Critical Significance of Human Factors in Ship Design

Thomas G. Dobie, M.D., Ph.D., FRAeS
Director, National Biodynamics Laboratory
University of New Orleans

Proceedings of the 2003 RVOC Meeting, 8 – 10 October, 2003
Large Lakes Observatory, University of Minnesota

ABSTRACT

There is a critical need for a human factors input whenever technology and people interact. When systems are functioning well, few seem to appreciate that this smooth operation is largely due to the prior thought and effort that has gone into optimizing the human factors element; when disaster strikes, however, there is a sudden demand for immediate rectification. As the ship design evolves and crew sizes diminish, even greater emphasis should be placed upon the man/machine interaction in order to ensure safety and efficiency during both routine and emergency operations. Severe ship motions limit the human ability to operate command and control and communication systems, navigate, perform routine maintenance and prepare food. In an emergency, such operations as refueling at sea and damage control can be severely hampered. The human being is susceptible to degraded performance in a number of ways. There are the purely physical limitations on both gross and fine motor skills imposed by the adverse effects of heavy seas. The former physical limitations include standing, walking, and carrying out operational and maintenance tasks that include major whole-body movements required to perform these types of operations. Fine motor skills include such fine movements as delicate control adjustments and computer operations. Knowledge of the sea/hull interaction and its potentially deleterious effect on the physical activities of crewmembers can provide valuable information for improved ship and equipment design as well as establishing guidelines for efficient heavy weather operations. In addition, ship motion can cause significant mental degradation leading to overall performance decrement and increased potential for injury. Motion sickness is an example of this type of malady. Seasickness is the most common cause of motion sickness and can have a profoundly adverse effect on human performance. There is also the sopite syndrome, a human response to provocative motion characterized by drowsiness and mood changes. It is not yet clear whether this is due to boredom, inactivity and loss of concentration or the result of the effects of provocative motion. Whatever, this soporific response can lead to inefficiency and accident proneness, that is not so readily identifiable by the sufferer or a supervisor. These motion responses are highly relevant to the RVOC research ship situation. Not only because of the plans to reduce the number of crewmembers, but also because a number of the research or academic team members may have little or no recent experience at sea, particularly in heavy weather. Attention to onboard habitability issues and fostering a high level of morale among crewmembers are also very important factors in support of crew retention, particularly in modern ships with smaller numbers of crewmembers. The author will address these issues and make recommendations to improve the incorporation of the human element in future ships.

INTRODUCTION

From the onset, there is a critical need for a human factors input in the design of new ships to ensure optimal interaction between technology and people in order to achieve maximal operational effectiveness. When all is well and systems are functioning correctly and efficiently, few appreciate the significance of the human factors component that has led to the smooth operation. In emergency situations, however, there is an immediate demand for action in order to rectify the problem. Although many human factors efforts are aimed at the very highest level of technology, one should remember that they are required at all levels in order to insure maximum efficiency. Anywhere a mix of people and technology interact you will find *human factors*; a branch of engineering in which the primary emphasis is on the human input. In discussing ship design there are two aspects to be considered. First, there is the human-technological interaction of man and machinery to which I have already alluded. Second, there is the additional matter of operating and controlling equipment and systems on a moving platform. In other words, technology goes beyond the question of manipulating machinery and is concerned with structures, in this case ship structures, work and rest spaces, noise, vibration, temperature, and the effects of provocative motion. All of these factors play a significant part in how an individual reacts with technology. As ship design evolves and in particular as crew sizes diminish, much greater emphasis should be placed upon the human factors input in order to maximize safety and efficiency during routine and emergency operations. In heavy seas, severe ship motions limit the human ability to operate command and control and communication systems, carry out necessary navigational tasks, perform routine ship maintenance and prepare food. This raises the fundamental question of seakeeping and the seaworthiness of new designs of ships. Should emergencies arise at sea, the situation becomes even more critical when crew numbers are reduced. All these considerations relate to commercial vessels as well as to naval vessels; only detailed tasks and operational procedures will vary.

The human operator working on a moving platform is susceptible to degraded performance in a number of ways. There are the purely physical limitations of both gross and fine motor skills involving whole-body motion imposed by heavy seas. These include standing, walking and carrying out operational and maintenance tasks that include major physical movement in order to carry out these mechanical operations. These physical limitations include motion induced interruptions (MII) which occur when local motions cause a person to lose balance or slip, thereby interrupting whatever task is being performed. Fine motor skills include delicate adjustment of controls, computer operations, and certain maintenance tasks involving electronic boards and components.

Physical operations carried out on a moving platform also induce fatigue and degradation of mental effort leading to an overall decrement of human performance and increased potential for injury. Motion sickness is another example of a response to provocative motion that causes diminished performance. Seasickness is the most common form of motion sickness and has a profoundly adverse effect on human performance. These various physical difficulties and human responses may be found individually but on many occasions, they occur together. In addition, it may be difficult to tease out the specific causes of diminished performance, particularly in heavy sea states. For convenience, however, we shall address these specific issues separately, as far as possible, and make some recommendations on their management.

SEAKEEPING

The importance of good seakeeping is discussed in NATO Standardization Agreement (STANAG) 4154, titled Common Procedures for Seakeeping in the Ship Design Process (12-13-2000), Section 11.2:

> *"The general desirability of good seakeeping performance is universally accepted and has been for almost as long as ships have been designed and built. In general terms, good seakeeping qualities permit a warship to operate in adverse weather conditions with minimum degradation of mission effectiveness."*

Seaworthiness includes all the aspects of the design of the ship that affect its ability to remain at sea in all conditions and carry out its pre-planned operational mission. Brown (1985) has reviewed the importance of designing ships with a high level of seaworthiness, otherwise there would be a high cost involved due to lost operating effectiveness. He pointed out that in surface vessels this loss has in some cases "a direct, physical cause" while in others "it is due to a degradation in the ability of the crew to carry out their tasks." As an example of problems with heavy seas, Brown discussed the average weather conditions over the North Atlantic Ocean and pointed out that there is "a general correlation between wave height and wind speed (Beaufort number) in the open ocean for a fully developed sea" (Table 1).

Table 1- Correlation of Wave Height and Wind Speed

Sea State	Wave Height (m)	Beaufort No.	Wind Speed (kts)
1 - 4	Up to 2.5	0 – 5	Up to 21
5	2.4 – 4	6	22 - 27
6	4 – 6	7	28 - 47
7 and over	7 and over	8 and over	Over 48

In terms of human factors issues, he stressed that provocative motions result in two forms of degradation on crewmember performance. First, the task becomes more difficult for the individual due to the effects, as we shall see later, of trying to work on a moving platform. Second, the individual performs less well because of the difficulties inherent in his situation. These human factors issues will be dealt with in greater detail later in this document, bearing in mind that not all systems are affected in the same way and to the same degree by a given severity of provocative motion,.

Brown provided his interpretation of the loss of operational effectiveness for a 3000-tonne *Leander* Class Frigate (overall length 108m) in Table 2, and then summarized these losses as a percentage of overall effectiveness for various sea states in Table 3

Table 2 - Loss of Fighting Effectiveness, 3000-tonne Frigate (108 m)

Sea State	Wave Height (m)	Effect
1 – 4	Up to 2.5	Nil
5	2.5 – 4	Inconvenience, work takes longer. Some effect on sensors. RAS difficult.
6	4 – 6	Up to ½ crew sick. Sleep difficult. All are tired, some exhausted. Helicopter operation difficult (quiescent period only). Many weapon systems degraded.
7 and over	Over 6	Ship is ineffective as a fighting unit.

Table 3 – Percentage Loss of Fighting Effectiveness, 3000-tonne Frigate

Sea State	% Loss
5	10
6	30
7 & over	95

Brown then interpreted the loss of operational effectiveness assumed in Table 2; the number of days that the appropriate sea state occurs, and by multiplying these two factors showed the equivalent number of lost days per year. By way of example, the appropriate figures for a ship of *Leander* size (3,000 tonnes, 108m) in average North Atlantic weather are shown in Table 4. He then described the r.m.s. pitch and heave values for a 108m and a 125m ship for different significant wave heights, and, assuming that the loss of effectiveness of the two vessels to be a function of vertical motion (pitch and heave), he calculated that the longer ship would lose 7.0 days compared to the 11.7 days for the shorter vessel.

Table 4 - Effective Days Lost. *Leander*, North Atlantic.

Sea State	% Year	No. of Days (out of 150)	% Loss of Effectiveness	Lost Days
1 – 4	62	93	0	-
5	22	33	10	3
6	11.5	17	30	5
Over 7	4.5	7	95	7
Total				15

Brown summarized his findings by concluding: the cost of lost effectiveness is very high; more data are needed to confirm his postulate; there is a considerable return on investing in a longer ship; and weapon systems should be selected on their ability to perform in bad weather and tested in realistic conditions.

STANAG 4154 states: “despite the clear link between poor seakeeping and reduced mission performance, seakeeping is not given sufficiently high priority when the naval requirements are defined.” That STANAG document suggests that it is not enough to cover this issue by stating: “Seakeeping performance shall be sufficient to maintain operational capabilities up to and including sea state 6", because it does not clearly define the environmental conditions to which the ship and systems are being designed to resist.

Apart form these human limitations, severe wave motions can have equally adverse effects on the operation of weapon systems and onboard helicopter deployment. In heavy seas, a ship is exposed to increased surface resistance that is usually aggravated by the air resistance caused by accompanying high winds. These problems can be intensified by wetness when the bow ships water. In particularly heavy seas slamming occurs because of the pressure that the sea imposes on the hull of the ship. These sudden changes in vertical acceleration have a seriously adverse effect on crewmembers' abilities to maintain postural stability and carry out their functions whatever they may be. These adverse provocative motions call for good seakeeping in order to minimize the effects on operational efficiency. It requires good judgment to assess the relative relationship between ship and wave direction (see polar diagram information and STANAG No. 4154, Chapter 12) and to decide whether it is desirable and operationally acceptable to change steering direction and/or ship speed to reduce motion effects. As Rawson and Tupper (1984) have pointed out such a decision requires a "thorough knowledge of both criteria and acceptance levels appropriate to the design and function of that particular vessel or to another with similar characteristics."

It is important to remember that crewmembers may well interpret a designer's ideas and instructions quite differently from his original intention since they all have widely different levels of experience. In addition, these interpretations may be quite unexpected when crewmembers are under stress. In practice a person tends to see what he expects to see and ignores what he does not expect to see. This introduces a question concerning automation. What systems should be automated and which should be left under the direct control of crewmembers? The latter solution in itself raises its own problems since, as we shall see elsewhere, group interaction can break down under certain conditions of stress. These matters emphasize the need for careful planning and system design to maximize crewmember efficiency in complex and stressful conditions, including those of operating in heavy seas.

The benefits of enhanced seakeeping performance are also highlighted in STANAG 4154, Section 11.2 and summarized here:

> *a. Health and safety of crew*
> *The design manager has an obligation to ensure that the crew has a safe working environment to the extent that is practical for a warship. The problem of injury is particularly relevant, however, given the current trend towards lower manning levels.*
>
> *b. Habitability and crew morale*
> *Crew effectiveness is addressed by taking account of motion induced fatigue and motion sickness. However, the longer term peacetime implications such as crew retention should be borne in mind.*
>
> *c. Crew tasks*
> *Ship motions can have both direct and indirect effects on crew task performance. Ship motions directly affect physically demanding tasks.*

Fine psychomotor tasks such as circuit board repair are also affected directly by the ship motions, but in a different way to physically demanding tasks. Cognitive tasks such as radar monitoring may be indirectly affected by ship motions, in that long exposure to severe motions may cause nausea and fatigue. Both these may contribute to task performance degradation.

d. System loss and damage
The loss of and damage to equipment and/or ship structure caused by excessive ship motions and motion phenomena will not only degrade military and operational effectiveness in wartime but will also increase through life running costs.

e. Fuel consumption
Involuntary speed loss due to added resistance is an accepted consequence of rough weather and is considered in some operability analyses. Increased fuel consumption for a given transit mission is not commonly addressed but could have a noticeable effect on through life fuel costs. Design considerations must be made for the additional fuel (and its implications on the displacement) required to maintain range and endurance.

f. Layout considerations
As the overall ship motion response is minimized for a given sea state the range of locations throughout the ship that satisfy particular motion criteria will be increased. This gives the designer greater flexibility with respect to the location of operationally important compartments and orientation of workstations. Layout considerations are important because they may provide relatively easy (and therefore cheap) solutions to some problems. For example maintaining visibility at the bridge or sheltering certain key locations may help crewmembers perform more effectively.

WHOLE-BODY VIBRATION

Whole-body vibration may affect subjective comfort, working efficiency and in the worst cases, impair health and safety. Although there have been many methods for rating the severity and defining the limits of exposure to whole-body vibration, none has been universally accepted. Early work suggested that exposure to vibration as low as 0.1 Hz to 1.0 Hz should be limited (Allen, 1974). Different methods have been suggested for determining the effect of complex vibrations as compared to sinusoidal vibration. Shoenberger (1976) suggested that the independent component method of estimating the effect of complex vibrations would underreport the accelerations, and recommended the use of a weighting technique to predict the severity of complex vibration environments based on frequency bands. Shoenberger's further work (1978) in this area refined the ISO weighting method for predicting accelerations, and determined the role of angular accelerations in human response to vibration by using a subjective intensity scale to compare response to translational and angular accelerations.

Although we are referring to whole-body vibration, in fact, vibration can be transmitted to the human body in a number of ways. First, as the name suggests, vibrations may be transmitted to the whole body surface simultaneously. Second, they may be transmitted to parts of the body surface such as the feet, or in the case of a seated crewmember, the buttocks. Third, vibrations may be applied to individual parts of the body. In addition, however, vibrations can affect human performance indirectly by affecting the stability objects in the operator's visual field, such as viewing visual display units that are vibrating. This causes blurring of vision and difficulty of interpretation.

In terms of whole-body vibration, this can conveniently be classified as either low frequency motion induced by sea conditions surrounding the vessel and vibrations of higher frequency originating from the engines, propeller shafts, and major pieces of onboard machinery. Higher frequency vibrations can also originate from hull responses following severe slamming in heavy seas. In general, whole-body vibration in the range from 2 – 12 Hz can have an effect on human performance (von Gierke et al., 1991). Even below that frequency range, however, Colwell (1989) has reported significant manual control problems during simulated surface effect ship motions in the range of 0.02 to 0.2 Hz, where the vertical r.m.s. magnitudes were 0.5 to 1 g. The effects of whole body vibration are many and various. They may cause performance deficits, fatigue, accident-proneness and even health hazards. Nevertheless, the picture is not absolutely clear, and there are many differences of opinion on the effects of whole-body vibrations. It is not only dependent on many variables, but as Griffin pointed out in 1990, there is no one simple predictor for all individuals and every occasion. This is certainly a matter that should be addressed in the design of new vessels, and in the installation of new equipment upon vessels. Because of the effect it can have on fine motor skills, this in itself is a matter that requires further consideration.

MOTION-INDUCED SICKNESS

Motion has long been recognized as an unpleasant consequence of employing some forms of transportation. Gay (1954) described motion sickness as a "physical state that develops in human beings and animals when they are subjected to oscillatory movements over which they have no control". As Birren (1949) pointed out, "Statistically there is nothing unusual about motion sickness, since more than half of the population may be made seasick and some investigators believe that everyone may be made motion-sick under appropriate conditions." In terms of seasickness, Birren believed that most people who experience a transient bout of motion sickness can exert themselves sufficiently to perform adequately when necessary. This response has already been mentioned when discussing "cognitive performance". It may be that for short duration exposures, individuals make an extra effort to carry out their primary task.

Malaise, general discomfort, sweating, nausea, and vomiting characterize motion sickness. Provocative motion environments involve many forms of transport, such as ships, aircraft, air-cushioned vehicles, and automobiles, all of which are important to both military and commercial services. The characteristics of the underlying stimuli are essentially the same, however, and so are the subjective responses. There is no difference in the effects caused by these provocative motion stimuli, whether they occur at sea, in the air, on amusement park rides, in an automobile, or even when riding on a camel. It is for this very reason that the responses have all been labeled motion sickness.

Motion sickness can also be produced in the absence of expected motion. Visual motion alone is sufficient to produce sickness, as in the case of fixed-base simulators, or when viewing wide-screen movies. These are becoming more common sources of this malady with the rapid escalation in the use of simulation. In summary, motion sickness is a response to real or apparent motion to which a person is not adapted. It is, therefore, a normal response to an abnormal environment. The relief and ultimately the apparent immunity from motion sickness, which usually occur with practice, are also part of the normal response. In terms of the inexperienced sailor, seasickness is the predictable response to adequate motion stimuli. Hill (1936) stated, "There is a world of difference between this and the equally normal response to identical stimuli on the part of the seasoned sailor. The gap is bridged by the process of adaptation." He summarized this as follows: "The establishment of immunity is Nature's cure, and to expedite this process is the single aim of rational treatment." Nevertheless, we believe that we can give Nature a helping hand, as we shall see later, in order to speed up the process of adaptation, both in terms of overcoming the malady and in preventing it.

There are many reasons why it is difficult to give a precise figure for the incidence of motion sickness because, as is the case with almost all maladies, a number of factors are involved (Dobie, in press); for example:

a) The characteristics of the stimulus in terms of frequency, intensity, direction, and duration. Experiments on vertical oscillators, which simulate the heave component of ship motion, show that the incidence increases as the frequency of the oscillation falls. The most provocative frequency has been shown to be around 0.2 Hz.
b) The susceptibility of the individual, based upon physiological characteristics, past experiences, psychological and personality factors.
c) Individual activity at the time of exposure to the stimulus, e.g., passengers are usually worse off than drivers.
d) Other factors, such as food, ambient air temperature, and certain odors.

The incidence of seasickness is extremely variable. For example, Hill (1936) estimated that over 90% of inexperienced passengers become seasick in very rough conditions and some 25% - 30% during the first two or three days in moderate seas. Chinn (1951) also reported that during the first two or three days of an Atlantic crossing, in moderate seas, 25%-30% of passengers on liners become seasick. In the United Kingdom, Pethybridge (1982) found that some 10% to 30% of naval crews suffered from seasickness during commonly experienced sea conditions and that this incidence rises to between 50% and 90% in the worst conditions. In the U.S. Navy, the Naval Medical Information Management Center reported that during the calendar years 1980 through 1992, 489,266 new cases of motion sickness were diagnosed and a further 106,932 revisits were recorded. This represents a significant loss of effective manpower and funds.

SOPITE SYNDROME

The sopite syndrome is a subjective response that is characterized by drowsiness and mental depression. Other symptoms include fatigue, difficulty in concentrating and disturbed sleep. Graybiel and Knepton (1976), unlike many of their predecessors in the field of motion sickness, reported that drowsiness is one of the cardinal symptoms of motion sickness. As long as 1912, Byrne stated that "effects of seasickness on the nervous system create psychic depression so extreme, and a disturbance of cerebral function of such magnitude, that self-control becomes impossible." In 1936, Hill reported that sleep had an important bearing on seasickness, pointing out that drowsiness, apathy and mental lethargy, without actual somnolence, were present.

In 1954, Schwab noted that motion sickness includes a variety of minor symptoms that escalate before actual nausea and vomiting occurs. It is interesting to note that he introduced the first symptom as "rather a subjective one and [it] is described as an uneasy feeling with a certain amount of lack of interest in the task being done." He noted that in such cases "no visible signs are shown by the subject at this point and a great many travelers bothered by motion sickness may pass through this phase alone and never develop further symptoms or complaints because of the termination of their trip." Schwab suggested that these people would not admit to being motion sick even if aware of "this subtle change in their normal habits." He continued to state that "this mild lack of interest in the immediate environment increases steadily and is accompanied by a certain amount of yawning." Could this be an early reference to what we now call the "sopite syndrome"? If so, it still begs the question as to whether it is part of motion sickness or a separate entity of some other origin.

Although Lawson and Mead (1998) indicated that this syndrome is little understood, nevertheless they suggested that it is a distinct syndrome from either what we know as motion sickness or a state of fatigue. They also considered that it could have particularly profound effects in different transport environments where, for other reasons, sleep disturbances already exist. We already know that sleep disturbances are very common at sea, and this may mask the sopite syndrome, if indeed it is a separate entity. Whether that is the case or not, we do know that sleepiness and fatigue are commonly reported in provocative motion environments. Lawson and Mead stress that the sopite syndrome does appear to have a different time course from the other symptoms of motion sickness, that it commonly appears before nausea, and persists after the nausea has disappeared. In our laboratory, we have noticed significant yawning and apparent sleepiness both before the onset of nausea and after the end of provocative motion. Also, we have reports of nausea during the follow-up period after these events took place.

It is clear that this issue requires further investigation in order to identify the cause of the symptoms associated with the sopite syndrome. They may simply be typical symptoms of low grade motion sickness occurring during and or after exposure to provocative motion. They may be associated with environmental factors such as high ambient temperature, isolation or exposure to enclosed spaces. Until these elements are investigated in a controlled fashion, this question of the sopite syndrome being a part of conventional motion sickness or a separate entity remains open to conjecture.

MANAGEMENT AND PREVENTION OF MOTION SICKNESS

There are basically two major aspects to this problem. First, an attempt must be made to reduce the levels of provocative motion to which the individual is exposed. This can be achieved by altering the design characteristics of the vessel or vehicle so as to minimize exposure to accelerations likely to cause further problems. This approach can be taken a step further by locating the key work areas on a ship on the center of rotation and design their workstations with the main axes of the hull. On the other hand, sleeping quarters could be located in areas calculated to experience mild provocative motion that might help to induce sleep. As far as the individual is concerned, it may help to provide an external frame of reference and we are currently investigating this possibility. It is also known to be protective if workstation and tasks are so designed as to minimize head movements, thereby reducing vestibular stimulation.

Commonly, people get their “sea legs” after a few days at sea, depending on their previous encounters with seasickness and the severity of the sea state when they first return to sea. There are many anti-motion sickness drugs available and it is not feasible to review this approach here. Apart from that constraint, the pharmacological approach to the treatment of motion sickness introduces many problems. The drug actions are variable both in terms of individual responses and the effects of an operational situation on these responses. Some of the potential side effects are not acceptable when the user is in control of sophisticated or potentially hazardous equipment, or making complex operational command and control decisions.

In view of the potential problems associated with anti-motion sickness medications, some form of behavioral desensitization has much to offer for preventing or treating motion sickness, particularly for persons who are regularly exposed to provocative motion environments. This form of therapy is particularly relevant to an occupational situation, where the vast majority of individuals exposed to provocative motion are likely to be carrying out skilled or potentially hazardous tasks. It is this group of people who can gain the greatest benefit from non-pharmacological procedures.

Dobie (1963, 1974) first described the concept of cognitive-behavioral anti-motion sickness training. The rationale of this program is based on relieving a person’s state of arousal associated with previous unpleasant responses to a provocative motion environment. Once the idea has been established in a person's mind that he or she may not have any "physical" reason for appearing to be more susceptible to motion sickness than others, this belief is reinforced by means of controlled exposures to non-specific provocative motion stimuli. While the technique appears to involve habituation and adaptation to a particular situation, our controlled studies have shown that mere repetitive exposure without counseling has not proven to be beneficial in protecting subjects against provocative motion. A key element in the cognitive-behavioral technique concerns the individual’s ability to learn to control the focus of cognitive processes. Emphasis is always placed on the normality of this protective response to provocative situations.

In the author’s opinion, the main difference between an individual who is apparently sensitive to motion and one who is seemingly not, is mostly a feature of the arousal which is created by exposure to a particular provocative motion environment. The so-called “resistant” individual enters that environment with zero arousal and can cope with a considerable amount of provocative stimulation before reaching his or her threshold of response (beginning to feel motion sick). At the same time, these relatively lengthy exposures to provocative motion allow time for habituation to take place. However, the matter is quite different for people who have a history of motion sickness. These individuals enter a provocative motion environment with a varying degree of arousal dependent on previous motion experiences, particularly if these exposures have caused motion sickness. Depending on the degree of arousal, the subject gets closer to the onset of motion sickness (threshold of response) in a shorter time. In more severe cases, this can occur on entering (or even before entering) the provocative motion environment. This also means that each exposure will be relatively short before the onset of motion sickness, and consequently there is little time to habituate, so that person fails to get their "sea-legs" without help.

This program still carries the highest success rate in the open literature and a long-term follow-up has shown that the protection afforded the individual remains with him or her (Dobie, 1974). We are now turning our attention to the question of prevention by means of facilitating adaptation to provocative motion environments. Although motion sickness is common at sea, in the air and in many virtual simulations of motion environments, extensive individual differences exist with regard to the ability to tolerate such provocative situations.

WHOLE-BODY MOTION

The effects of whole-body motion involve both motion-induced interruptions (MII) and motion induced fatigue (MIF). MII refers to a situation that occurs when local motions cause an individual to lose balance or to slip, thereby interrupting whatever task is being performed. Applebee, McNamara and Baitis introduced this concept in 1980. In defining this loss of postural control, the original workers applied simple acceleration thresholds to task performance and then predicted that individuals would experience MII if those acceleration thresholds were exceeded. Calculations were made in the time domain to predict the occurrence of MII. In 1989, Graham extended this concept to the frequency domain thereby making it more conducive to the prediction methods of ship motion. The MII model predicts a loss of balance while standing when the tipping moment is greater than the righting moment provided by the individual's stance width. In the model related to frequency domain, the ratio of an individual's half stance width to the height of his or her center of gravity is defined as the tipping coefficient. This coefficient is then used to evaluate when a tip will occur. The result is expressed as the number of MII per minute.

In 1995, Baitis et al. published a report on MII based on experiments in the Naval Biodynamics Laboratory Ship Motion Simulator (SMS). In this study they concluded that the magnitude of the coefficient of friction for surfaces typically found on the interior and exterior of a ship is usually much larger than either the lateral or fore and aft tipping coefficient, so that tipping MII will usually occur before sliding takes place. They also noted that the individual's MII did not necessarily occur according to the threshold crossing that is implied by a rigid body theory. Graham had suggested this simple postural stability model because of the difficulty of using an exact representation of the human body. His simple rigid body was based on one similar to the size and shape of the average human body.

Baitis et al. also noted that individuals had different techniques for maintaining bodily stability for lateral as opposed to fore and aft MII. They concluded that human subjects were better at avoiding MII than would be anticipated when using the rigid body model with nominal tipping coefficient. This is perhaps not surprising and of course would be significantly affected by an individual's experience on a moving platform. As would be expected, individuals who had already gained their "sea legs" are better at maintaining an upright posture than are naïve subjects. The studies by Baitis et al. were carried out on the SMS, which only had 3 degrees of freedom (heave, pitch and roll). They suggested that further work was necessary, such as including the missing ship motion components, in order to see what effect they had on the occurrence of MII. They felt that the addition of sway and yaw to the lateral ship motions would complicate an individual's ability to maintain an upright posture.

At the National Biodynamics Laboratory, we have conducted such a study. We have carried out a number of simulator experiments in order to augment that existing experimental MII database previously developed by the Naval Biodynamics Laboratory, just described. What was then the Naval Biodynamics Laboratory became the National Biodynamics Laboratory, so the same SMS in which the initial study was performed was still available. In addition, however, we now have a new 6 degrees of freedom motion platform as well. This allowed us to carry out further studies with the additional three degrees of freedom, albeit with a reduced heave component, as well as using the SMS.

The evaluation of gross motor ability (MII), using observer ratings and objective data from force-plate recordings, has revealed reliable differences in performance across the motion profiles simulating different headings into sea state 5. However, the addition of the extra degrees of freedom did not significantly increase the number of MII. Provocative ship motions have been shown to cause a high musculo-skeletal load as well as motor challenges, thereby increasing workload. Both fine and gross motor skills were compromised by low frequency ship motion. In terms of fine motor skills, tracking tasks involving smooth adjustments were more sensitive to provocative ship motion than ballistic movements.

The more provocative simulated headings produced more problems on some tasks from trial 1 to trial 2, indicating fatigue. While the less provocative simulated headings provided evidence of compensatory learning (fewer MII on trial 2 relative to trial 1). It was also clear that some tasks were relatively unaffected by a given simulated heading (walking and standing facing the bow), but another task (standing facing port) was considerably compromised. These results were understandable given knowledge of normal postural reactions in response to motion.

INFLUENCE OF VISUAL REFERENCE

While studying this MII problem on the 6DOF motion platform at NBDL, we observed that the lack of an external visual reference had increased the number of MII. In order to investigate this matter further the frequency of MII was recorded under conditions that did and did not provide subjects with a view of the outside world. Each subject has carried out a number of standing and walking tasks on the moving platform on two separate occasions; starting with or without an external visual reference followed by the reverse order on the second exposure, completely counterbalanced for each group (males and females). In addition to scoring MII by two independent observers, force plate data were collected in the standing conditions.

In this second study (Dobie, May and Flanagan 2003), the most provocative simulated heading found in the previous MII study was used with the same performance tasks and dependent measures to evaluate the influence of visual reference. In one session, subjects performed the task with a view of the walls of the stationary test cell within which the motion platform was housed (simulating above deck conditions). In another session, curtains attached to the sides of the motion platform precluded this view. It was clear that many more MII occurred, especially for the most difficult task, when the view of the test cell (simulated outside world) was precluded.

The results clearly showed that the subjects experienced more MII when the installed curtains have excluded an external visual reference. This has indicated that an external reference has been supportive in terms of improving postural stability on the moving platform. This finding has suggested that the provision of visual displays, as a replacement in compartments that did not permit a view of the real (outside) world would be beneficial. It is suggested that such depictions provide enhanced optic flow and motion parallax that serve to help a person's anticipation of bodily movement. It has also been evident that individual's began to adopt new strategies that involved increased weight shifts in order to maximize postural control. The improved postural stability would not only improve performance, but it would also reduce the likelihood of accidents and might also reduce the incidence of motion sickness.

While crew performance aboard ship is the main area of concern, deployment of other vessels from ships and safe operability of these other vessels as they interact is a significant performance question as well. The effect on human performance may vary from the host vessel to other vessels such as helicopters or smaller boats, even though both vessels are responding to the same parameters of wave height, wind speed, etc. (Baitis et al., 1984).

GROSS AND FINE MOTOR SKILLS

When talking about whole-body motion and whole-body vibration, much of the significance lies in the effect of these provocative stimuli on subjective gross and fine motor skills. This is a typical example of the interaction of these underlying variables and the mechanism whereby they may interfere with performance. It is more difficult to carry out tasks requiring gross motor skills in a moving environment than in a static environment however, the degree of the decrement of performance will vary with a number of factors. First, the severity of the hull/sea interaction, the weight and complexity of the components that involve gross motor activity, and the experience of the individual, both in carrying out the task and in standing and working on a moving platform. Ship motion may directly interfere with performance by interrupting the task, or it may indirectly interfere with gross and fine motor skills by affecting motivation or resulting in fatigue, (Wertheim, 1998).

We have already addressed the issue of the effect of whole-body vibrations on fine motor skills. However, they can also be affected by whole-body motion. This leads to a consideration of the type of manipulative controls being used onboard ship, whether these involve a keyboard, mouse, trackball or touch screen, and whether or not the operator's arms are supported or unsupported. In 1980, McLeod and Poulton carried out a study of the influence of ship motion on manual control skills. They found that the response to motion ranged from "virtual destruction" to a complete absence of adverse effects. In that study, they examined three manual control tasks that included: movement of the unsupported arms, continuous fine movement during which the arms were restrained or ballistic manual tasks with an unsupported arm. They found that a tracking task that called for a continuous whole arm movement was, not surprisingly, very badly affected. In the case of a tracking task using fine movements with supported arms, this was affected but not badly so. Lastly, the ballistic task involving digit keying was virtually unaffected. These were relatively short duration tasks so that fatigue and what might be called chronic motion sickness were not involved. They suggested that it would be beneficial to try to design the man-control interface onboard ships around motion-resistant tasks.

These matters are still of considerable interest and further work will be useful to obtain a better understanding of the various cognitive and physical gross and fine motor maneuvers likely to be performed on a moving platform, particularly over a longer period of time.

COGNITIVE PERFORMANCE

In modern ships, much of the work is perhaps more mental than physical when compared with the situation many years ago. It is clearly of interest, therefore, to know whether or not provocative motion has significant effects on the efficient performance of a cognitive task, with or without a small psychomotor component such as is required manipulating a computer terminal. The question of increased mental workload, particularly against a background of stress, merits careful consideration, but where do we start? In 1979, Moray was of the opinion that there was no satisfactory definition of mental workload. As Kantowitz and Sorkin (1983) pointed out, it is many things to many people. In their list they included, information processing and attention; the time available to carry out the task, and stress and arousal. Williges and Wierwille (1979) discussed three broad ways to obtain measures of mental workload. First, subjective opinions based on rating scales or interviews. Second, measures of spare mental capacity obtained from information theory (Senders, 1970). Finally, the primary task method that assumed that as mental workload increased, performance of the primary task was decreased. On the other hand, when discussing the psychophysiological aspects of motion sickness, Birren (1949) put forward different evidence. He observed that most individuals who are transiently motion sick could exert themselves to a level of adequate performance when necessary. He referred to this as "peak efficiency", as distinct from the daily routine that he called "maintenance efficiency".

In 1986, Wilson et al. conducted an experiment in the NBDL SMS in an attempt to investigate the effects of single frequency heave and roll motions on cognitive performance. The experimental sessions were planned to last two hours but an unspecified number of subjects aborted before that time. These workers showed that four out of five subjects demonstrated significant slowing of cognitive processing during heave motion alone. They described this as extending from slight to large adverse effects across these four subjects whereas there was no such reported difference on the accuracy of performance during exposure to roll motion. They suggested that, under these conditions, the subjects might have adopted a personal strategy whereby they reduced processing speed in order to maintain accuracy. They noted little evidence that roll-only motion had any adverse effect on cognitive performance, however; only one of the five subjects exhibited any adverse effect on their cognitive processing in that situation.

In 1987, Pingree et al. measured task performance on a hovercraft during mild and severe motion conditions while at sea. They found no significant detrimental effects due to motion in terms of the three computer-based cognitive tasks that they used. On the other hand, there have been other reports of sea trials that seemed to indicate loss of cognitive performance due to exposure to provocative motion. Wiker et al. (1980) carried out a study at sea in which they gathered data on six different measures of cognitive performance from crewmembers on three different vessels and reported significant decrements of performance on five of the six measures. Brand and Perry (1967) and Sapov and Kuleshov (1975) also reported significant reductions in performance during ship motion. In the latter study, the recorded decrements occurred early in the trial and then cognitive performance improved, suggesting a strong relationship to the detrimental effects of motion sickness.

During a simulator experiment at NBDL, cognitive tasks such as display manning and decision-making were carried out and Crossland in 1994 and Conwell Holcombe and Holcombe in 1996 reported on these. The study only found degradations in fine and gross motor movement but none in terms of cognitive skills. In 1996, Wertheim also reported that cognitive tasks were not directly affected by ship motion and reaffirmed this view in 1998.

It seems, therefore, that there is really no hard evidence that there are any direct effects of provocative motion on cognitive performance, although there are clearly indirect effects such as degradations of fine motor skills and the subjective effects of motion sickness. It may be that individuals maintain a higher level of efficiency, both in terms of cognitive performance and performance in general, during provocative motion until such time as they are no longer able to do so, as suggested by Birren in 1949. This might become clearer if one were to carry out longer duration exposures.

Following a recent questionnaire study carried out in the NATO fleet during heavy weather in the North Atlantic in wintertime, Colwell (1998) reported that disturbed sleep was particularly significant as a cause of performance decrement on the following day and that motion sickness also adversely affected performance. As a result, this matter was evaluated further in a controlled experiment at NBDL. Volunteer subjects were exposed to provocative motion for a period of 72 hours in the SMS. There were two subjects in the simulator on each occasion, and they worked a six-hours on, six-hours off shift routine. In the SMS they were exposed to two levels of provocative motion: simulating a mild sea state for 24 hours; a heavy sea state for 24 hours and finally the original mild sea state for 24 hours. On a separate occasion, seven days later they were exposed to a calm sea state for 72 hours represented by a static cab. During both experimental sessions the subjects performed a battery of performance tasks during the duty periods. These tasks were aimed at assessing cognitive performance under conditions of provocative motion. However, like most computer-administered tasks they involved sensory and motor actions as well as cognitive abilities.

Measures of both speed and accuracy were recorded for each task. Only three performance measures provided significant main effects for motion. The inaccuracy of time estimates in the speed estimation task (Decision Making) was significantly higher for the motion as opposed to the static condition. This may be a true motion effect on a cognitive ability, since other measures involving a button press response were not similarly affected by motion. The reaction time for the local consistent condition (Concentration) resulted in faster reaction time under motion than static conditions ($p < 0.023$). This could be due to heightened arousal produced by the simulated ship motion. The average deviation for the pursuit-tracking task ($p > 0.015$) was found to be lower in the motion condition and this could have been due to increased arousal under motion conditions.

In conclusion, the results in the literature concerning motion effects on cognitive performance are equivocal at best. This may be attributed to the relatively low level cognitive tasks so far employed. The performance of such tasks is reliable and free of downward trends even in the face of increasing motion sickness symptomatology. When subjects do stop performing a task, they do so abruptly and valid predictors of when they will give up may be developed from monitoring subjective measures of well being. To date, however, studies on motion effects on truly high level cognitive functioning have not been conducted.

MOTION INDUCED FATIGUE

In this context we are referring to fatigue that is the result of a biodynamics problem, or what has been called "weariness after exertion" (Powell and Crossland, 1998), rather than the result of either lack of sleep or motion sickness. In 1989, Colwell, in reviewing naval biodynamics problems, felt that motion-induced fatigue was indeed significant. He suggested that this was an important source of performance degradation for the naval community that implied a higher incidence of mistakes, some of which might not be noticed by a supervisor. This problem also has relevance to commercial fleets. This is a complex matter, however, as Powell and Crossland wrote in 1998. Reports of motion-induced fatigue include other features, however, including lack of motivation. In their view central fatigue, as distinct from muscle fatigue (weariness after exertion) is perhaps the main contributor to fatigue at sea. This is in keeping with the results found by Baitis et al. (1995) during their MII study in which they reported that the measured levels of energy expenditure (muscle fatigue) were relatively small compared to the subjects' capacity to perform work. They did, however, recognize the fact that more severe ship motions could well raise the crew's energy expenditure to limits that could be significant. In this matter of human energy expenditure, Wertheim et al. (1997) found that peak oxygen consumption, as a measure of physical workload, might indeed be lower in a moving rather than a stationary environment. This is an interesting observation but, as these workers stated, one which had no obvious theoretical explanation. This brings one back to the question of motivation as an explanation, rather than a complex cardio-respiratory response. Before leaving this question of motion-induced fatigue, it must be said that without question it is much harder to work in a moving environment. Very much more muscular effort is involved in maintaining bodily posture as well as carrying out a particular task. It is further complicated, as we shall see later, by the question of lack of sleep due to heavy workloads and to the debilitating effects of motion sickness.

SLEEP REQUIREMENTS

Sleep management is a critically important consideration "assuring that fighting men and women, at all levels, have sufficient sleep for maintaining their combat effectiveness" (Naitoh et al., 1986). This situation has become more acute since crewmembers have been required to operate both night and day, thereby interrupting and/or losing their sleep. Filor (1996) has aptly described seafaring as the "original 24-hr society". During prolonged duty periods, there may be one or more intense continuous work sessions and this situation is more likely to occur as crew sizes are reduced.

In 1995, Bonnet and Arand's studies have shown that the reduction of nocturnal sleep by as little as 1.5 hours for one night caused a 32% reduction in daytime alertness as measured by the Multiple Sleep Latency Test. Their data have shown that significant sleep loss exists in one third or more of the normal adult populations. They point out that it is not surprising that fatigue plays an important part in 10% of fatal car accidents. These figures highlight what they call the "alertness function of sleep and the increasing consequence of sleepiness…" This situation emphasizes the need to address the sleep issue as part of the human factors considerations in designing new classes of vessels, particularly when the numbers of crewmembers may well be at a critically low level.

Van Dongen et al. (2003) have pointed out that experimental reports on the "effects of long-term chronic sleep restriction have bordered on the anecdotal, lacking adequate sample sizes and control groups." They also note that other studies that have evaluated the cumulative effects of restricting sleep to 4-6 hours per night for up to a week have produced conflicting results. For those reasons, these workers stressed the need to investigate possible adaptation to restricted sleep by means of chronic experimental designs that permitted quantitative measures of the temporal profiles of waking responses to be obtained reliably over days. In their highly controlled experiments Van Dongen et al. found that chronic sleep restriction of the nightly sleep period to either 6 or 4 hours daily for 14 days resulted in significant cumulative cognitive performance deficits relative to the 8 hours nightly sleep period. In particular, significant differences among conditions in the rate of change across days were found for psychomotor vigilance task performance, digit symbol substitution and serial addition/subtraction performance. Those subjects who had been allowed 8 hours sleep per night showed only minor non-significant increases in lapses of behavioral alertness over the 14-day period.

When chronic sleep restriction has been compared with total sleep deprivation, it has been found that in the 4-hour sleep condition, lapses in alertness and reductions in working memory dropped to levels that were equivalent to those that had been seen after 2 nights without sleep. The throughput of cognitive performance after 14 days of 4 hours restricted sleep was found to be the same as that after 1 night without any sleep. Those in the 6-hour sleep group also showed impairment of in terms of lapses in alertness and working memory performance equivalent to those tested after I night of total sleep loss. In terms of subjective sleepiness, chronic restriction of the nightly sleep period to either 6 or 4 hours daily for 14 days caused a relatively small but significant build up of subjective sleepiness as measured by the Stanford Sleepiness Scale (SSS) when compared with the 8-hour sleep group. In terms of the rate of change across days, those in the 8-hour sleep group showed only minor non-significant increases in self-rated sleepiness, whereas the others in the 6 and 4-hour groups showed similar rates of change over days.

Van Dongen and his colleagues opined that since chronic restriction of nightly sleep between 4 and 6 hours per night for 14 days caused deficits in cognitive performance comparable to those found after 1 to 2 days of total sleep deprivation it seemed that even moderate sleep restriction, if continued night after night, could seriously degrade neurobehavioral functions in young healthy adults. They further believed that claims that humans can adapt to chronic sleep restriction within a few days were not supported by their findings.

As Phillips (2000) has pointed out: "…seafaring involves rest and sleep in a 24-h-a-day work environment that usually involves time-zone crossings, noise, heat, cold and motion." Most of these stressors other than, perhaps, time-zone crossings apply to the crewmembers of the RVOC Program. He has reported that, in terms of the association between sleep and accidents, investigators classify either being asleep, or being sleep deprived while on watch, are closely associated. Being woken at odd hours, sleeping during the day, working instead of sleeping and sleep hygiene were rated as having a moderate association and sleeping accommodation and sleeping routine had the lowest classification.

The effects of fatigue and lack of sleep are particularly important features in terms of degrading operational efficiency. These problems have increased in significance since crews are required to function both night and day, thereby losing sleep. In addition, when crew sizes are reduced, there will be strong temptations to increase the length of duty periods for others when certain individuals are unavailable, or in emergency situations. Recent evidence strongly suggests that chronic sleep loss carries a significant penalty in terms of degrading performance and it is folly to believe that crewmembers can "get used" to coping without sleep and not incur performance penalties.

EFFECTS OF NOISE

Jones (1983) has pointed out that sound is critically important to the well being and efficiency of the human being since the spoken word underlies communication, knowledge and culture. However, the human ear has been overburdened in recent years with the advent of industry and its wide use of a great variety of machinery. Unfortunately, much of the sound that we now hear is a contaminant and it is this aspect of sound that we now recognize as noise. We are all well aware that hearing loss can result from long term exposure to intense noise, so it is most important to protect an individual's hearing from this otherwise inevitable damage. This can be achieved by a combination of three basic precautions. First, by modifying the sound source in order to reduce the noise output. Second, by changing the transmission pathway so as to reduce the level of noise at the ear. Third, by reducing the duration of exposure to a potentially hazardous noise level or by providing personal protective equipment and ensuring that it is correctly fitted and worn in a noisy environment. In terms of performance, noise can certainly have a profound effect on verbal communication that is both distracting and annoying. In noisy work areas, it is very difficult to hold a prolonged conversation over a distance of one meter if the noise level reaches 78 db (A). These disturbing features of noise reflect heavily on the habitability of ships, as do other environmental factors, such as general comfort, space, heat and cold and illumination. In turn, the level of habitability plays heavily on each and every individual's attitude toward the workplace and the effect that it has on the important question of retention.

In certain naval conditions, such as on an aircraft carrier at night, crewmembers could be described as being "environmentally blind and deaf". For that reason, we are looking into the possibility of utilizing other pathways. Communication methods and devices have traditionally relied on audiovisual modes to convey the message from a source to a recipient. These are capable of conveying considerable amounts of information within a reasonable time period with acceptable accuracy. A lesser-known and relatively uncommon mode is tactile communication. A tactile communication device (TCD) has been proven capable of communicating numbers to users with visual and hearing impairments and a control group (Gonzales, 1996). If advances in the TCD result in the ability to perceive complex messages, the outcome of this development could be a form of silent and non-vision-dependent communication system. The discrimination of four numbers with little or no practice suggests the possible development of a watch or pager system with the TCD. If the alphabet or other symbols can be perceived haptically, the perception of complex messages may be possible.

The non-auditory effects of noise are less well defined. Intermittent noise is more distracting than continuous; high pitch noise more distracting than low, and non-localized noise is more annoying than localized noise. In general terms, the non-auditory effects seem to act as a non-specific stressor, which means that in a ship-board multi-stress environment it can be difficult to identify those effects that are specifically due to noise, rather than other stressors that may also be present. In terms of overall performance, however, noise alone can have an insidious effect by inducing fatigue and stress. Poulton (1972) observed that noise has "two quite distinct effects upon a person", namely those of distraction on the one hand and arousal on the other. Distraction is most likely to adversely affect functions that call for prolonged continuous attention. Increased arousal may be beneficial in the performance of uninteresting routine tasks, since the individual tries harder and does better. If the level of arousal is too high, however, the person may try too hard and his or her performance becomes degraded. The theoretical inverted U-curves relating to performance and arousal are sometimes called the Yerkes-Dodson law (1908).

As already mentioned, intermittent noise is more distracting than continuous, since it causes distraction and the receiver is less likely to adapt to his type of noise. Poulton (1977) addressed the issue of the effects of continuous intense noise on performance. He pointed out that Stevens (1972) had concluded that noise has no direct harmful effects on man, apart from producing deafness and degraded performance. Poulton was adamant concerning the suggestion that continuous intense noise masks auditory feedback and inner speech and that that this could account for all of the deterioration in performance caused by continuous noise. However, Broadbent, (1978), one of the distinguished researchers in that field, rebutted Poulton's notion that the effects of noise were due to acoustic masking. Broadbent emphasized that there are three harmful effects of noise on skilled performance. First, a reduction in the detection of visual signals reported with risky criteria of judgement. Second, increased inefficiency, which causes errors or sometimes, slows responses. Third, the tendency to concentrate on certain parts of a complex display at the expense of others. These are potentially serious degradations of performance that play an important role in command and control situations.

Broadbent (1953) had previously reported on the effects of noise on paced performance and vigilance using a 5-choice serial reaction task that was "paced" or "unpaced", in a monotonous environment with no time cues, as used for a vigilance task. In general, he noted that the error rates were significantly higher during exposure to noise and only started to show after 5 minutes of exposure. Broadbent (1954) also reported impaired performance "when watch-keeping on a display made up of steam-pressure gauges, in 100dB noise as compared with 70dB." On the other hand, subjects who carried out a simpler task that consisted of watch keeping on a display made up of small lights, showed no overall adverse effects due to noise. However, in the easier task, some evidence of a reduction in performance began to appear as the duration increased, while parts of the task continued to be performed adequately, others were not. Broadbent concluded that noise effects are functions of individual differences, signal visibility and duration of performance.

Jones (1983) discussed the question of the interaction of noise with other stressors to see if there was a common mechanism, acting either synergistically or antagonistically. He pointed out that the effects were not found to interact. As previously noted, he stated that sleep loss and noise have been shown to be antagonistic. In terms of incentive and noise, their joint effects appear to depend upon how the incentive is given. Apart from the effect with sleep deprivation, Jones concluded that evidence of interactions between loud noise and other stressors is somewhat equivocal. In terms of efficiency, as assessed in the laboratory, the effects of noise are complex. The effect seems to depend largely on the particular task and the attitude of the individual.

CONCLUSION

When designing a new vessel it is never too early to consider the human element. Optimal performance will only be achieved when the crew component is designed in from day one, rather than added at the last moment as an afterthought. Before we can begin to design an efficient person-machine system, we must have a very definite idea in all our minds what the final product is intended to do. That means that we must have as clear an understanding of what the person can and cannot do, equally as much as we know about the vessel's capabilities and its onboard technological systems and equipment. We must also have a working knowledge of how these human and non-human subsets interact so that we can optimize this union. This requires a multiple team effort including many and various disciplines. The problems are more important today than ever before because of the plans to reduce crew sizes and the need to encourage crew retention. The goal is exciting and the ultimate prize is a highly efficient ship that can operate effectively under difficult conditions with the minimal, experienced human complement to ensure that successful outcome.

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