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Investigating fatigue in marine accident investigations

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Abstract

The marine system operates around the clock, by mariners who often live on the vessels they operate, sleeping in what can be a noisy, dynamic, and stressful environment. On occasion, fatigue adversely affects mariner performance and an accident results. Fatigue degrades a person's cognitive skills by, among other effects, slowing reaction time, reducing vigilance, and adversely affecting decision making, all skills necessary for effective navigation and system diagnosis. Research has shown that people need about 8 hours of sleep a day, and receiving less than that can lead to fatigue-degraded performance. Fatigue results from factors that shorten or interrupt sleep, such as working during times when one would otherwise sleep, which can disrupt circadian sleep rhythms. Other causes of fatigue include medical conditions such as obstructive sleep apnea, prescribed and over the counter medications, and extended time remaining awake. Accident investigations have linked mariner errors to their fatigue, but investigators have used different measures to determine fatigue and its relationship to accident causation. This paper proposes a systematic method to determine whether fatigue adversely affected mariner performance in an accident. An investigation of a marine accident, in which the operator's fatigue was caused by a medical condition and disrupted circadian rhythms, illustrates how the method can be applied.

Keywords: fatigue; human error; cognitive performance, marine accident investigation

1. Introduction

As our understanding of fatigue and its effects on human performance has increased, there has been an increasing recognition of the hazards that operator fatigue poses to marine safety. For example, in 2003 the United Kingdom's Marine Accident Investigation Branch (MAIB) investigated the grounding of a general cargo ship [1], concluding that the chief officer had fallen asleep, sometime between 0405 and 0415 (local time) while on watch and alone on

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the bridge. It then conducted a study of vessel bridge watchkeeping to determine the extent to which fatigue, among other issues, affected marine safety [2]. The study examined all collisions, groundings, contacts, and near collisions that had occurred in the United Kingdom between 1995 and 2003. Investigators found that "a third of all the groundings involved a fatigued officer alone on the bridge at night (p. 3)." In the United States, the National Transportation Safety Board investigated three major fatigue-related accidents within a six-year period, from 1980 through 1995.

Following these accidents the United States Coast Guard funded several research studies [3, 4] to better understand mariner fatigue and the threat it posed to marine safety. One [3], which used similar methodology to that of the MAIB study, examined accidents retrospectively, using subject matter experts to determine the role mariner fatigue may have played in marine accidents over a period of time, while the other [4], asked mariners on several vessels to record the hours in which they slept and their alertness levels throughout the day. The latter study found that mariners received, on average, considerably less sleep each day while serving on a vessel than they had while off-duty, to the extent that they were accruing a substantial sleep debt. Both studies concluded that mariner fatigue was a threat to marine safety.

Since these studies were conducted other major marine accidents occurred in which mariner fatigue was identified as a factor. In this period researchers also considerably enhanced our understanding of fatigue, its causes, and its effects on human performance. Research has shown that well before operators are so fatigued that they can no longer remain awake without considerable difficulty, their cognitive performance is degraded and their ability to perform their tasks with the necessary alertness impaired.

Applying the findings of research on fatigue to marine accident investigations can be challenging. While the research has been consistent, conducting accident investigations requires investigators to make decisions regarding data collection in often challenging circumstances and to answer practical questions regarding marine safety at the same time. Further, a variety of methodologies has been employed to determine the presence of fatigue and its role in accident causation, presenting investigators with the difficulty of having to select among alternative methods to assess and identify the role of fatigue in an accident. The purpose of this paper is to suggest a method that investigators can apply to marine accident investigations to determine whether mariner fatigue played a role in the accident or incident under investigation, and if so, how.

1.1. Fatigue

Most people need about 8 hours of sleep per day and when allowed to sleep without restriction, over several days people who have slept as little as one to two hours per day less than their basic sleep requirements will accrue a sleep debt [5]. Researchers [6, 7] suggest that a two-process neurobiological model regulates sleepiness and affects the extent of fatigue. One, referred to as the homeostatic sleep drive, creates a pressure or need for sleep that increases the longer one has been awake, a need that is then dissipated by accruing sleep. The drive serves to balance the need for fatigue with the wakefulness and alertness that is gained with adequate sleep. With sufficient sleep, one wakes up and remains alert until one has been awake for a sufficient time that the need for sleep is perceived, which then increases the longer one remains awake.

A second mechanism, found among all mammals, operates diurnally, in a schedule that approximates the 24-hour day [8]. This drive, referred to as a circadian pacemaker, affects not only sleepiness and fatigue, but other circadian (or daily) rhythms that fluctuate according to time of day such as body temperature, endocrine levels, metabolism rate, and other physiological functions. It leads to people becoming fatigued about the same time each day, more typically at night, becoming hungry about the same times, and so on. Because most people sleep at night and are awake during the day, the two drives are considered to be synchronized when over a period of time people sleep and remain awake about the same time each 24-hour period.

The two drives can become unsynchronized by flying across multiple time zones, working schedules that are different from one that had been maintained, or engaging in another activity over time that changes work/sleep times. Such changes disrupt the circadian sleep rhythm because the circadian pacemaker is slow to adapt, rarely adjusting by more than 1 hour per day [9]. Consequently, when trying to remain awake during a time when one had recently been sleeping, one will have difficulty sleeping, even if one had been awake sufficiently long for the homeostatic sleep drive to be causing sleepiness. Conversely, trying to sleep during the day, when one has ordinarily been awake, results in reduced sleep time and degraded quality of sleep. As Van Dongen noted [6]:

> During shift work, the temporal changes in the homeostatic sleep pressure and circadian wake pressure are no longer properly synchronized. As a consequence, the pressure for wakefulness soon exceeds the pressure for sleep, and awakening occurs before the homeostatic pressure for sleep has been sufficiently dissipated. The resulting "sleep debt" contributes further to sleepiness and performance impairment during the night [p. 1142].

Other causes of fatigue include extended time awake, spent performing a task or tasks. Using highway and industrial accident data, researchers have shown that, after correcting for exposure, accident risk "increased in an approximately exponential fashion with time on shift [p. 504, 8]." Finally, some medical conditions and medications are fatiguing as well. Sleep disorders such as obstructive sleep apnea and restless leg syndrome are fatiguing because they interrupt both the quality and quantity of sleep [10]. Sleep apnea, however, when properly treated, typically by the use of a continuous positive airway pressure device, effectively treats the condition with few, if any, adverse side effects. Medical conditions that cause pain or discomfort to the extent that sleep is interrupted are also fatiguing. Similarly, certain medications such as opiates, benzodiazepines and over the counter medications such as some antihistamines, are sedating and hence, fatigue-inducing.

1.2. Fatigue and cognitive performance

Initial fatigue research focused on understanding the nature and quality of sleep. Consequently, early efforts to investigate accidents in which fatigue was suspected could only determine fatigue from fairly gross measures, such as occurred when a person demonstrably fell asleep while performing a task, a person articulated his or her fatigue, or was heard exclaiming other evidence of being tired. However in recent years researchers have demonstrated that cognitive performance will be degraded in the absence of overt manifestations of fatigue. Even mildly or moderately fatigued individuals do not perform as well as rested individuals do on measures of reaction time, vigilance, short term memory, and attention [11, 12]. The extent of the performance degradation varies with the degree of fatigue, within a range of individual differences. In general, the more fatigued the person, the more cognitive performance will be degraded. Nonetheless, even mild fatigue, which would otherwise be insufficient to be noticeable to colleagues, adversely affects cognitive performance. As Lin and Dinges wrote [12, p. 384],

> The results from our meta-analysis support the conclusions of previous reviews that short-term total SD (sleep deprivation) has a significant deleterious effect across most cognitive domains. As anticipated, the combined effect size for simple attention and vigilance tasks was the largest among all the categories studied.

Given the research findings, the effects of fatigue-related cognitive degradation would be expected to be demonstrated in tasks that require monitoring, attention, and mental calculation/diagnosis, well before an operator has fallen asleep. In the marine transportation mode where many operator tasks, such as navigating and engineering system oversight, engage these skills, the adverse effects of fatigue on marine safety are apparent. Further, because individual ability to recognize one's own performance degradation from fatigue is unreliable [10], basing fatigue recognition on the mariners' recollections or those of their colleagues may not be accurate. People are not particularly good at determining when their own cognitive abilities have been adversely affected by fatigue.

1.3. The marine environment and fatigue

Fatigue-related cognitive impairment affects individuals regardless of occupation. However, some occupations are associated with unique factors that can disrupt or reduce sleep and hence, cause fatigue. The marine environment is unique in ways noted because most mariners live on the vessels on which they serve and work fixed schedules with disruptions to rest periods not uncommon. In addition, much of the work of mariners, particularly engineers and deck officers, is cognitively demanding and over time overseeing system performance, vessel navigation, and determining the effects of sea state and wind changes on vessel performance, among numerous other task requirements, will be fatiguing.

Mariners also tend to maintain unique work schedules, some working six hours on duty, referred to as "on watch," from midnight to 0600, or 0600 to noon, then 6 hours later, from noon to 1800 or 1800 to midnight, in a schedule known as six and six or six on/six off, for six hours on duty and six hours off duty. During off-watch times, and while vessels are docked mariners may be engaged in other work-related activities as well. Under the best of circumstances, in such a schedule a mariner's sleep will be disrupted from the eight hours of uninterrupted sleep that is ideal to less than six hours after one shift and two or more after the other. Other mariners maintain schedules in which they are on duty for four hours, typically from midnight to 0400, from 0400 to 0800, or from 0800 to noon, and again 12 hours later for four hours as well. This schedule, referred to as four and eight, calls for four hours on duty followed by eight hours off watch, but also, potentially on duty. In each schedule, mariners would work the same block of time in the day, followed by the off watch period, and work a nighttime correlate of that time period. The schedule would be maintained for as long as the mariner is serving on the vessel, a time frame that can last several weeks or months. Working in proximity to one's habitat also makes it fairly easy for mariners to be interrupted from their sleep to assist in unplanned work-related tasks.

Researchers have examined the effects of watch schedules on mariner fatigue. One study of mariners in a simulated six on/six off schedule found that the schedule "induces high levels of sleepiness during the night watch but also during the early morning watch [13, p. 1201]." Similarly, a study of mariners maintaining a simulated 4 on/8 off schedule [14], found that regardless of the watch schedule, mariners were, on average, sleeping less than the 8 hour optimum, but that those maintaining the 0400-0800 and 1600 to 2000 watch schedules slept the least, averaging 6.6 hours of sleep per day, a finding similar to that of researchers in the Coast Guard-funded study of mariners conducted almost 15 years earlier [15]. Another study that compared mariner performance in the six on/six off to the four on/ eight off schedule found the former group of mariners to be significantly more fatigued than the latter, with the six on/six off schedule "associated with shorter sleep periods and with a four-fold higher risk of excessive sleepiness than the mixed type shift system [16, p. 421]." Researchers have also cited aspects of the marine environment such as high ambient temperature and high noise levels [15], vessel vibration and light intrusion [17], as factors that tend to exacerbate the adverse effects of the work schedule that mariners maintain.

In summary, research has been consistent in demonstrating that mariners are not receiving adequate rest. Studies have shown that "mariners sleep an average of 6.6 hours per 24-hour period while on shipboard duty—this is 1.3 hours less than average sleep duration at home [4, p. viii]" and that "the current work-rest scheduling for watchstanders does not allow the circadian rhythm of alertness to adapt to the work schedule [4, p. 30]." Other researchers determined that "the potential for fatigue at sea is high due to seafarers' exposure to a large number of recognizable risk factors …[and] that it is the combined effect of these risk factors that is most strongly associated with fatigue… [18, p. 8]."

Governmental mariner work schedule requirements address time on task and daily sleep needs that are consistent with the homeostatic sleep drive, but not schedules that are consistent with the circadian sleep drive. Rules for mariners operating internationally and within the waters of many countries, as established by the International Maritime Organization, require mariners to obtain 10 hours of rest in any 24-hour period, and no less than 77 hours of rest in any seven-day period. One of the daily rest periods must be at least six hours in length. Exceptions include emergencies and participation in emergency drills. In the United States, the Coast Guard requires licensed or rated mariners to adhere to similar work/rest rules. In addition, after the Exxon Valdez grounding, the United States government established rest requirements for tanker crewmembers. They can work no more than 15 hours in any 24-hour period or more than 36 hours in any 72-hour period, again except in an emergency or when participating in a drill. None of the rules require regularity in the times of the required rest.

1.4. Mariner fatigue and safety

As noted, several major accidents have been attributed to mariner fatigue, including the 1989 grounding of the tankship Exxon Valdez [19]. Others include the 1989 grounding of the tankship Royal Majesty [20], attributed to "the master's impaired judgment from acute fatigue." The mariner had, except for a few brief naps, been on duty for 35 hours through the time of the accident. Fatigue was also cited in the 1995 grounding of the passenger vessel Star Princess [21], which was attributed to the pilot's poor performance, "which may have been exacerbated by chronic fatigue caused by sleep apnea." In addition, the 2003 grounding of the general cargo ship Jambo [1] was attributed to the chief officer's missing a key waypoint because he had fallen asleep on the bridge, and the 2011 collision involving the tankship Eagle Otome [22] was attributed, in part, to the pilot's fatigue, the result of "his untreated obstructive sleep apnea and his work schedule, which did not permit adequate sleep (p. 60)." After the Exxon Valdez accident the United States Coast Guard commissioned a study of the accidents it had investigated to determine the influence of fatigue in the causes of those accidents [4]. It found that "fatigue was a contributing factor in 16% of critical vessel casualties and 33% of personnel injuries.

2. Marine accident investigations

Accident investigations are typically conducted by or for government agencies, using largely legal logic that relies on the preponderance of evidence to determine the role of different factors in an accident's cause or causes, rather than on statistical inference as in empirical research [23]. The logic used in investigations is counterfactual, where investigators strive to determine whether an accident would have occurred in the absence of specified events, and whether the events would have occurred in the absence of specific errors and/or system malfunctions [24]. To determine if a mariner's error led to an accident, investigators must have sufficient evidence to allow a determination that without that error the accident would not have occurred. Applying the logic of accident investigations to determine the role of fatigue requires making three separate but related determinations to establish that a mariner was 1) fatigued, 2) committed an error that is consistent with the research on cognitive performance degradations from fatigue, and 3) that no reasonable alternative can be found to fatigue to adequately explain the cause of the error.

Therefore, to investigate the role that fatigue may have played in an accident, investigators need to establish first that the mariner was fatigued at the time. Research on fatigue causation cites essentially four non-medical causes of fatigue, insufficient sleep in the hours immediately preceding an event, which leads to acute fatigue, sleep loss in the days or nights preceding the accident, which leads to chronic fatigue, extended time awake on task that leads to fatigue from the effects of the extended wakefulness and the demands of the task over time, and shift work or rapid time zone change that leads to circadian sleep disruption.

To determine the potential fatiguing effects of these factors investigators need information on the medical condition and medication use of the mariner at the time of the accident, a history of the hours the mariner spent performing particular jobs in the 24 hours before the accident, a description of those tasks, and the mariner's sleep/wake schedule each day in the weeks preceding an accident. Realistically, because few can accurately recall the times spent sleeping or being awake more than 3 or 4 days afterwards, investigators rely on relatively brief sleep/wake histories. The U. S. Coast Guard, for example, asks mariners to provide their sleep/wake hours for the 96 hours preceding an accident or incident, information that, while not as comprehensive as desired, nevertheless is of considerable value to determining fatigue.

Assuming no medical condition or medication may have been present or been used to interfere with a mariner's sleep, the 96-history provides investigators with critical information; the total number of hours slept each day and the regularity of that sleep. With this information investigators can determine the extent to which: 1) the mariner received the needed eight or so hours of sleep in each 24-hour period before the accident, 2) sleep and wake times were consistent each day, 3) the two sleep drives were synchronized, and 4) whether the time awake performing a task and the nature of the task were sufficient to have been fatiguing.

Investigators then must analyze the information on the 96-hour history, or equivalent information on the mariner's sleep and wake times and their regularity, to make a determination regarding adequacy of rest. While no metrics have been established to reliably and firmly establish a particular sleep amount or sleep schedule as definitively fatiguing for any one individual mariner, and with recognition of the difficulties inherent in retrospectively determining whether someone was fatigued at a point in time, the research has nevertheless been consistent so that a determination of fatigue can be made. That is, the knowledge that most people need about eight hours of sleep each 24 hours with regularity, that inconsistent sleep/wake times, extended periods of wakefulness, repeated 24-hour periods with less than 8 hours of sleep, and more than 18 hours of wakefulness each 24-hour period are fatiguing provides investigators the basis to allow them to determine whether a mariner was fatigued based on the documented history of quality and quantity of sleep. The more of the fatigue-inducing factors that are present, the greater the difference between actual sleep and 8 hours of daily sleep, and the greater the irregularity of sleep, the more likely the mariner was fatigued.

Relying on a documented history of sleep-wake times is preferred to simply asking the mariner how well-rested he or she was at the time of the accident because it eliminates the opportunity for mariners to subjectively and retrospectively gauge their own fatigue levels, eliminates variation in subjective feelings of fatigue, and because research has shown that there is considerable variability in people’s ability to accurately gauge their own fatigue levels [10]. Further, because people show degradation in cognitive performance with even mild-to moderate sleep deprivation, mariner recollections of their alertness may not accurately reflect fatigue that can lead to degraded cognitive performance.

Further, a documented history of sleep-wake times allows investigators to question mariners to obtain additional information on the quality of their sleep, to add to the information on their documented sleep times. For example, documented information on sleep-wake time history allows investigators to ask mariners about changes in their sleep environments during specific sleep periods, potential factors leading to sleep disruption, and other information that can enhance available sleep history information. This is a factor in the superiority of documented sleep-wake times to the retrospective application of bio mathematical models to determine fatigue because these models do not allow for the inclusion of follow up information on sleep quality and sleep disruptions. Further, research has not demonstrated the reliability of the retrospective application of the models, and the validity of their application to real-world settings such as vessels has not been established.

If the sleep/wake history supports a determination that a mariner has been fatigued, investigators then must examine the error or errors the mariner committed to assess the extent to which the errors are consistent with fatigue. Applying the findings of research on the effects of fatigue on performance to mariner errors such errors as those that demonstrate slowness in cognitive processes, especially involving monitoring, vigilance, interpreting or diagnosis, recognition, and prediction in dynamic circumstances could be attributed to the effects of fatigue. Gross decision making errors, particularly those made in a static environment such as while a vessel is docked, would not generally be fatigue-related. By contrast, errors of a mariner failing to recognize that the predicted path of an oncoming vessel may be conflicting with that of his or her own vessel, or the error of missing one or more critical pieces of information about one vessel while monitoring another, would be consistent with fatigue because of their consistency with errors of vigilance and data interpretation.

Assuming an error is consistent with fatigue, investigators then need to rule out potentially competing alternative explanations for the cause of error to determine that a fatigued mariner committed the error or errors in question because he or she was fatigued. Errors of comprehension or interpretation, for example, can also be attributed inexperience or inadequate training, if the evidence supports those determinations. In other words, some errors can be explained by causes other than fatigue, but to determine that fatigue led to an error, merely establishing that the mariner was fatigued by itself is insufficient to make such a determination if an alternative to fatigue can also account for the error. However, if no alternative explanation such as inexperience and inadequate training can be applied then such factors can be excluded as potential explanations, and fatigue applied to explain the error.

2.1 An example

This method of identifying fatigue can be applied to an investigation of a collision in which a tanker, the Eagle Otome, collided with one vessel that was docked, then with another vessel approaching it from the opposite direction, in a narrow waterway [22]. The accident occurred largely because the pilot who was conning, or controlling the navigation of the tanker was somewhat late in ordering a vessel heading change that was needed to traverse an upcoming bend in the waterway. The pilot, who was responsible for vessel navigation, had been engaged in a radio call with a crewmember of another vessel as the vessel approached the bend. When he had completed the call and recognized the need for the turn, he compensated for the delay by ordering a larger heading change than was typically used because the vessel was closer to the waterway bend that it should have been for initiating the turn. The pilot thus called for a turn at a point in time and distance that was closer to the actual waterway bend than should have been the case to have correctly initiated the turn. While traversing the bend the vessel, because of the excessive turn the pilot had requested, came too close to the waterway bank and as a result, the vessel lost steering effectiveness as it began to shear as a result of hydrodynamic forces associated with proximity to the bank. The sequence of collisions began shortly thereafter.

The pilot's errors of being late in recognizing the need for and in ordering the turn are consistent with degraded cognitive performance. Despite being engaged in radio communications at the point when he should have ordered a heading change, he was able to monitor the vessel's progress and should have been able to recognize the need for a turn when appropriate. Difficulty in shifting attention from one task to another, in this case from the radio communication to vessel navigation, is also consistent with degraded cognitive performance of fatigue. In effect, the pilot's error was in doing the right action, i.e., calling for a turn, but at a point in time that was too late for it to have been performed safely.

Investigators considered other explanations for the pilot's errors but ruled them out. The task was not beyond the skill level of the pilot and he had considerable experience in that job, having completed two years of training and having served as a pilot in that waterway for four years before the accident. His performance history was good; he had not been involved in previous accidents and incidents and he had no record of violations as a mariner. Therefore, investigators were unable to identify other possible explanations for the pilot's error.

Investigators identified two different sources of fatigue that adversely affected the pilot's cognitive performance. He had been diagnosed with sleep apnea but was not treating it, and his work schedule in the days preceding the accident would have disrupted his circadian sleep pattern. Two days before the accident he worked 27 hours straight, from 0700 through the night to 1000 the next morning. He then slept from 1015 the day before the accident to 1700 that afternoon, and again from 2100 until he was awakened at 0230 upon being told to report to the accident vessel for his next assignment. Although he slept the day and night before the accident, researchers have shown that disrupted circadian sleep patterns such as his would have resulted in poor quality daytime sleep so that the sleep he obtained during the day would have been insufficient to have compensated for his acute sleep loss the night before. In addition, the sleep he had gotten at night would not have been able to compensate for his sleep loss because of his being awakened at 0230, a particularly poor time to be awakened because of the deep sleep phase he would likely have been in at that time, a phase in which sleep disruption can be particularly insidious.

Thus, given three pieces of information about the pilot, his sleep/wake schedule in the days before the accident, the nature of his errors, and the quality and quantity of his previous experience, investigators had sufficient information to determine that his errors were affected by his fatigue. This method of assessing fatigue has face validity based on research findings on fatigue. It provides a systematic, objective means to determine the role of fatigue in an accident. In the case of the Eagle Otome discussed above, the method described allows investigators to answer three critical questions about fatigue:

- Was the mariner fatigued, if so
- Was the mariner's error consistent with being fatigued, if so
- Were there other causes of the mariner's error or errors?

If the answer to the first two questions is yes and to the final question, no, then sufficient evidence exists to determine that the mariner was fatigued at the time of the accident.

3. Discussion

The method proposed to investigate fatigue in a marine accident investigation addresses the major causes of fatigue in the marine environment, acute and chronic fatigue from disrupted circadian sleep patterns, extended time on task or from insufficient sleep in a 24-hour period, and medical condition and medication use, and relating the sleep information to mariner errors to determine whether fatigue played a role. It is systematic and objective, two requirements for accident investigations, it meets the logical requirements of investigations, and it can be readily applied to real world settings such as marine accident investigations. While the method has face validity based on research on fatigue causes and their effects on cognitive performance, additional research assess is needed to assess its reliability. Repeated applications in accident investigations can also help to determine its value as an investigative tool.

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