, 2001). In addition, the workload, the emotions, and motivations of people are always linked to human fatigue (Montgomery et al., 1995). Hockey (2013) defined mental fatigue as a lack of motivation, which was caused by decreased rewards of task engagement over time. As shown in Table 1, most researchers suggested that human fatigue is a psychophysiological condition caused by exertion, and there is still no definition that considers the specific consequences of fatigue and the effects of both exertion and subjective feelings. Phillips (2015) claimed that the definition of human fatigue should include experiential fatigue as a central aspect. Hence, a novel definition that accounts for the interactions between subjective feelings and exertion concerning psychophysiological states is proposed in this study.

Table 1: Summary of human fatigue definitions

Source	Cause				Consequence		
	Exertion	Subjective feelings	Rest	Health	Perceived condition	Psychophysiological depletion	Performance decrement
Phillips, 2015	√					√	
Shen et al., 2006					√		
Trejo et al., 2015					√	√	
Alonso et al., 2016	√					√	
Hirshkowitz, 2013	√					√	
Dodge, 1982	√						√
Charbonnier et al., 2016	√						√
Gander, 2001			√				√
Job and Dalziel, 2001			√			√	
Van Cutsem et al., 2017	√					√	
Hockey, 2013		√			√		
Montgomery et al., 1995		√					
Oxford dictionaries				√			

2.2 Identification of key fatigue-inducing factors

Historically, researchers investigated causal factors of human fatigue through questionnaires, interviews, task analyses, and literature reviews (Bal et al., 2015, Sallinen and Hublin, 2015). More specifically, Sallinen and Hublin (2015) identified the causal factors of human fatigue in road transportation by conducting a literature review. Paterson et al. (2014) surveyed to understand the contributing causal factors of human fatigue, and identified three leading causes of human fatigue, namely sleep history, circadian factors, and task-related factors. Bal et al. (2015) analyzed causal factors of human fatigue in seafarers using task analyses and interviews. Through thoroughly examining the daily operations of seafarers, they identified the potential causal factors of human fatigue by interviewing seafarers.

To quantitatively select key causal factors of human fatigue, Bal et al. (2015) adopted the analytic hierarchy process (AHP) method, which utilizes pair-wise comparisons to identify critical factors. However, it is computationally intensive and not suitable for situations where a vast number of causal factors are involved (Bal et al., 2015). To the best of the authors' knowledge,

quantitative evaluation of causal factors of human fatigue are still lacking. Moreover, the complex inter-relationships between these causal factors remain unclear (Bal et al., 2015). To effectively deal with the complex inter-relationships, the authors postulate that causal networks can be used to perform causal factors evaluation.

Causal networks have been used to deal with problems in different domains such as philosophy, health and environment, and tourism (Hollnagel, 1998, De Ambroggi and Trucco, 2011). Essentially, a causal network can be used to visually and effectively express the inter-relationships between causal factors (Hollnagel, 1998). De Ambroggi and Trucco (2011) established a causal network of performance shaping factors (PSF) to analyze the their effect on human errors. Although causal networks have been widely used in various problem contexts, they have never been utilized to deal with human fatigue issues.

2.3 A novel definition of human fatigue

In this study, a novel definition was proposed to achieve the following improvements: (1) to focus on task-related human fatigue, the definition indicates that the causes of human fatigue are work-related. (2) The definition indicates the multidimensional consequences of human fatigue. Some researchers have divided fatigue into mental and physical fatigue (Trejo et al., 2015) based on physical or mental exertion. Nevertheless, this study proposes to combine them, as physical fatigue interacts with mental fatigue (Van Cutsem et al., 2017). (3) The definition optimizes face validity by using an experiential and operational definition. To enable causal factors to be identified via subjective methods, such as surveys and interviews, everyday language should be used to define human fatigue (Phillips, 2015). In addition, the consequences of fatigue can be assessed by subjective feelings. According to Table 1, the existing definitions basically fail to

satisfy these aspects. Based on the understanding above and the current definitions, the following novel definition is proposed:

Task-related human fatigue is a suboptimal physical, emotional, motivational, cognitive condition caused by a prolonged period of exposure to task-related stimuli.

Instead of using a phrase such as "psychophysiological," the authors explicitly indicate the multiple dimensions of fatigue using everyday language. Fatigue is normally considered a decrement in physical and mental conditions. Nevertheless, in some studies, the mental condition is always confused with cognitive states (Van Cutsem et al., 2017). Cognitive fatigue was sometimes used instead of mental fatigue, as "mental fatigue" was induced by typical cognitive tasks. Several multi-dimension fatigue scales (Zuraida and Iridiastadi, 2015, Ahsberg et al., 2000) show that fatigue includes various aspects, such as physical, cognitive, emotional, and motivational aspects. Therefore, the definition proposed in this study implies that people under fatigue may experience performance decrement, a lack of motivation, a bad mood, and even impaired cognitive capacity, which is in line with the idea of Zuraida and Iridiastadi (2015) and Van Cutsem et al. (2017).

The definition implies that fatigue is a degree relative to a specific optimal condition, where the optimal state is the average health condition after the individual is fully recovered and rested (Phillips, 2015). Defining fatigue as a relative condition enables people to recognize fatigue states based on experience. Additionally, it is in line with the idea that fatigue is a decrement in psychophysiological states (Phillips, 2015).

The reasons why "*a prolonged period of exposure to task-related stimuli*" is used as the cause of human fatigue can be explained from three aspects. First, fatigue is a gradual and cumulative

phenomenon (Charbonnier et al., 2016); hence, the definition highlights the time effects of task-related factors. Second, instead of "exertion," "task-related stimuli" are used as the cause. The term "stimuli" is in line with the definition of Dodge (1982) and Hirshkowitz (2013). According to the definition of Phillips (2015), the term "exertion" emphasizes that people have to put forth efforts. Nevertheless, people may experience fatigue under low-demand work conditions because such conditions are boring and monotonous. Also, people may have emotional fatigue due to psychological factors such as feeling decreased rewards of task engagement over time or even feeling unwillingness to engage in some tasks (Hockey, 2013). Hence, the term "stimuli" is used.

3.Methodology

Since causal factors of human fatigue are task-specific, it is necessary to elicit factors with a focus on VTS operations. Hence, the authors propose a task-driven approach for factors elicitation and a causal network-based approach for selecting causal factors.

3.1 Participants

This study involved a sample of 68 VTSOs, recruited from a VTS centre in Singapore. Specifically, eight VTSOs (male = 7; female = 1) were recruited for the unstructured interview. They had an average age of 35 years old (standard deviation (SD) = 5 years), with an average experience of 8 years. The other 60 VTSOs participated in the questionnaire-based fatigue survey, where VTSOs reported the importance of causal factors and how often they suffered from the fatigue symptoms (1 = never, 5 = always). In total, questionnaires from 48 licensed VTSOs (male=40, female=8), with an average age of 41 years old and an average experience of 11 years, were collected. The response rate of 80% is acceptable (Liu et al., 2017). The participants were informed of the objectives of this study and of the definition of task-related human fatigue in advance. They were required to sign informed consent for participating in this study. This research

complied with the American Psychological Association Code of Ethics (Stricker, 2010) and was approved by the institutional review board. The informed consent was obtained from each participant.

3.2 Task-driven identification of causal factors

Figure 1 shows the framework of the proposed task-driven causal factor identification method. A two-month field observation was conducted in VTS centres in Singapore to understand the daily tasks of VTSOs. Field observations were carried out in a naturistic and passive manner, i.e., with the researcher standing beside an operator without interrupting his or her work.
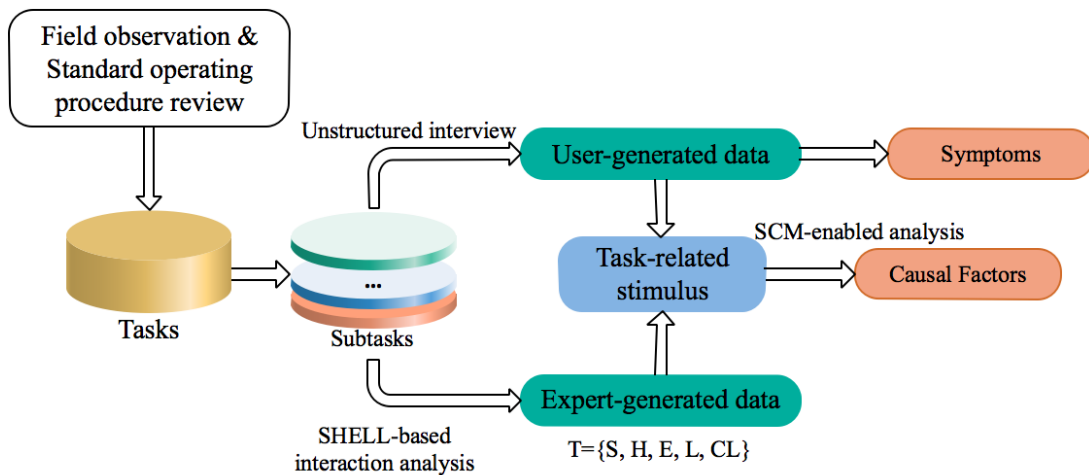

Figure 1: Framework of the Task-driven Causal Factors Identification

Hierarchy task analysis (HTA) is employed to hierarchically decompose the main task into subtasks to facilitate a better understanding of an operational process. Edwards (1981) indicated that human should interact with several aspects, when he or she is performing any tasks. So, he proposed the SHELL model, which is named after the initial letters of its components, Software, Hardware, Environment, and Liveware. Based on this theory, SHELL-based interaction analysis was conducted to elicit causal factors from expert knowledge, as shown in Figure 1. Any subtask T_n could be represented as $T_n \rightarrow \{S_n, H_n, E_n, L_n, CL_n\}$, as shown in Figure 2. Experts analyzed each subtask and figure out how VTSOs interact with the system, including software, hardware,

environment and other liveware. Specifically, S refers to non-physical and intangible aspects of a target industry that govern how the industry operates and how the information within the industry is organized. Software factors such as safety procedures, regulations and work sector characteristics have an influence on workload and may cause human fatigue. H refers to physical elements such as operating consoles, seats and computers. E tackles the context in which tasks are executed. L deals with the human elements of the target industry. CL means a central human element, the one who conducts the task.

With an understanding of VTS operations and interacting factors, an unstructured interview with eight operators was conducted. The unstructured interviews consist of three crucial stages: asking open-ended questions, probing for details, and seeking to verify unclear points. The operators were asked to recall the challenges or problems they face in performing each subtask or interacting with each element. Probing questions were generated when an operator mentioned any fatigue patterns so as to examine more details regarding the fatigue. According to the novel definition, fatigue patterns can include physical, emotional, motivational, and cognitive decrements. Finally, the interviewer repeated what she/he heard so that the interviewees could confirm the information summarized. To encourage operators to explore their knowledge and provide more information about fatigue, their identities were kept anonymous throughout the study.
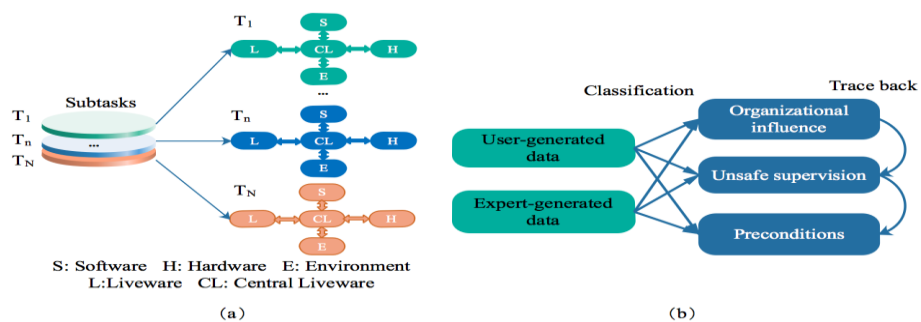

Figure 2: Illustration of (a) SHELL-based interaction analysis and (b) SCM-based analysis

The core concept of the Swiss Cheese Model (SCM) postulates that both direct and indirect factors, including preconditions, unsafe supervision, and organizational influences, cause accidents (Reason, 1990). For the factors belonging to preconditions, their corresponding indirect factors fall under unsafe supervision and organizational influences. Figure 2(b) illustrates the process for SCM-enabled causal factor analysis. Based on the framework of Human Factors Analysis and Classification System for Maritime Accidents (HFACS-MA), unsafe supervision includes inappropriately planned operations, the failure to rectify known problems, inadequate supervision, and violations by supervisors (Chen et al., 2013). Organizational influences consist of the organizational climate, resource management and regulatory processes (Chen et al., 2013).

3.3. Network-based Evaluation

A causal network of human fatigue was established to evaluate the causal factors and their complex interrelationships. The specific steps for realizing the causal network are summarized as follows:

1. Analyze the inter-relationships between any two causal factors;

2. Add the necessary virtual nodes;

3. Rate the strength of each node; and

4. Establish a matrix to model the causal network.

There are two types of influence, i.e. direct and indirect, that one causal factor can have on another. Figure 3 shows the inter-relationships among the causal factors. For the direct influence (A), CF_j interacts with CF_k by directly affecting CF_i. Regarding the indirect influence (B), CF_j interacts with CF_k by affecting the interaction between CF_i and CF_k. In this study, a matrix is established to present the inter-relationships among the causal factors. In general, direct influences can be represented by the entries of the matrix itself; however, representing indirect influences is

more challenging (De Ambroggi and Trucco, 2011). To address this issue, i.e., representing indirect influence, a virtual node (V) is introduced to convert an indirect influence into a direct influence. By using the virtual node, the indirect influence can be treated as that CF_j influences CF_k indirectly through the virtual element, V_j. In this manner, the introduction of virtual node V_j enables the indirect influence of CF_i on CF_k. to be more clearly illustrated.
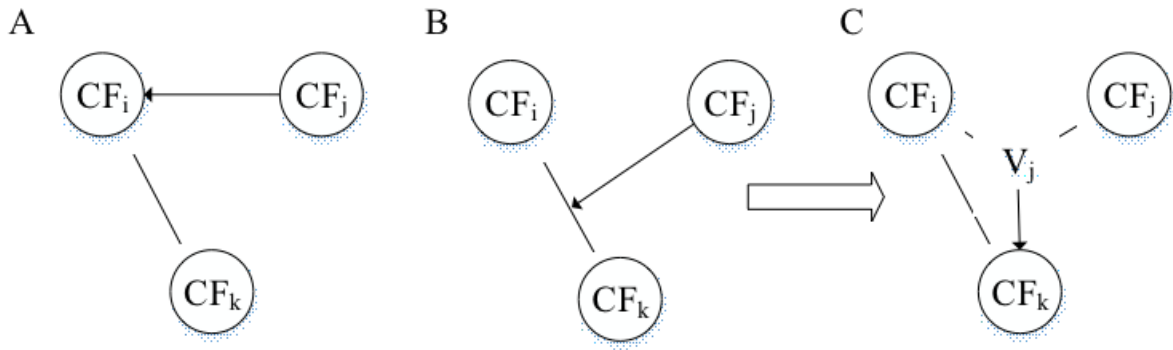

Figure 3: Illustration of the inter-relations among causal factors (*CFs*)

Basically, the causal network utilizes all causal factors, virtual nodes, and fatigue symptoms (SF) as elements. To rate the importance of each element, an ordinal scale, i.e., low, moderate, and high (Miles and Huberman, 1984), is adopted. The ordinal scale is subsequently converted into a comparative format where "1" denotes "low", "3" represents "moderate" and "5" indicates "high". The following matrix represents the inter-relations of any two elements:

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} \tag{1}$$

$$\text{For } i \neq j, c_{ij} = \begin{cases} 1 & E_j \text{ has effects on} E_i. \\ 0 & E_j \text{ has no effects on } E_i. \end{cases}$$

$$\text{For } i = j, c_{ij} = \begin{cases} 1 & \text{if the rate of } E_i \text{ is low;} \\ 3 & \text{if the rate of } E_i \text{ is moderate;} \\ 5 & \text{if the rate of } E_i \text{ is high.} \end{cases}$$

Each column of *C* is a principal eigenvector of the effects of the *jth* element on the *ith* element. For *i=j*, c_{ij} refers to the strength of the *ith* node. Table 2 illustrates the item format of the questionnaires.

Table 2: Demonstration of item format in the questionnaires

	CF$_1$	CF$_2$	SF$_1$
CF$_1$	Low/moderate/high	0/1	0/1
CF$_2$	0/1	Low/moderate/high	0/1
SF$_1$	0/1	0/1	Low/moderate/high

For each factor involved in the causal network, its importance can be determined by out-degree (*kout*) and in-degree (*kin*), which refers to the number of adjacent nodes and jointly considers the direction and strength of the inter-relations with adjacent nodes (Freeman, 1977). The out-degree and in-degree are calculated by Eq. (2) and (3):

$$kout_i = \sum_{j=1}^{n} c_{jj} \times c_{ij}, j \neq i \tag{2}$$

$$kin_i = \sum_{j=1}^{n} c_{jj} \times c_{ji}, j \neq i \tag{3}$$

where *kout$_i$* refers to the out-degree of the *ith* node, and *kin$_i$* denotes the in-degree of *ith* node, and c$_{ij}$ is inter-relation strength between factor i and factor j

$$T = \frac{kout}{kin} \tag{4}$$

T is the ratio of out-degree and in-degree. For a causal factor, whose *T* is larger than the threshold α, the causal factor can be classified as indirect factor *(Niemeijer and de Groot, 2008)*. α is set to be 10 in this study. Hence, indirect factors have a larger number of out-degree than in-degree (Niemeijer and de Groot, 2008). For a causal factor, whose *T* is smaller than the threshold *β*, the causal factor can be classified as individual resilience. β is normarlly set to be smaller than

0.5. Hence, individual resilience has a larger amount of in-degree and a smaller amount of out-degree. The remaining causal factors, whose out-degree is roughly equal to the in-degree are state factors, named as task-related stimuli in this study.

Based on the out-degree and in-degree, the influence power of the *ith* node, I_i, can be represented by Eq. (5) as follows.
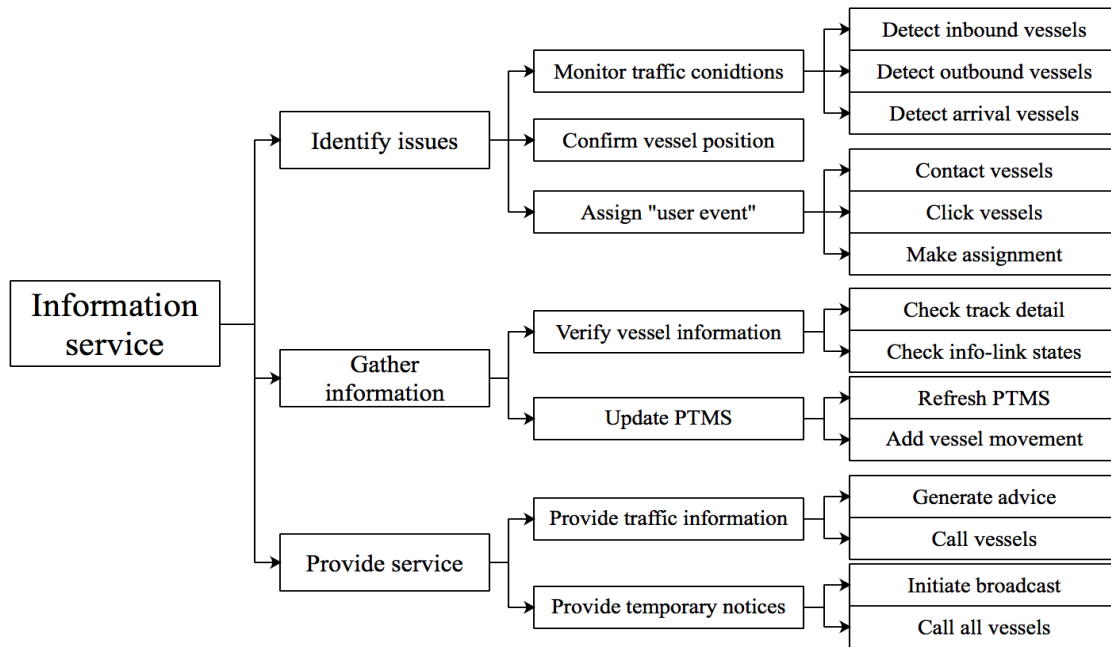
$$I_i = c_{ii} + kout_i + kin_i \tag{5}$$

Basically, the influence of power indicates the impact of a node on its adjacent nodes. To determine the importance of a node, both its influence on its adjacent nodes and the range of influence need to be assessed. By considering the general properties of the causal network, the number of paths from the root nodes to the end of the chain node that passes through the *ith* node is defined as its influence range (Np_i). Np_i, which is a classical problem in network analysis, can be determined by using a depth-first search (DFS) algorithm.

4. Results and discussion

4.1 Task analysis and factors identification

The VTS of Singapore provided only the information service (INS) to vessels. Figure 4 depicts the hierarchical analysis of the INS. First, VTSOs identify potential unsafe events by monitoring the traffic conditions of vessels and communicating with the masters or pilots. Second, once a possible hazardous event is spotted, VTSOs will gather the basic information and refresh the port traffic management system (PTMS) to check vessel movements. Finally, based on the information gathered, VTSOs will provide corresponding advice to the vessels, such as the intentions of other vessels, the number of vessels in the vicinity, and the type of vessels in the vicinity. At times, VTSOs may broadcast temporary notices to all vessels under special conditions, such as poor visibility.

Figure 4: Hierarchical analysis of INS

The task analysis identified 23 task-related factors, as listed in Table 3.

Table 3: Task-related factors

Operations	Task-related factors
Detect inbound/outbound vessels / arrival vessels	CF1: Continuous monitoring or tracking
	CF2: Too many vessel traffic regulations
	CF3: Too many vessels with the same icons
	CF4: Overlap of vessel information
	CF5: Marker or notes left by other operators
	CF6: Too large display
Confirm vessel movement/ verify vessel information/ Update information	CF7: A large amount of information
	CF8: Key information masked
	CF9: Information updated by AIS is not complete/ consistent
	CF10: Sensing information affected by light reflection
	CF11: Slow feedback of hardware system
	CF12: Demand to memorize information
Provide Temporary Notices	CF13: No or slow feedback
	CF14: Work interrupted by assignments from manager

	CF15: Need to collect information from different systems and masters/pilots
Provide traffic information	CF16: Inefficient communication due to language barrier
	CF17: Communication is interrupted by other pilots
	CF18: Too many unnecessary alarms
	CF19: Ambiguous alarms
	CF20: Time pressure in providing information
Assign User Event (UE)	CF16: Inefficient communication due to language barrier
	CF21: Too many steps to make assignments
	CF22: Lack of experience
	CF23: Difficult in clicking vessels using a mouse

Besides these task-related factors, 24 factors were collected by SCM-based analysis, as listed in Table 4.

Table 4: The causal factors identified by SCM-based analysis

Organizational influence	Unsafe supervision	Preconditions
CF24: Safety culture	CF28: Work arrangement	CF37: Information management system
CF25: Organizational rules	CF29: Revision of SOP	CF38: Night shift
CF26: Organizational structure	CF30: Staffing levels	CF39: Recovery/ rest
CF27: Organizational policies	CF31: Team interaction	CF40: Individual capacity
	CF32: Training	CF41: Health and wellness condition
	CF33: Safety management system	CF42: Subjective feelings
	CF34: Update equipment	CF43: Interface design
	CF35: Recruitment policies	CF44: Environment
	CF36: Work sector division	CF45: Usability of equipment
		CF46: Time on task
		CF47: Workload

4.2 Symptoms of human fatigue in VTS

Table 5 shows the results related to the top ten fatigue symptoms in VTS. The mean value listed in the third column indicates the impact of fatigue symptoms. VTSOs suffer from multidimensional fatigue. Besides, physical fatigue seems to be more serious than cognitive fatigue in VTS. There are six physical symptoms ranked in the top ten, while there are only two cognitive symptoms in Table 5. Owing to the dynamic workload and high intensity of information, cognitive fatigue was normally received more attention in VTS studies (Li et al., 2019). While this study indicated that VTSOs suffered from a high possibility of physical fatigue. Accordingly, the countermeasure technologies should focus more on physical fatigue (May and Baldwin, 2009).

In addition to physical and cognitive symptoms, symptoms related to motivation and emotion could be found in Table 5. The top-ranking symptom of human fatigue is "eyes feel strained"; also, its SD is smaller than most other symptoms. The decrement in cognitive states does not seem to be serious, as cognitive symptoms have a low ranking. Moreover, the symptom of "cannot sense information" has the largest SD. It can be deducted that some operators suffer from impaired cognitive capacities, while others can maintain their information-processing capacity.

Table 5: Fatigue symptoms in VTS

Category	Descriptions	Mean	SD
Physical	SF1: Eyes feel strained	4.18	0.38
Physical	SF2: Feel tired in the whole body	3.47	0.49
Physical	SF3: Feel stiff in the neck and shoulder	3.37	1.30
Physical	SF4: Flickering in eyes	3.06	1.19
Motivational	SF5: Lack of motivation, would rather be doing something else	3.06	1.30
Emotional	SF6: Bad mood, fed up with the task	2.96	1.05
Physical	SF7: Hearing ability reduced	2.65	1.19
Cognitive	SF8: Increased response time	2.65	0.32
Emotional	SF9: Find the task monotonous	2.55	0.97
Cognitive	SF10: Cannot sense information	1.94	2.87

4.3 Key causal factors of human fatigue in VTS

In this study, the factors ranked in the top 25% were identified as key causal factors and are analyzed below. Table 6 shows the key causal factors and their rankings in three dimensions: (1) a1 is the rank of the influence power (I) of each causal factor. (2) a2 is the rank of the influence range (Np) of each causal factor. (3) a3 is the rank of influence power.

Table 6: Key causal factors of human fatigue in VTS

Causal factors	T	a1	a2	a3	Final Rank
Rest/recovery	0.13	2	8	1	1
Workload	0.13	1	1	10	2
Health and wellness condition	0.375	5	7	15	3
Safety culture	∞	6	4	16	4
Amount of information	1.83	11	14	2	5
Organizational rules	∞	10	5	18	6
Overlap of vessel information	1.67	12	26	8	7
Subjective feelings	0.5	9	21	22	8
Marker or notes	1.67	20	26	5	9
Continuous monitoring	0.625	22	29	3	10
Language barrier	1	25	27	4	11
Unnecessary alarms	1.4	24	30	6	12

Following the division method described in Section 3.3, "Safety culture" and "organizational rules" were classified as indirect causal factors, as their T values are larger than threshold α; they have high rankings in both influence power and influence range. As previously mentioned, influence power indicates the influence of a node on adjacent nodes; the influence range indicates the ranges of its impact. Hence, the results indicate that "safety culture" and "organizational rules" have great effects on the entire fatigue causal network.

"Rest/ recovery," "workload," "subjective feelings," and "health and wellness condition" are individual resilience that can be considered as preconditions of human fatigue, as their T values isare smaller than threshold $β$. Table 6 shows that all of them except "subjective feelings" are highly ranked in the three dimensions. Considering the three dimensions, "rest" was ranked first. Hence, the "work/rest arrangement" of VTS requires more development. VTSOs work in shift

work; hence, they always suffer from the problem of rest and recovery. "Workload" was ranked second; its a3 ranking is much lower than that of "rest." a3 shows the subjective feelings of VTSOs. It can be concluded that operators felt the problem of "rest" is more serious than "workload." VTSOs did not work close to the limits of their capacity. Nevertheless, they felt a lack of motivation to continue their work.

Other key factors include "language barrier," "amount of information," "marker or notes," "unnecessary alarms," "overlap of vessel information," and "continuous monitoring." They are task-related stimuli and direct causal factors of human fatigue in VTS, as they have a high ranking in a3. A factor with a high ranking in a3 means that operators encountered the factor very frequently and felt that the factor is critical. These task-related stimuli are discussed below:

Language barrier: From the task decomposition, it appears that VTSOs frequently communicate with the pilots of vessels coming from different countries. Nevertheless, the communication can be easily interrupted by the "language barrier," as the crews of vessels maybe not proficient in English. During the unstructured interview, the VTSOs mentioned that pilots may ignore advice or even insist in speaking their language during the communication.

Amount of information: From the task analysis of VTS operations, VTSOs frequently worked close to the limits of their information-processing capacity. They have to handle numerous warnings, calls from vessels, traffic information, and so on. The effort required to process high-density information and make adequate decisions simultaneously can be daunting and may potentially induce a high workload. Due to its direct effect on workload, this factor ranks high in both a1 and a2.

Overlap of vessel information: The identification information of a vessel, including its name, call number, and type, is displayed next to its icon. Nevertheless, when a vessel is close to another vessel, their information always overlaps, as shown in Figure 5. In such a case, VTSOs have to drag the information labels manually. According to the field observation, VTSOs spent most of their time dealing with the overlapping information.

Figure 5: Information overlap   Figure 6: Maker and notes

Markers or notes: VTSOs used "markers or notes" to mark the vessels that require their attention, as shown in Figure 6. However, there is no standard in making markers. As a result, operators make markers according to their preferences and working habits. They may be confused by markers or notes left by other operators.

Unnecessary alarms: The integrated VTS alarm system was developed to assist in identifying potentially unsafe issues. However, the VTSOs mentioned that most of these alarms are unnecessary. These unnecessary alarms induce distrust in systems, resulting in a slow response to the alarm system.

Continuous monitoring: With the increase in automation technology in VTS, the role of a VTSO tends to change from a controller to a monitor, whose main task is monitoring tasks. Thousands of laboratory experiments have demonstrated that human vigilance will easily be interrupted when people are working on monitoring tasks (Masoudian and Razavi, 2018). Also,

VTSOs mentioned that their eyes felt strained after continuous monitoring. This factor was ranked just after "rest" and "amount of information" in a3.

In summary, the causal network-based evaluation provides a comprehensive assessment of three aspects: the influence range, influence impact, and subjective rate of importance. In general, operators could identify direct task-related stimuli according to their experience. Nevertheless, the importance of indirect causal factors could not be determined by subjective feelings. The proposed network can well fill this gap (Liu et al., 2017).

4.4 Recommendations for recruiting and training VTS personnel

Some recommendations can be generated for recruiting and training suitable candidates to reduce the risks of human fatigue. According to the international chapter "Recommendation (V103) on Standards for Training and Certification of VTS Personnel" (Hughes, 2009, Saint Germain en Laye, 2009), there are five tests in selecting VTS personnel, namely entry requirements, aptitude assessment, assessment of prior learning, medical/physical requirements, and personal attributes assessment.

For entry requirements, V103 mentioned that the candidate should be fluent in English. However, in this study, the "language barrier" was still identified as a critical causal factor, though VTS operators of Singapore are good at English. This study revealed that the language problem was caused by masters/pilots instead of VTS operators, since some master/pilots cannot understand English well. Hence, the language courses might be given to VTS operators to help them better understand the normally used languages of the masters/pilots.

Consistent with V103, this study indicated the importance of information processing and pointed out the specific tasks that require information capacity. For example, it is reported that too

much information is required in verifying vessel identity, as shown in Table 3. Based on this, a test for verifying vessel identity can be developed to select or train candidates. Moreover, the participants in this study, who are experienced VTS operators, pointed out that information overload was still serious in VTS (as shown in Table 6). As discussed in Section 4.3, rearranging vessel information to reduce information overlap and redesigning the vessel alarm system to manage the amounts of warnings might be helpful.

The medical/physical requirement is a critical part of selecting VTS personnel. According to the analysis in Section 4.2, VTS personnel has a great chance of suffering from physical fatigue, such as strained eyes and stiff neck. Hence, candidates should not have optical problems and spine-related problems. Moreover, some training courses about how to maintain the body and restore these physical problems might be conducted.

Personal attributes assessment is the last but important step in selecting VTS personnel. Normally, a sense of responsibility and willingness to cooperate with others is considered in existing recruiting procedures. Besides these teamwork-related attributes, this study pointed out the importance of subjective feelings, which induce motivational and emotional fatigue, as shown in Tables 5 and 6. Based on the fatigue symptoms and causal factors identified, a person who can endure monotonous tasks and prolonged monitoring might be more suitable for VTS operation.

There are strict procedures worked out for recruiting and training VTS personnel (Saint Germain en Laye, 2009). Nevertheless, some specific problems would occur in particular situations. Therefore, this study provides a task-related method to identify and evaluate the specific causal factors of human fatigue in VTS. The results are promising and valuable to help with the improvements in recruiting and training VTS personnel in real practice.

5. Conclusion

It is desirable to identify the task-related causal factors of human fatigue and to design corresponding preventive interventions to manage human fatigue subsequently. Based on this understanding, the authors conducted this study to identify the key causal factors of human fatigue in VTS. This work has the following contributions:

- A novel definition of human fatigue. The definition points out the multidimensional consequences of human fatigue and defines the scope of causes.

- A task-driven approach was proposed to systematically elicit causal factors in the human-system interactions and the underlying organizational factors. The proposed causal network-based evaluation method integrates three dimensions of judgments, and is feasible to be extended.

- Several key causal factors and symptoms were identified in VTS. It is found that VTSOs suffered from more serious physical fatigue than cognitive fatigue. Moreover, the factors and symptoms identified can provide references and guidelines for recruiting VTS personnel and properly designing required training and rest activities.

This study provides insightful guidance for mitigating human fatigue to safety managers and lays the foundation for further explorations of context-aware safety management. Due to the limited data, this study mainly identifies key factors from the empirical view of VTSOs, while more precise objective measurements will be considered, and the fatigue model will be generated correspondingly in the future as well. Hence, the authors would like to recommend two potential future research directions: (1) Evaluate the importance of a factor by the frequency of its corresponding task. If an operator always conducts a task, he/she may be frequently stimulated by

a specific factor. (2) Evaluate the importance of a factor by its consequences. The symptoms of human fatigue heavily depend on their causes, so it is worthwhile to consider the results of causal factors in evaluation.

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