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Effects of Motion at Sea on Crew Performance: A Survey

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Current efforts to minimize ship crews now more than ever require all persons on board to be fully functional and capable of conducting their prescribed duties and responsibilities. However, inherent in the nature of any maritime profession, ships and, therefore, people are exposed to a multitude of motions as a result of weather and sea conditions. Coincident with these motions are a host of physiological, biomechanical, and psychological responses that can quickly reduce even the best efforts of the crew to a fraction of their utility when performed on a stable platform. Ship motions limit a crew's ability to perform essential command, control, and communications functions, navigation tasks, maintenance responsibilities, and even the preparation of food. Additionally, and more importantly, emergency situations may become more threatening in a situation where only a portion of the crew is able to respond effectively. This survey is intended to provide a working knowledge of effects of ship motions on crew performance, fatigue, and motivation. This information can then be used to improve ship and equipment design, and lead to enhanced vessel effectiveness and performance and, more importantly, to enhanced safety of the individuals on board. As ship design evolves and crew sizes decrease, greater emphasis must be placed upon the human factor input in order to ensure safety and efficiency during both routine and emergency operations.

Introduction

GIVEN the current efforts to optimize ships' crew numbers to the minimum number possible, a given crew's effectiveness and ability to perform their required tasks is of paramount importance. Ships are designed to function at a specified level of readiness with their given complement intact and fully functional. Each individual is responsible for a portion of the workload, and reduced performance from even a small number of crew members may threaten the overall operability of the ship and the safety of others on board. Inherent in seagoing services is the unpredictability of weather and the subsequent motions induced on a ship at sea. Coincidental to those motions are a variety of physiological and biomechanical events that can quickly reduce even the best of efforts to a fraction of what they would be ashore on a stable platform. Ship motions limit a crews' ability to perform essential command, control, and communications functions, navigation tasks, maintenance responsibilities, and even the preparation of food. Additionally, and more importantly, emergency situations may become more threatening in a situation where only a portion of the crew is able to respond effectively.

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The motions of a vessel at sea may create disturbances in a number of ways, the most common and well known being motion sickness. However, these motions also disturb the balance of crew members, increase the energy expenditure of persons working on board, and often result in increased levels of fatigue and drowsiness. The intent of this survey is to provide a working knowledge of the multiple issues regarding motion effects on people at sea. These will include:

- Historical information regarding motion sickness.
- Symptomatology and the types of motion sickness most commonly encountered.
- Susceptibility of people to motion sickness.
- Physiological causes of motion sickness and related theories explaining it's occurrence.
- Types of motion primarily responsible for provoking sickness.
- Performance implications from both a biomechanical and physiological perspective.
- Operability criteria currently used to delimit ship motions.
- Various means of preventing motion sickness ranging from personal behavioral measures to design considerations to be incorporated into vessel design and construction.

Historical perspective

From as far back as written records go, seasickness is documented as having an adverse effect on sailors. In fact, the Greek word "naus," meaning ship, is the root of the word "nausea" meaning "an inclination to vomit" (Reason & Brand 1975, Griffin 1990). It's worth observing from a historical view the degree to which seasickness has affected those in the maritime environment. Both Griffin (1991b) and Dobie (2000) cite a variety of studies in their discussions of the history of the study of motion sickness at sea, some of which are included here:

- Data from the Navy Medical Information Management Center indicate that between 1980 and 1992, 489 266 new recruits in the Navy were diagnosed with motion sickness, and a further 106 932 revisits were recorded (Dobie 2000).
- Within the United Kingdom, Pethybridge (1982) found that 10% to 30% of naval crewmembers suffered from seasickness during commonly experienced sea conditions and that this incidence rises to between 50% to 90% in the worst conditions.
- Pethybridge et al (1978) found that 67% and 73% of the crew of two British Royal Navy ships had been seasick during their career, and 42% and 56% had been sick in the past 12 months. During sea trials over five days in rough weather, 38% and 47% of the crew on the two vessels were sick on at least one occasion.
- Attias et al (1987) reported that aboard a 300 ton vessel in Sea States 2 and 3, 53% of those not receiving seasickness medication were sick on the first two days and 23% were sick on the third day.
- Handford et al (1954) found a 34% incidence rate of vomiting among troops on a military transport ship crossing the Atlantic.
- Trumbull et al (1960) found the incidence of vomiting reported on military transport ships traveling across the Atlantic to vary from 8.5% to 22.1 % on three crossings.
- Bruner (1955) observed from a questionnaire survey of 699 men aboard destroyers involved in escort duty in the U.S. Navy that 39% were never sick, 39% were occasionally sick, 10% were often sick, and 13% were almost always sick.
- Chinn (1951) reported during the first two or three days of an Atlantic crossing in moderate seas 25% to 30% of passengers on liners became seasick.
- Hill (1936) estimated that over 90% of inexperienced passengers become seasick in very rough conditions and some 25% to 30% became seasick during the first two or three days in moderate seas.

Even from this small historical sampling of information, it is readily apparent that motion sickness is quite prevalent among the maritime community. Given these figures, one can only speculate about the relative effectiveness of the crews in question and it has been the effort of numerous recent studies to quantify the effects of motion and motion sickness on crew performance. However, before pursuing this topic further, a more thorough examination of motion sickness is warranted.

Motion sickness

Motion sickness is a generic term for the discomfort and associated emesis (vomiting) induced by a variety of motion conditions: on ships, in aircraft, or in vehicles, on a swing or amusement park ride, in zero gravity environments (space), and even in elevators. Actually, the term "motion sickness" is somewhat of a misnomer from two perspectives. First, it can be induced in the *absence* of motion as during a virtual reality simulation, and secondly, *sickness* implies that it is a type of disease, when in fact it is a perfectly normal response of a healthy individual without any functional disorders (Benson 1999). Although the symptoms and physiological responses are consistent for all motions, seasickness is emphasized within the context of this paper.

The effects of seasickness are well known and most often proceed in an orderly sequence of events. Frequently, however, people are not aware of the motion as the source of their discomfort and will attribute it to other factors such as food, smells, temperature, or clothing (Griffin 1991a). The time scale of the sequence of events generally depends on the person's individual susceptibility and the intensity of the motion. According to Benson (1999), epigastric discomfort, or stomach awareness, is usually the first symptom. This is followed by deterioration of well-being and nausea of increasing intensity. Facial pallor arises from the constriction of surface blood vessels and in some persons, a greenish tinge may even become apparent (Griffin 1990). Sweating also occurs, even when temperatures would not normally make it necessary. A rapid exacerbation of symptoms known as the "avalanche phenomenon" follows which includes: increased salivation, bodily warmth, and light-headedness. Griffin (1990) also reports other typical indicators as yawning, irregularities in breathing, drowsiness, headaches, and feelings of indifference to one's fate. Finally, the culmination of symptoms usually results in vomiting. In highly susceptible people, or those with a low capacity for adapting to the motion, vomiting may continue for several days resulting in anorexia, depression, apathy and an incapacity to carry out duties or to look out for their own safety. These effects can then be compounded by the resulting dehydration and electrolyte imbalances due to repeated vomiting.

Treisman (1977) asserts that the unusual and apparently inappropriate vomiting response has been attributed to a consequence of natural evolution: the various sensory systems that indicate body movements may give abnormal perceptions of orientation after the ingestion of some poisonous substances. Vomiting in this case would be an appropriate act for survival; however, in the case of motion sickness it is anything but useful. As previously discussed, it can contribute to severe dehydration and incapacitation.

In its most extreme condition, motion sickness incapacitates those affected by it, but its less dramatic symptoms are more far-reaching. Many people suffer the misery of motion sickness without vomiting, and their decreased motivation and apathy makes these individuals safety concerns not only for themselves, but for others around them and for the very ship itself, depending on the nature of work for which they are responsible. Additionally, crewmembers otherwise immune to motion sickness often find themselves burdened with additional tasks and responsibilities to ensure proper functioning of the ship.

Sopite syndrome

Sopite syndrome was termed by Graybiel & Knepton (1976) and is a less familiar condition in which the associated symptoms of drowsiness and mental depression sometimes constitute the sole manifestation of motion sickness. They investigated this syndrome and reported that typical symptoms include yawning, drowsiness, disinclination for work (either physical or mental), and lack of participation in group activities. This response occurs much more frequently in the presence of other motion sickness symptoms; however, during experiments conducted within a slow rotation room, the sopite syndrome response was observed alone (Graybiel & Knepton 1976).

More currently, information from the naval fleet has pointed to unexpectedly high rates of motion sickness and unrecognized cases of sopite syndrome, even in deep draft ships, which normally do not experience provocative motions. This has led to new research from the National Biodynamic Laboratory in New Orleans to further observe the effects of sopite syndrome as it directly relates to a crew's ability to perform their tasks and the increased potential for accidents (National Biodynamics Laboratory Website 2001).

Other motion sicknesses

As discussed earlier, motion sickness can be induced by a variety of unfamiliar motions as well as in the complete absence of motion. People are susceptible to varying degrees of motion-induced sickness from all modes of transportation including cars, trains, and aircraft, in addition to space sickness and even in some cases, elevator sickness.

Fixed based simulators and wide screen movies (e.g., IMAX™ movie screens) create strong sensations of visual movement without concurrent vestibular, or inner ear, sensations of motion. More on the physiological causes of motion sickness will be discussed shortly; however, suffice it to say here that conflicts between visual input from the eyes and vestibular input regarding balance and motion from the inner ear are the primary causes of this type of motion sickness. Table 1 illustrates the range of motion stimuli for which motion sickness symptoms have been reported.

Susceptibility

There is wide variation in susceptibility to motion sickness, both *between* different persons (inter-subject variability) and *within* an individual on different occasions (intra-subject variability) (Griffin 1990). These differences are attributed to psychological variables including the experience, personality, and adaptability of the person, and to different individual dependencies on vestibular, visual, or somatosensory information. In other words, people of all ages, genders, and predispositions may become motion sick at one or more times in their lives. However, certain trends and predisposing factors have been observed:

- Females appear to become sick more often than males in a ratio of 1.7 to 1 (Benson 1999, Lawther & Griffin 1985). The increase in susceptibility among females might be attributed to anatomical differences or an effect of hormones (Reason & Brand 1975).
- Children have the highest tolerance to motion sickness, with cases rare below the age of two, and susceptibility appearing to be at a maximum between 2 and 12 years. Tolerance then appears to gradually increase throughout life (Benson 1999, Lawther & Griffin 1985, Wertheim 1998a). Benson (1999) points out, however, that the elderly are not immune, and that 22% of those suffering from seasickness on a Channel Island Ferry (English Channel) were over the age of 59.
- Sleep deprivation magnifies the occurrence of motion sickness because it interferes with the vestibular system habituation process. In the maritime environment, this is often a compounded problem since the sleeping conditions aboard a vessel are often not conducive to restful sleep (Dowd 1974).
- There is evidence that seasickness is an enduring trait in that some people are not affected at all, while others are affected by a variety of motions throughout the course of their lives with no age-related abatement (Guedry 1991a).
- A person's personality and past motion experiences affect and influence their future outlook towards attempts at conquering their symptoms and placing themselves in provoking motion environments (Guedry 1991a).
- Some studies have suggested that motion sickness tends to be greater in introverts (Kottenhoff & Lindahl 1960); this may partly be due to their being slower adaptors (Reason & Graybiel 1972).

Additional factors that influence an individual's susceptibility to becoming motion sick include the type, frequency, duration, and intensity of the motion encountered. (A more detailed account of the motion characteristics provoking sickness will be discussed in a later section of this paper.) Activity levels of the person are also involved in one's vulnerability to motion sickness, i.e., lab studies aboard aircraft and ships have found that persons who maintain their effort and mental concentration on a particular task are less likely to become sick than those who are not as occupied. In other words, relaxation and time for introspection allow for more accurate reporting and discrimination of bodily sensations that lead to motion sickness (Benson 1999). On a more subconscious level, a person's willingness to vomit may also play a role in their ability to obtain relief, albeit temporary. In other words, those who reflexively vomit with little effort are more likely to adapt to a motion environment, while those who regard it as a major event and resist the urge often remain severely ill with little or no relief (Guedry 1991a).

Reason & Brand (1975) offer a more complex theory to explain susceptibility. They propose that at every instant in time, the body expects its sensory system to send signals in a recognizable combination. It is possible to gradually learn a new combination of signals, but during this period of learning, the mismatch signal gives rise to symptoms of motion sickness. The susceptibility to motion sickness depends on the *rate* at which the internal model of these expected combinations of motion signals can be changed. Reason and Brand suggested three relevant characteristics that affect this rate change: *receptivity, adaptability,* and *retentiveness. Receptivity* refers to a person's internal amplification of the motion stimulus, or the range of motion stimuli that produce a response. For instance, a given motion stimuli may be significantly damped in some individuals, while others may amplify the signal. *Adaptability* is the rate at which the internal model of expected motion is changed and refers to the capability of an individual to adapt to the motion while reducing motion sickness symptoms. This is often referred to as the process of getting one's "sea legs." Receptivity and adaptability are not necessarily positively related, as a highly receptive person may actually adapt very rapidly—fast enough to reduce sensory mismatch before the neurochemical link achieves threshold level and seasickness occurs. *Retentiveness* refers to a person's ability to retain the internal model of motion and repeatedly adapt to a motion environment in successive exposures, i.e., the case of returning to sea after several days in port and experiencing no motion sickness.

Finally, there are a number of temporary predisposing factors that influence one's susceptibility to motion sickness: temporary gastrointestinal upset, inner ear inflammation, alcohol ingestion, and headache increase one's potential for motion sickness, while anxiety or fear associated with sickness may heighten one's sense of arousal leading to increased susceptibility (Guedry 1991a).

Adaptation

It is somewhat comforting to know that, over time, habituation (or adaptation) occurs. Acquiring one's "sea legs" may take anywhere from a few hours to several days, and in about 5% of the population, it does not occur at all. The time to adapt is generally influenced by individual differences such as those mentioned above, and by the type of wave movements encountered (Wertheim 1998a). Motion sickness may be elicited in as little as a few seconds or minutes in the case of some laboratory or fairground apparatus, while it takes significantly longer in response to typical ship motions (Griffin 1990). Figure 1 shows the form of the variation of motion sickness incidence (MSI) over time for a population exposed to ship motions, where MSI is defined as the percentage of people who vomit.

Motion sickness theories

Physiology

Inherent in the discussion of motion sickness theory is a brief understanding of the physiology of motion sickness. The primary mechanism responsible for feelings of nausea and malaise is our vestibular system, or inner ear. The vestibular system's most important function is to detect motion of the head and body relative to the earth and to generate reflexive motor activity that improves motion control while motion is in progress (Guedry 1991b). The vestibular system's role in motion sickness was ascertained when it was discovered that people without functioning vestibular systems, either due to illness or genetic defect, could not become motion sick (Benson 1999).

The vestibular system is located in small cavities hollowed out of bone within each ear. Inside these small cavities are located the sensory receptors themselves: the otoliths and semi-circular canals. The otoliths can best be described as linear acceleration transducers that detect *translational* acceleration in the vertical, horizontal front/back, and horizontal sideways directions. Without delving into too much detail, membranes within the otolith organs (the utricle and the saccule) vary in density and thus impose deflections on microscopic hairs (cilia) under linear accelerations. These deflection signals are sent to the brain where they are processed as either motion or head tilt. According to Griffin (1990), all except the most primitive forms of life have evolved receptors capable of detecting translational acceleration, and it may be presumed that their prime purpose is to detect the direction of gravity: the ability to also detect translational motion is an inevitable result.

The three semicircular canals within each ear are arranged in orthogonal planes and function to detect *angular* accelerations in the three orthogonal axes. In a similar fashion to the otoliths, angular accelerations displace fluid within the semicircular canals that deflect another receptor organ, thus transmitting a signal to the brain about the motion. Figures 2 and 3 are provided to illustrate the orientation and structure of the vestibular system.

Griffin (1990) notes that the vestibular organs, as transducers, must lack the linearity, wide frequency response, high dynamic range, low cross-axis sensitivity, low cross-talk, and low thermal sensitivity of many modern accelerometers. These characteristics inherently prevent them from correctly resolving some motions and are, therefore, thought to be the cause of various forms of disorientation and motion sickness.

Working in concert with the vestibular apparatus are both our visual and proprioceptive systems. In the case of simulator sickness, no motion at all is required to elicit a sickness response: a wide field of view in which the movements are sufficiently realistic to suggest the viewer is in motion, or a smaller field of view in which there are discrepancies between the visual scene and movements of the body will often provoke motion sickness (Griffin 1990). Griffin also indicates

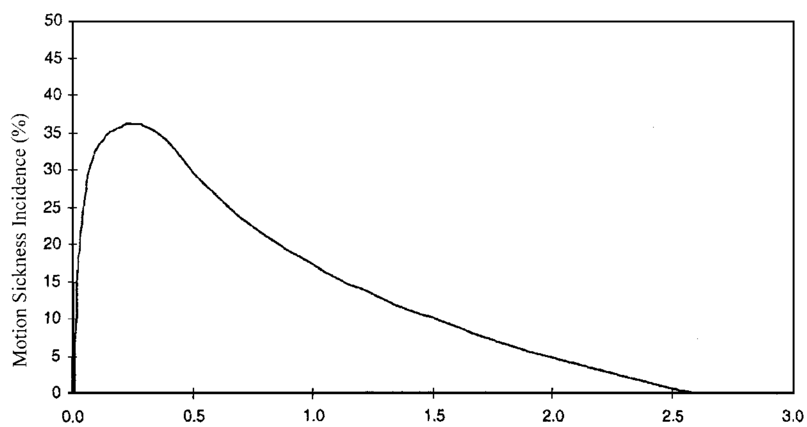

Fig. 1 Motion sickness incidence (MSI) over time for a population exposed to ship motions where MSI is the percentage of people who vomit (Crossland 1998)

there is evidence that those with previous experience of how stimuli *normally* occur together are more likely to experience symptoms of sickness in a simulation than those who have never experienced that particular environment.

The proprioceptive, or somatosensory, system includes pressure-sensing receptors in the skin and sensory processes of muscles and joints. This system responds to force and displacement and gives rise to a sense of body movement or applied force. Griffin (1990) states that although somatosensory stimulation alone is not enough to provoke motion sickness, it is possible that it influences the interpretation of visual or vestibular stimulation, which can cause sickness. For example, receptors in the neck may contribute to the interpretation of motion, and complex interactions have been found between cervico-ocular and vestibulo-ocular reflexes. To summarize these, the vestibular, visual, and proprioceptive systems all work together to allow a person to control motion relative to the earth and to detect the direction of gravity in order to maintain balance. Motion sickness is generally provided when there are conflicting signals among these systems, as will be discussed in the next section.

Theories

The universal susceptibility and wide range of common causes of motion sickness may easily lead one to believe that it is well understood; however, it is the *consequences* of motion sickness, previously discussed, that are far more understood than the *mechanisms* by which it occurs. The wide range of stimulation that causes sickness is representative of a complex event with no single cause and no simply defined mechanisms. Figure 4 illustrates some of the many relevant factors implicated in the cause of motion sickness.

A variety of theories currently exists which attempt to explain why and how motion sickness occurs; however, none are able to quantitatively predict the range of motion sickness to be expected from a given motion stimulus (Griffin 1991a). Griffin (1990) also points out that many of these older theories (e.g., motion sickness is caused by the movement of either the viscera or the blood and that by several alternative mechanisms these lead to the desire to vomit) are now solely a source of amusement. Currently the most widely accepted theory is known by several names: *conflict mismatch theory, sensory rearrangement theory* (Reason & Brand 1975), and *neural mismatch theory* (Benson 1999). These theories all describe the cause of motion sickness via the same proposition: *that the vestibular apparatus within the inner ear provides the brain with information about self motion that does not match the sensations of motion generated by visual or kinaesthetic (proprioceptive) systems, or what is expected from previous experience* (Wertheim 1998a). The prime example of this phenomenon is a person inside a ship cabin at sea. While the vestibular system is registering vertical and angular accelerations, the visual system does not register any motion at all and thus a conflict of the senses occurs. An understanding of this theory immediately provides explanation for a well known remedy for seasickness: by providing the visual senses with a stable horizon as seen from a weather deck or through a large porthole, the severity and incidence of motion sickness is reduced.

The sensory mismatch may be of either an *inter*sensory conflict or an *intra*sensory conflict. To further explain, an intersensory conflict implies incompatible signals from the two primary sensory organs: the eyes and the vestibular system. Intersensory conflict may be of two types:

- Type 1: Both the eyes and vestibular system signal motion, but of an incompatible kind and the two systems do not accord with expectation based on previous experience.
- Type 2: Either visual signals are processed without vestibular input or vestibular signals are processed without visual input.

Intrasensory conflict is one in which the signals within the inner ear are at variance with one another. In other words, the linear acceleration transducers (otoliths) are registering motion of a different type than the angular acceleration transducers (semicircular canals). Type 1 and 2 phenomena occur here as well:

- Type 1: Both the otoliths and semicircular canals signal motion, but of an incompatible kind and the two systems do not accord with expectation.
- Type 2: Either otolith signals are processed without semicircular canal input or vice versa.

Table 2 further illustrates the category and type of conflict while Table 3 shows the various motions or circumstances leading to these conflict types.

Although the sensory conflict theory provides a useful mechanism for understanding and predicting whether some combination of motion stimuli might be nauseogenic motions,

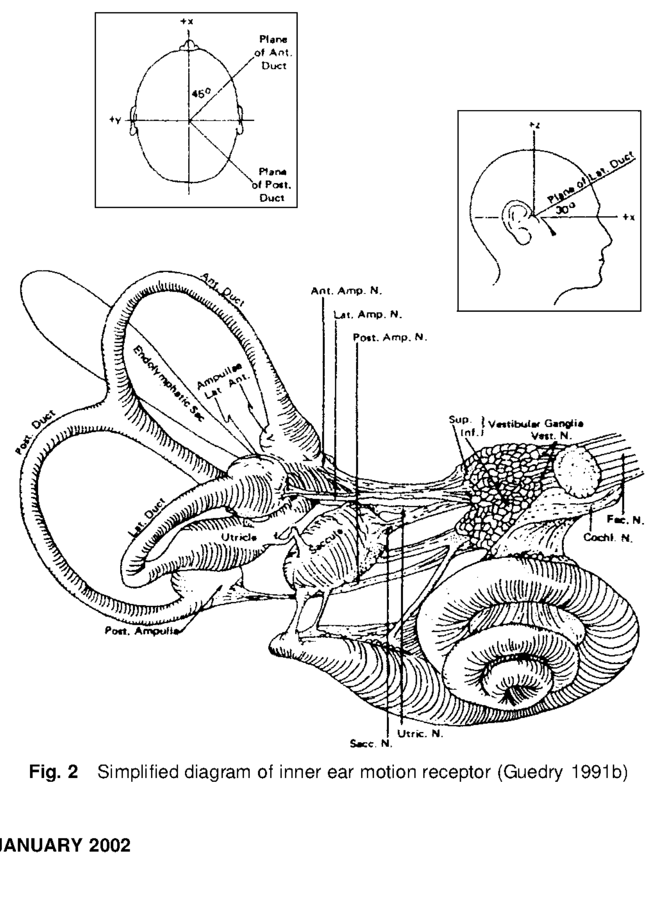

Fig. 2 Simplified diagram of inner ear motion receptor (Guedry 1991b)

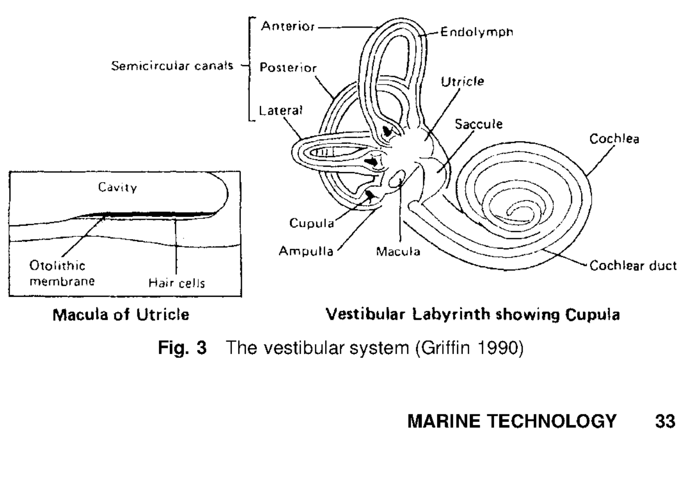

Fig. 3 The vestibular system (Griffin 1990)

Table 1 Some examples of environments, activities, and devices that can cause symptoms of motion sickness (Griffin 1990)

Boats	Camel rides
Ships	Elephant rides
Submarines	
Hydrofoils	Simulators
Hovercraft	
Swimming	Fairground devices
Fixed-wing aircraft	Cinerama
Helicopters	Inverting or distorting glasses
Spacecraft	Microfiche readers
Cars	Rotation about off-vertical axis
Coaches	Coriolis stimulation
Buses	Low frequency translational oscillation
Trains	
Tanks	

it does not indicate how sensory conflict can be measured and it does not provide quantitative information such as the extent of symptoms or how they depend on the magnitude of motion, the type of motion, or the duration of motion (Griffin 1990, 1991a).

Alternative theories have also attempted to explain motion sickness, but they are generally discounted in light of more current information and the validity of conflict mismatch theory. As previously mentioned, some hypotheses relate sickness to somatosensory proprioception of joint or visceral movement, while others have blamed the "sloshing of the blood" or the fluctuating mechanical pressure of the blood or stomach. As Griffin (1990) notes, these explanations are discounted by the fact that individuals with a nonfunctioning vestibular system do not become motion sick. "Overstimulation" theories attributed sickness to excessive stimulation of the vestibular system and orientated the discussion towards whether the otoliths or the semicircular canals were respon-

Table 2 Types and categories of sensory conflict (Griffin 1991a)

Type of Conflict	Category of Conflict: Intersensory (Visual – Vestibular)	Category of Conflict: Intrasensory (Canal – Otolith)
Type I	Visual and vestibular systems simultaneously signal different (i.e. contradictory or uncorrelated) information.	Canals and otoliths simultaneously signal different (i.e. contradictory or uncorrelated) information.
Type IIa	Visual system signals in the absence of an expected vestibular signal.	Canals signal in the absence of an expected otolith signal.
Type IIb	Vestibular system signals in the absence of an expected visual signal.	Otoliths signal in the absence of an expected canal signal.

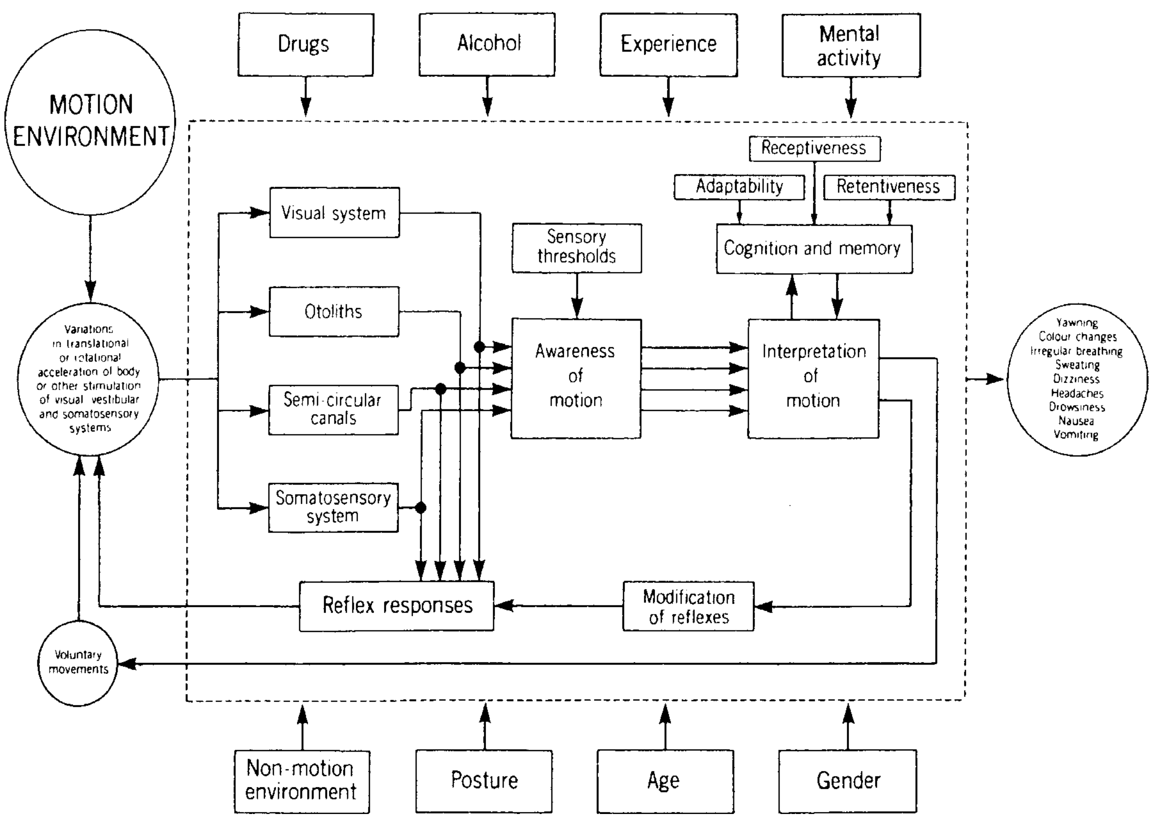

Fig. 4 Conceptual model of factors possibly involved in causation of motion sickness (Griffin 1990)

Table 3 Type of motion cue mismatch produced by various stimuli (Griffin 1991a)

	Category of Motion Cue Mismatch	
Type of Conflict	**Intersensory (Visual [A] - Vestibular [B])**	**Intrasensory (Canal [A] - Otolith [B])**
Type I A and B simultaneously give contradictory or uncorrelated information	Watching waves from a ship Use of binoculars in a moving vehicle Making head movements when vision is distorted by optical device "Pseudo Coriolis" stimulation	Making head movements whilst rotating (Coriolis or cross-coupled stimulation) Making head movements in an abnormal acceleration environment which may be constant (hyper- or hypo-gravity) or fluctuating (linear oscillation) Space sickness Vestibular disorders
Type IIa A signals in absence of expected B signals	Cinerama sickness Simulator sickness Circular vection	Positional alcohol nystagmus Caloric stimulation of semi-circular canals Vestibular disorders
Type IIb B signals in absence of expected A signals	Looking inside moving vehicle without external visual reference (below deck in a boat) Reading in a moving vehicle	Low-frequency (<0.5 Hz) translational oscillation Rotating linear acceleration vector ("barbecue spit" rotation, rotation about an off-vertical axis)

sible. These theories eventually evolved into the current premise out of the realization that *all* the motion sensory systems were involved.

Motion characteristics

Significant research has been conducted to determine the characteristics of motion that are most nauseogenic and that create the greatest malaise among sailors. Although there are specific ship motions that cause people to become seasick, the exact nature of the relation of the ship's motion to the sickness it causes is not well defined. Both shipboard surveys and laboratory studies have been conducted to determine the effects of motion type (roll, pitch, and heave), motion frequency and acceleration, and exposure duration.

The model of McCauley & O'Hanlon (1974) relating vertical motion frequency and acceleration with motion sickness incidence is the most widely cited, despite recent controversy. In a series of experiments, they subjected over 500 subjects to vertical sinusoidal motion in a ship motion simulator. Twenty-five combinations of 10 frequencies (from 0.083 to 0.700 Hz) and various magnitudes (from 0.27 to 5.5 $m \cdot s^{-2}$ rms) were used. Subjects were exposed for up to 2 hours while seated with their heads in a head rest. McCauley and O'Hanlon quantified the severity of the effects of motion by determining the incidence of vomiting as a percentage of those exposed to motion, and labeled this result *Motion Sickness Incidence* (MSI). They found that the vertical component of motion was primarily responsible for inducing motion sickness, with little or no effects from the pitch and roll motions, and that the maximum sensitivity to motion sickness occurred at 0.167 Hz (Griffin 1990). Figure 5 illustrates the percentage of subjects who vomited in histogram form for the 22 conditions with a MSI greater than 0%. These results are also shown in Fig. 6 as smoothed three-dimensional contours based on a mathematical approximation to the results.

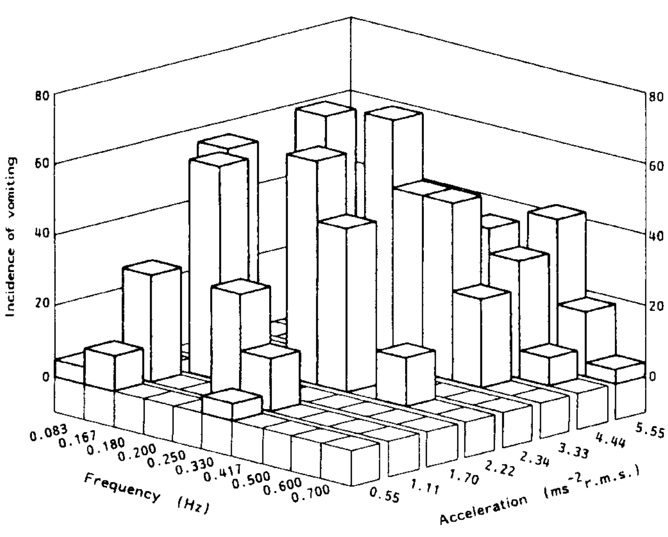

Fig. 5 Incidence of vomiting associated with exposure to various magnitudes and frequencies of vertical oscillation according to McCauley et al (1976)

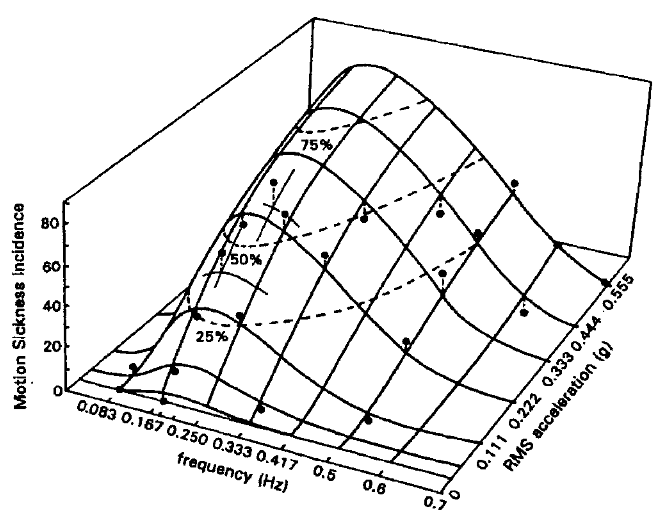

Fig. 6 The model of McCauley et al (1976), describing incidence of motion sickness with subjects inside a ship motion simulator moving sinusoidally in the vertical direction. Incidence of motion sickness was measured in terms of the percentage of subjects vomiting within 2 hours of exposure (Wertheim 1996a, Bos & Bles 2000)

Lawther and Griffin (1985) conducted similar work, measuring the motions of a car ferry operating in the English Channel and the consequent sickness among passengers. Data were analyzed for 17 voyages of up to 6 hours in duration, involving 4915 passengers. In order to understand the type of motion most strongly correlated with motion sickness, they recorded the acceleration time histories of motion over a 100 sec period (Fig. 7) and the corresponding acceleration power spectral densities over a 4 hr period (Fig. 8).

From these results, it is apparent that the vertical and pitch motions are quite similar, as are the lateral and roll motions. This is because vertical and lateral motions are influenced by pitching and rolling, respectively. Obviously the magnitudes of the translational motions vary with position around the vessel due to the influences of these two rotational motions. As those who have been to sea are aware, vertical motions are greatest at the bow and stern and are the least amidships, while lateral motion increases with in-

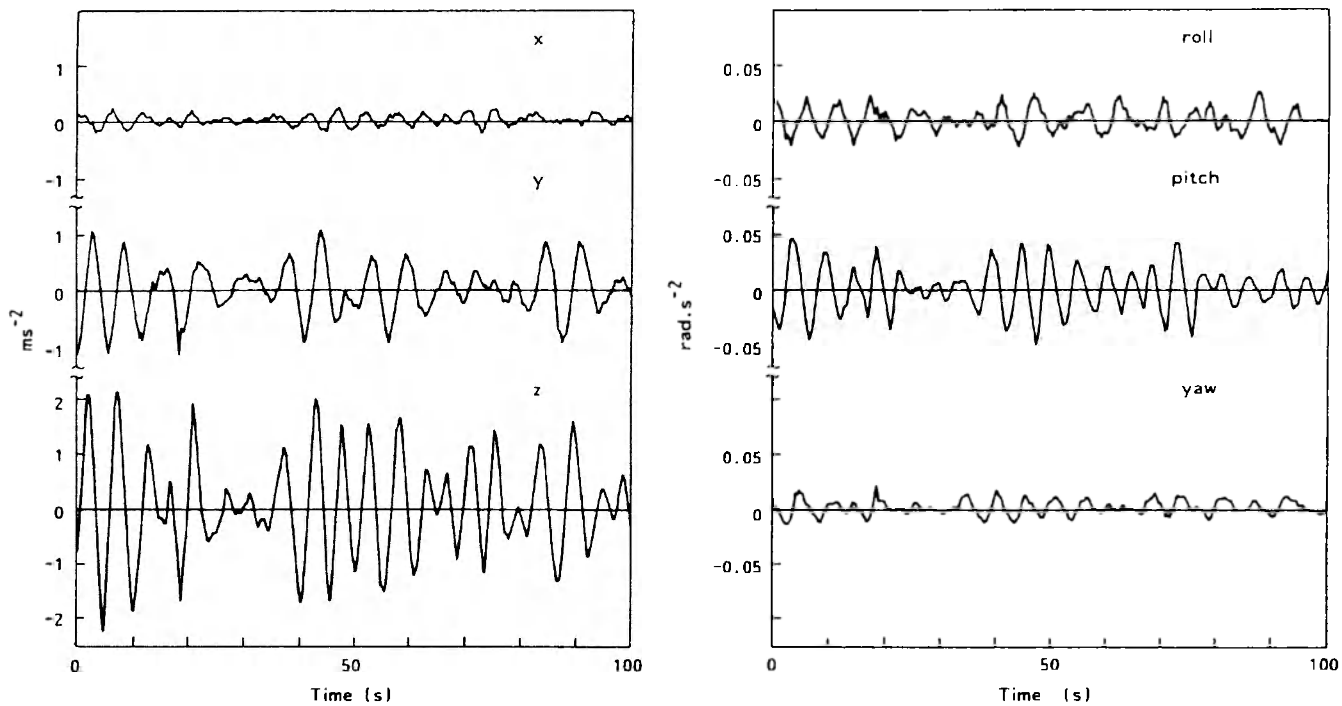

Fig. 7 Example acceleration time histories for six axes of motion of a ship (Griffin 1990)

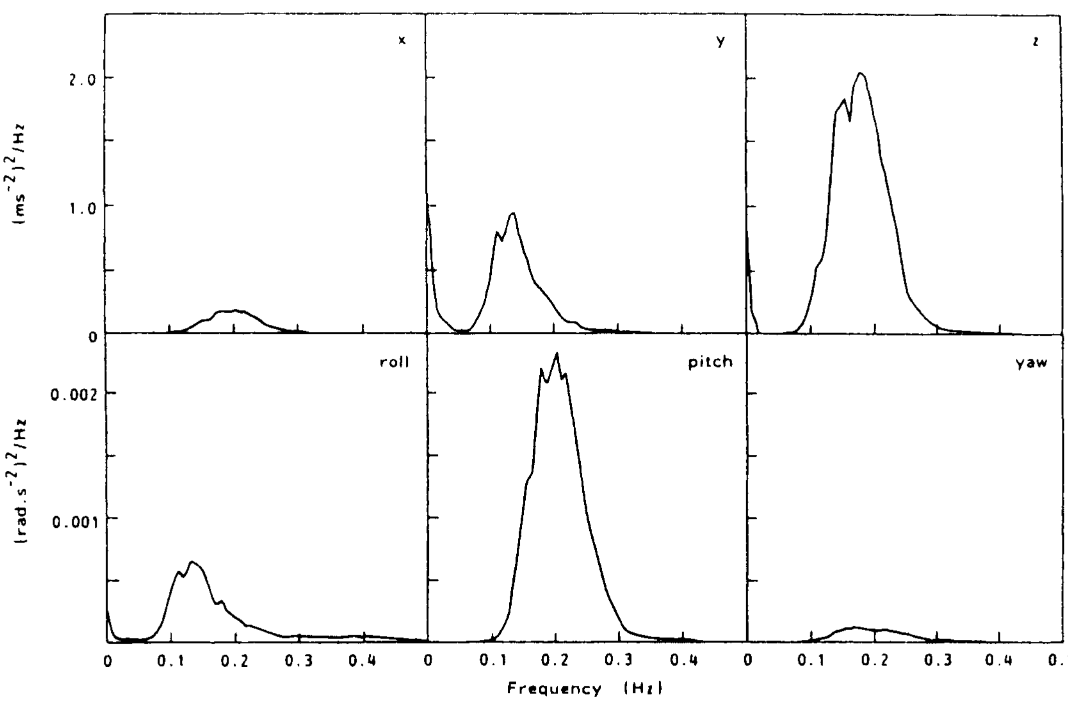

Fig. 8 Acceleration power spectral densities for the six axes of motion of a ship: frequency of resolution 0.01 Hz; duration 4 hours (Griffin 1990)

creasing height above the waterline. Figure 9 illustrates exactly how the spectra of translational motion on one vessel varied with longitudinal, lateral, and vertical position within the vessel while experiencing vertical plane (heave and pitch) motion.

The results of Lawther and Griffin were similar to those of McCauley and O'Hanlon in that the strongest correlations between Motion Sickness Incidence and motion were in the z-axis direction, both in magnitude and duration of exposure. However, position aboard a vessel is a significant factor in how one perceives a given motion, and although roll and pitch motions were not found to be as influential in inducing seasickness, Lawther & Griffin (1985) acknowledge that these motions should not be discounted.

Griffin (1990) also notes that although ship motions vary according to environmental and operational conditions, the motions illustrated above are representative of many vessels operating in moderate seas. He also asserts that the principal effect of worsening sea conditions is an increase in the *magnitudes* of the motions rather than a change in their *frequency*. Observing that the principal vertical frequency is approximately 0.2 Hz, one can readily understand why ships are so nauseogenic—this is very near the frequency where motion sickness is at its most sensitive.

There are two existing models for *predicting* initial exposure Motion Sickness Incidence from the amplitude, frequency, and duration of exposure to ship motions. In both cases, MSI is expressed in units of percent, representing the percent of the population that has vomited after exposure of a specified duration. Using the motion conditions observed by McCauley et al (1976) and Lawther & Griffin (1987, 1988) (51 from ship motion simulator experiments and 22 from at-sea observations), two models were developed to predict the occurrence of motion sickness.

1. Motion Sickness Incidence (MSI), McCauley et al (1976) and O'Hanlon & McCauley (1974).
2. Vomiting Incidence (VI), Lawther & Griffin (1987, 1988).

For a more detailed presentation of these two methods, Colwell (1989, 1994) reviews these models, including a comparison of their relative accuracy for predicting MSI observed in experiments and at sea.

Currently, International Standard Organization (ISO 2631, 1997) and British Standard Organization (BS 6841, 1987) employ the VI model for predicting Motion Sickness Incidence and establishing guidance on the prediction of motion sickness from measurements of vertical oscillation. A "motion sickness dose value" is defined, which may be used to predict the percentage of persons likely to vomit after exposure to known magnitudes and durations of vertical oscillation in the frequency range 0.4 to 0.5 Hz. The motion sickness dose value is defined as:

$$MSDV_z = \left(\int_0^T a_z^2 (t) dt \right)^{1/2}$$

where a_z is the frequency-weighted z-axis acceleration and T is the period. Guidance on frequency weighting the accelerations before integration is presented within ISO 2631 and BS 6841. Figure 10 graphically illustrates the frequency weighting that was derived from the experimental observations and illustrates that the greatest sensitivity to acceleration is in the range 0.125 to 0.25 Hz with a rapid reduction in sensitivity at higher frequencies.

Using the motion sickness dose value, the actual number of adults who are likely to vomit may be approximated by

$$MSI = K_m \cdot MSDV_z$$

where K_m is a constant, which may vary according to the exposed population. For a mixed population of unadapted male and female adults, K_m = 1/3 is suggested. The standards identify the large variability in the susceptibility among different individuals, e.g., females are more prone to motion sickness than males and that the prevalence of symptoms declines with age. Therefore, it is noted that K_m should be adjusted accordingly. Figure 11 shows the predicted magnitudes of vertical oscillation required for 10%, 20%, and 40% of persons to vomit within 2 hours. Colwell (1994) notes that both the MSI and VI methods mentioned above share three problems in modeling the naval environment:

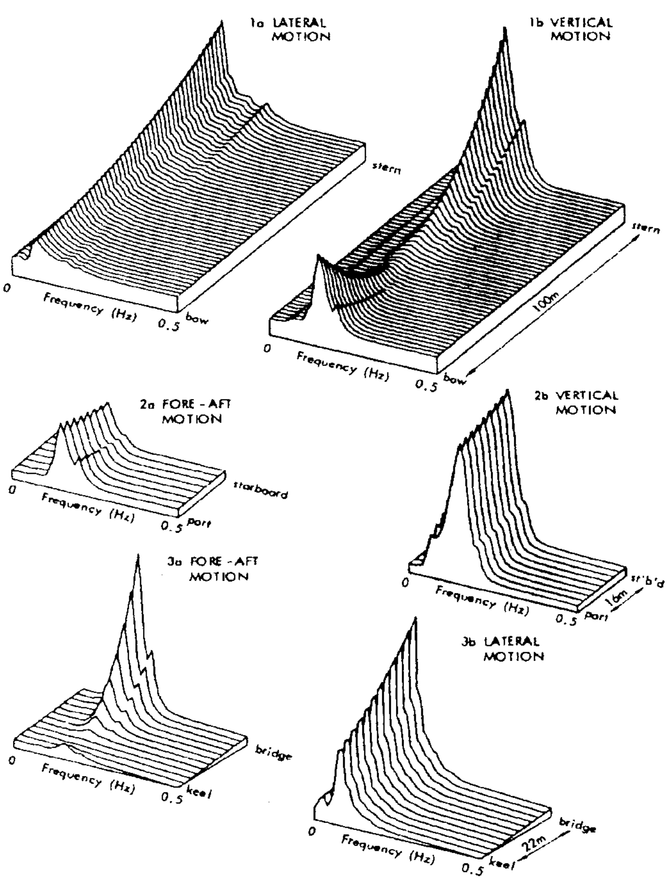

Fig. 9 Variation in acceleration power spectra of translational motion as a function of position in a ship (Griffin 1991b)

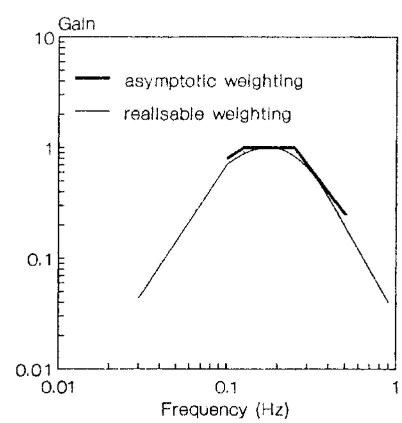

Fig. 10 Frequency-weighting as defined in ISO 2631 and BS 6841. Graph shows straight line "asymptotic approximations" to the illustrated realizable weighting defined by the standard for use in instrumentation (Griffin 1991)

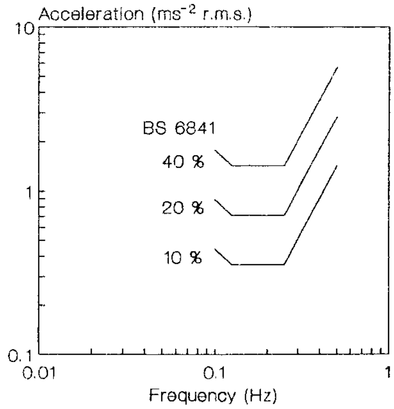

Fig. 11 Vertical z-axis acceleration expected to cause 10%, 20%, and 40% incidence of vomiting during 2 hour exposures according to International Standard 2631 and British Standard 6841. Incidence will double if magnitude is doubled or exposure duration is increased by a factor of four (Griffin 1991a)

- They are based on single-frequency experimental data.
- The ameliorating effects of habituation due to long-term or repeated exposure are not modeled.
- The predicted incidence of motion sickness is not necessarily a good measure of human performance.

A portion of Colwell's research is, therefore, devoted to modeling a habituation function to account for the adaptation expected to occur over time.

In more recent work conducted by Wertheim et al (1998), greater effects of pitch and roll on motion sickness have been observed. Wertheim argues that the commonly accepted theory of vertical motion being responsible for motion sickness is not entirely valid. First, many data on which this assumption is based have been collected from very large passenger ships which typically have relatively small pitch and roll movements (e.g., the Lawther and Griffin study). It is well known that smaller vessels such as Coast Guard patrol boats and pilot boats suffer to a greater extent from pitch and roll motions and are much more seasickness provoking. Second, the McCauley and O'Hanlon experiments included only heave in their model because no significant sickness effects had been observed with pitch and roll motions with amplitudes of up to 10 deg. They therefore *assumed* that there were simply no effects of pitch and roll on seasickness. Finally, Wertheim asserts that the quantification of motion sickness using the Motion Sickness Incidence metric is inaccurate because motion sickness is not an all or nothing phenomenon. Rather, the feelings and symptoms leading up to vomiting constitute equally representative measures of motion sickness in their impact on well-being and performance, yet cannot be accounted for in the MSI index.

Therefore, Wertheim et al (1998) set out to reanalyze the effects of pitch and roll on motion sickness. In a series of experiments conducted within the TNO Ship Motion Simulator, it was found that pitch and roll play a larger role in seasickness than had previously been accorded. The results indicated that pitch and roll exacerbated relatively small heave motions that by themselves would normally be tolerable. These results suggest that the McCauley et al model should be modified to include an interaction among roll, pitch, and heave. In other words roll and pitch play a stronger role in producing motion sickness when heave is relatively small than when it is large (Wertheim et al 1998).

However, as Bos & Bles (2000) indicate, to describe motion sickness incidence with six degrees of freedom is a challenging task. Inter- and intra-individual variability in sickness sensitivity is large, and motions may be quite complex (multiple frequency components, phase angles, and interactions). Therefore, thousands of vomiting volunteers would be needed to obtain sufficient statistical significance of the parameters of functions that fit these data best.

Because such a six-degree-of-freedom model of motion sickness does not exist, Bos and Bles are continuing research in this area. Their work includes a further refinement of McCauley and O'Hanlon's model describing motion sickness incidence with respect to vertical motion. Figure 12 illustrates this model, which when compared with Fig. 6 illustrated previously, is somewhat similar with a more clearly defined peak motion sickness incidence at 0.16 Hz. Bos & Bles (2000) also state that the same principles that led to the successful prediction of sickness in response to vertical motions only, will also lead to effective predictions of sickness to all kinds of complex motion.

Performance implications

Kehoe et al (1983) have suggested that U.S. frigates may have only 15% of full combat availability during winter months in the northern latitudes of the North Atlantic as a result of the deleterious effects of ship motion on weapons systems operability. Though many elements contribute to weapon system operability, a crew's ability to perform their tasks is also a significant factor. Ship motions influence a crew's ability to conduct their prescribed duties in a number of ways. Wertheim classified the impediments to performance based on their actions on individuals; he differentiates between *general* and *specific* effects of a given motion. General effects refer to any task or performance carried out in a moving environment. They might be of a motivational nature (i.e., motion sickness), an energetical nature (i.e., motion-induced fatigue caused by added muscular effort to maintain balance), or of a biomechanical nature (i.e., interference with task performance due to loss of balance). Specific effects are defined as those that interfere with specific human abilities such as cognition or perception (Wertheim 1998a). What follows is a more detailed discussion of these general and specific effects of motion on human performance.

General effects

Motivational—Motivational effects refer specifically to the psychological and physiological responses to a provocative motion. The sickness and nausea as well as the drowsiness and apathy associated with seasickness significantly reduce one's motivation to conduct their required tasks and duties. The concept of peak efficiency serves to explain why even severely sick individuals can continue to operate essential

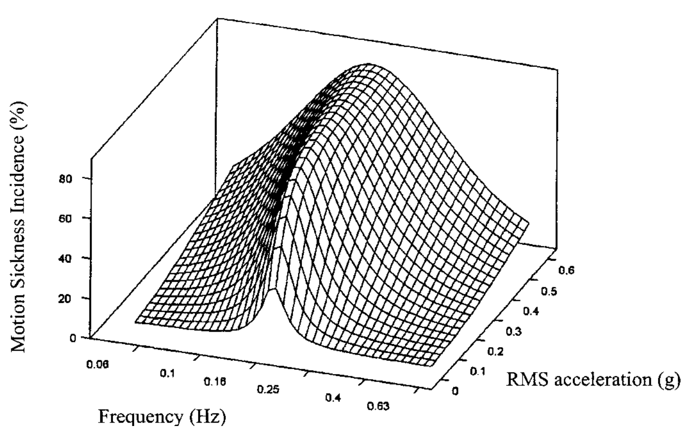

Fig. 12 The model of Bos and Bles predicting motion sickness incidence from vertical oscillation and acceleration (Bos & Bles 2000)

tasks associated with personal hygiene and health. Birren (1949) suggests that peak efficiency is likely to be unaffected by all except the most severe forms of sickness because of a crew member's capacity to exert themselves in these and other crisis situations that may arise. However, maintenance efficiency, or their ability to conduct daily work, may suffer severe decrements as a result of seasickness.

Energetical—Those who have served at sea know that it is more difficult to perform any given physical task on a ship than ashore. Significant attention has been given to *Motion Induced Fatigue* (MIF) and its effects on crew performance. Due to the extra effort required to maintain one's balance, operations on a moving platform often induce fatigue and degrade mental effort, in turn leading to decreased human performance. The physical fatigue associated with ship motions has important implications for today's minimally manned vessels. Because of minimally sized crews, any decrease in performance capabilities has significant implications for the ship's operational effectiveness. Because so many members of the human factors community are of the psychology discipline, the focus of fatigue studies has been on mental fatigue and relatively few studies have been conducted on physical fatigue (Wertheim 1998a). More established physical fatigue information would significantly benefit the maritime community by contributing to models that estimate the operability of a crew in a given sea state.

In recent experiments at the TNO ship motion simulator, efforts have been made to quantify the effects of motion on physical energy expenditure. A brief understanding of basic exercise physiology is necessary to comprehend the nature and results of these experiments. First, a quantifiable measure of workload must be defined. Oxygen consumption is considered the best indicator of physical work for a given task and it requires measurement of inhaled and exhaled gas ratios. Because of individual differences in health and fitness level, *absolute* oxygen consumption is not a good measure; rather, a person's *relative* oxygen consumption for a given workload as compared to their individual capacity for maximum consumption is considered a more effective measure.

Relative workload is, therefore, defined as the amount of oxygen consumed when working on a task expressed as a percentage of the person's maximum level of oxygen consumption, as determined separately by a graded exercise test. This percentage can then be related to the maximum amount of time a person can carry out a task by the empirical relation:

$$\mathrm{TTE} = 5700 * 10^{-0.031*\mathrm{P}}$$

TTE is the Time To Exhaustion in minutes (the amount of time the task can be carried out), and P is the amount of oxygen consumed as a percentage of maximum capacity for oxygen consumption (Wertheim et al 1997). Figure 13 graphically depicts this function and shows that when a task requires approximately 35% of maximum aerobic capacity, it can be carried out continuously for the duration of an 8-hr work day. When P increases beyond 35%, TTE begins to decline significantly, even with relatively small increases of P. Therefore, the elevation of energy consumption, as caused by ship motions, should not exceed about 40% of the total work capacity of the subjects. Otherwise, the demand for aerobic power is too high for steady state work during a normal 8-hr working day.

Using the TNO ship motion simulator, researchers found that an individual's maximum capacity for oxygen was significantly reduced in the presence of motions. Absolute oxygen consumption was not significantly increased during the tests in which subjects were required to either walk on a treadmill, cycle on a bicycle ergometer, or move boxes from one location to another within the moving ship motion simulator. However, workload was significantly increased once it was expressed as a percentage of the subjects' [reduced] maximum capacity for oxygen consumption within the moving environment. Fatigue appeared to be increased by 100%, indicating that within a moving ship motion simulator, the maximum time during which a subject would be able to continue cycling until exhaustion was halved, as compared to when the tasks were carried out in a stationary motion simulator.

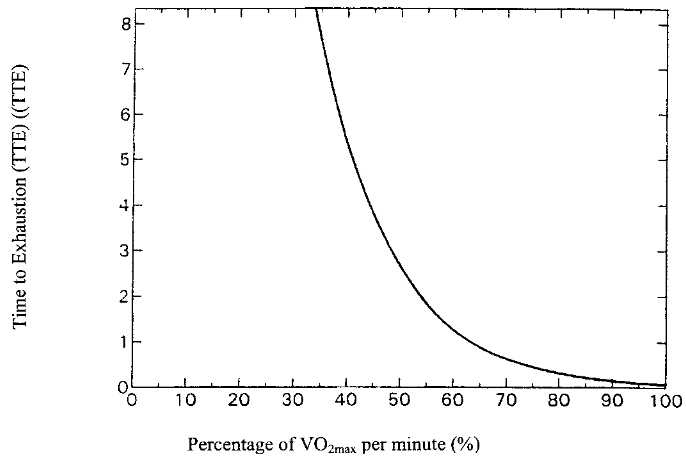

Fig. 13 Relation between amount of oxygen consumed when carrying out a physical task, expressed as a percentage of maximum capacity for oxygen consumption (P), and the maximum amount of time the task can be carried out when working continuously in hours (Time To Exhaustion [TTE]) (Wertheim et al 1997)

Empirical data from Rodahl & Vokac (1979) also indicate that ship motions are responsible for added energy expenditure. During coastal fishing it was found that when steering the boat, the skipper worked at 37% of maximal aerobic power—considerably higher than when standing still ashore. This additional effort was attributed to the need to counterbalance the motions. Finally, Åstrand et al (1973) reported that during coastal fishing, heart rate and oxygen consumption were markedly higher in conditions of rough weather than during calm weather.

Biomechanical—In any motion environment, the potential for losing one's balance is always present and dramatically increases with heightened sea states. A *Motion Induced Interruption* (MII) is defined as *an incident where ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their allotted task to pay attention to keeping upright.* The definition includes the ship motion-induced interruptions of the crew in all non-seated tasks such as standing, walking, lifting, and moving objects (Crossland & Rich 2000). According to Baitis et al (1995) and Crossland & Rich (2000), MIIs include three distinct phenomena:

- Stumbling due to a momentary loss of postural stability.
- Sliding due to the forces induced by the ship overcoming the frictional forces between movable objects (e.g., the individual's shoes) and the deck.
- The very occasional and potentially the most serious conditions where lift-off occurs due to motion forces exceeding the restraining force of gravity.

The most frequent type of MII is typically due to a loss of balance. Sliding is somewhat less prevalent because of the large coefficients of friction (except in the case of wet decks), and the third type of MII, crewmembers becoming airborne, is the least prevalent because the incidence of ship motions this severe is relatively rare.

In general terms, the MII model predicts a person will lose balance when the tipping moment exceeds the righting moment provided by the separation of the person's feet. In this model, the human body is considered to be a rigid object and the ratio of the persons' half-stance width (l) to the height of the person's center of gravity (h) is a parameter of primary importance, called the *tipping coefficient.* Figure 14 shows the assumed model for tipping in both athwartships and longitudinal tipping condition. This coefficient is used to evaluate the probability of tipping, which is expressed as the number of MIIs per minute. The greater the frequency of MIIs, the greater the difficulty the crew will have in performing their required tasks. MIIs are currently used to generate criteria for when it is either safe or dangerous to perform particular tasks on ships. These limits are expressed in terms of the number of MIIs per minute and will be discussed in more detail in the Operability Criteria section.

The expressions which predict the occurrence of either sliding or tipping MIIs are essentially the same. They are simple functions of the horizontal and normal accelerations or forces in the ship system and two types of coefficients, friction and tipping. The horizontal forces are composed of the lateral and longitudinal accelerations while the normal forces are composed of the vertical accelerations including gravity. Table 4 summarizes these expressions for the simplified case where the vertical acceleration is assumed to be just g. For a more detailed derivation MII theory and these expressions, see Graham (1990) and Graham et al (1992).

The variables in Table 4 are defined as follows:

$\eta_i, i = 1, \ldots, 6$ = motions surge, sway, heave, roll, pitch, and yaw
$D = (D_1, D_2, D_3)$ = displacement
$S_{s/p}$ = starboard and port sliding estimator functions
$T_{s/p/f/a}$ = starboard, port, forward, and aft tipping estimator functions
μ_s = static friction coefficient
d, h, l = see Fig. 14
g = gravitational acceleration

Different tipping coefficients are associated with the location and type of tasks to be performed, e.g., the number of MIIs may be increased when the condition of the deck is poor or when there are other environmental stressors such as wind, rain, snow, and ice. In a series of experiments conducted by the Defence Evaluation and Research Agency (DERA) in England, Royal Navy sailors were asked to perform a set of tasks in a Large Motion Simulator (LMS) to experimentally determine tipping coefficients for various tasks. Table 5 summarizes the empirical tipping coefficients determined from these experiments—the lower the tipping coefficient, the lower the threshold of accelerations that can be tolerated for that task, i.e., the harder the task is to perform. It is also important to note that tipping coefficients markedly differ from one axis of tipping to another, or from the side to side versus the front to back direction; however, because people naturally adopt the most resistant stance by standing sideways to the predominant motion, it is recommended that only transverse tipping be considered (Crossland & Rich 2000). Additionally, because the MII model uses rigid-body theory to model a human subject, actual MIIs for a given motion are overestimations because of crewmembers' experience at taking corrective action at sea such as altering posture or anticipating motions—also described as acquiring "sea legs" (NATO 1997, Baitis et al 1995, Dobie 2000).

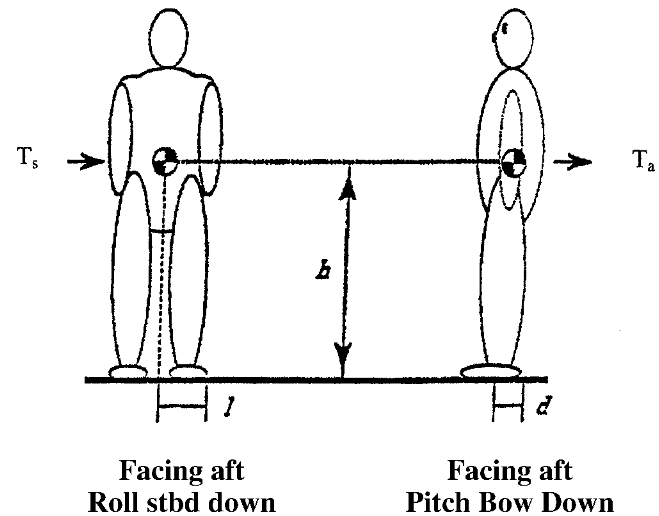

Fig. 14 Assumed model for a person on deck facing aft for lateral or longitudinal tips (Baitis et al 1995)

Specific effects

The specific effects of a motion environment on human performance refer to interference with specific human abilities or skills. These may be further categorized into complex tasks, cognitive tasks, motor tasks, and perceptual tasks.

Complex tasks—Most tasks humans must perform on board a vessel, such as those carried out on the bridge or navigation centers of ships, are quite complex in terms of the many skills required to perform each and are thus quite difficult to study. According to Wertheim (1996a), recent experiments at the TNO Human Factors Research Institute attempted to study the effects of motion on a complex task design. The experiments attempted to simulate a simplified, albeit real, naval task which consisted of making decisions on the basis of interpreting radar images and memorizing the information. The task was comprised of a combination of cognitive, perceptual, and fine motor skills, and the experiments conducted within the ship motion simulator observed a

Table 4 Expressions for predicting occurrence of sliding or tipping MIIs (Baitis et al 1995)

Slide	Lateral Tip	Longitudinal Tip
$S_s = (\ddot{D}_2 + g\eta_4) - \mu_3 \ddot{D}_3$ $S_s > \mu_s g$ $S_p = (-\ddot{D}_2 - g\eta_4) - \mu_3 \ddot{D}_3$ $S_p > \mu_s g$	$T_s = (-\frac{1}{3}h\ddot{\eta}_4 + \ddot{D}_2 + g\eta_4) - \frac{l}{h}\ddot{D}_3$ $T_s > \frac{l}{h}g$ $T_p = (\frac{1}{3}h\ddot{\eta}_4 - \ddot{D}_2 - g\eta_4) - \frac{l}{h}\ddot{D}_3$ $T_p > \frac{l}{h}g$	$T_a = (\ddot{D}_1 + \frac{1}{3}h\ddot{\eta}_5) - \frac{d}{h}\ddot{D}_3$ $T_a > \frac{d}{h}g$ $T_f = (\ddot{D}_1 - \frac{1}{3}h\ddot{\eta}_5) - \frac{d}{h}\ddot{D}_3$ $T_f > \frac{d}{h}g$

Table 5 Tipping coefficients determined from Large Motion Simulator (LMS) in condition H5DOF (Higher Frequency 5 Degrees of Freedom—ship traveling at 15 knots in bow quartering seas of significant wave height 3.14 m and zero crossing period of 9 sec) and L5DOF (Lower Frequency 5 Degrees of Freedom—ship traveling at 15 knots in stern quartering seas of significant wave height 2.43 m and zero crossing period of 9 sec) (Crossland & Rich 2000)

Task	H5DOF	L5DOF	Average
Standing aft	0.232	0.254	0.243
Loading	0.162	0.178	0.170
Standing arms aloft	0.242	0.293	0.268
Walking on treadmill	0.288	0.257	0.273
Standing athwartships	0.133	0.178	0.156
Counting task	0.250	0.233	0.242
All tasks	0.218	0.232	0.222

small, but significant, reduction in information transfer. Wertheim noted that the problem with interpreting this effect is that it cannot be explained as a motion interference with one particular skill. Therefore, it is very difficult to make generalizations to other tasks with different skill structures (Wertheim 1996a). The alternative is to observe the motion effects on the very basic classes of tasks underlying these complex tasks. These may be categorized as cognitive tasks (attention, memory, pattern recognition), motor tasks (manual tracking, fast button press reactions), and perceptual tasks (visual or auditory detection).

Cognitive tasks—There is an obvious trend on board ships today in the increasing quantity of mental work required when compared with ships years ago. Tasks on board vessels today, whether they include tracking a blip on radar, writing a sentence, listening to a direction, or adding a set of numbers to plot a course, require human cognitive and psychomotor abilities such as mathematical reasoning, verbal comprehension, verbal reasoning and visual perception. Numerous studies have, therefore, been conducted to determine the effects of motion on cognitive abilities. These have been conducted both within a ship motion simulator and at sea during sea trials, and in no case did researchers find degradations to cognitive abilities (Wertheim 1996a, Holcombe 1997). However, this conclusion is somewhat contrary to sailors' experiences on ships who appear to be more easily fatigued when working aboard a ship. In fact, as has already been discussed, a person's maximum capacity for oxygen consumption is reduced within a moving environment. Therefore, this would seem to explain what many call mental, or cognitive, fatigue in which lapses of attention and drowsiness interfere with cognitive performance. Wertheim (1998b) points out, however, that there is no psychological evidence that cognitive performance deteriorates only as a function of the amount of time one is working. In other words, what is construed as mental fatigue is most likely really a manifestation of physical fatigue.

In the most recent study to determine whether motion effects degrade cognitive task performance, Wertheim hypothesized that previous studies may not have observed any decrements in mental performance because subjects unconsciously place more effort into the tasks to maintain the same level of proficiency. Therefore, an experiment was conducted to measure an index of mental effort (heart rate variability), to observe whether or not this was indeed the case (Wertheim 1998b). Using a ship motion simulator in which subjects were required to perform various cognitive tasks, it was concluded that mental effort did not increase, thus further validating that motion effects do not influence cognitive tasks.

Finally, Wertheim notes that many of these experiments were conducted within the ship motion simulator, which is limited in its motion abilities. Therefore, continued research in this area with higher sea states was recommended, being careful not to confound the motivational effects of seasickness with the direct effects of the ship movements on cognitive activity (Wertheim & Kistemaker 1997).

Motor tasks—Motor skills include such tasks as manual tracking or fast button press reactions, and they will vary with a number of factors in a moving environment. The severity of the hull/sea interaction, the weight and complexity of components calling for performing a gross motor task, and the experience of the individual in both carrying out the task and working on a moving platform will all play roles in motor skill performance (Dobie 2000).

In a study conducted by McLeod et al (1980), the effects of motion were observed on three distinct manual motor skills: tracing with an unsupported movement of the arm, tracking with a supported arm, and keyboard digit punching with unsupported hands. Both the tracing and tracking tasks showed marked degradations under moving conditions, whereas the digit-keying task was virtually unaffected. The results indicate that the degree to which the arms are supported, as well as the nature of the task itself, has a direct effect on the performance quality (e.g., fine motor control skills versus ballistic type finger punching skills).

Other studies indicating a reduced motor control due to ship motions were conducted by Crossland & Lloyd (1993) and Wertheim (1995). These showed interference with a paper and pencil task and a visuo-motor computer tracking task, respectively. Holcombe's (1997) study also recorded statistically significant differences between a static and dynamic ship motion simulator condition for hand steadiness, arm-hand steadiness, visual perception, and the speed at which psychomotor tasks were completed. Despite these results being somewhat inconclusive, it can be said that ship movements can interfere to some extent with fine motor control, but not necessarily always. As Dobie (2000) indicates, this has special implications for the type of work that requires adjustment of controls or maintenance of electronic boards and components.

Perceptual tasks—Perceptual tasks refer to those that require visual or auditory detection of various signals. Wertheim cites Malone's (1981) study of a long duration radar monitoring task in which no motion-induced performance decrement was observed (Wertheim 1991a). Additional experiments indicated that biomechanical effects might indirectly interfere with perceptual performance when perception itself is not affected. In other words, in the absence of oculomotor factors, there is little or no evidence that perception is affected by ship movements. Experiments conducted by Wertheim found that tasks requiring fine oculomotor control, performance was indeed impaired (Wertheim & Kistemaker 1997). Additional impediments to perceptual performance may occur when vibration of a visual display creates blur; however, this condition is not likely to occur as the result of ship motions, except possibly in slamming situations.

Operability criteria

Given the biomechanical and physiological effects of motion at sea (balance interference, motion sickness, drowsiness, reduced motivation), it is necessary to establish general motion limitations that define when ships may operate without degradation due to these motions. Initially, these limits were specified in terms of root mean square (RMS) pitch and roll angles or by limitations on vertical and lateral accelerations. A typical constraint value for personnel operations on deck is a RMS roll angle of four degrees, which is obviously in itself not enough to curtail operations. Therefore, it is not the *inclination* of the deck at these specified angles that constitutes a problem, but rather the lateral and vertical accelerations *associated* with them (Baitis et al 1995). It should also be noted that each of these limits is usually applied independent of the other, i.e., if *one* of the limits is exceeded, the *entire* system is considered inoperable.

More recent work conducted by Baitis et al (1984) resulted in Motion Sickness Incidence (MSI) and Motion Induced Interruptions (MII) criteria. The North Atlantic Treaty Organization Standard Agreement 4154 (NATO STANAG 4154), includes both the older angular and acceleration limits as well as the more modern MSI and MII criteria. The MSI model replaces the limit for vertical acceleration and takes into account the human sensitivity to different frequencies of motion; however, it does not take into account the habituation associated with spending time at sea. Note also that the MSI model continues to employ the theory of McCauley & O'Hanlon, which attributes seasickness primarily to the vertical component of ship motion. An MSI rate of 20% of a ship's complement in a 4-hr exposure is considered reasonable and is based on tests using subjects with no prior exposure to the motion. It would be expected that a crew that had acclimated after several days at sea would experience lower levels of motion sickness (NATO 1997). For the MSI calculation given previously, a twofold increase in the magnitude of the motion, or a fourfold increase in exposure duration, has the effect of doubling the predicted incidence of vomiting. Therefore, the USCG criterion of 5% in a 30-min period is an equivalent limit.

The MII model, by definition, incorporates roll, pitch, and lateral acceleration and thus replaces the limits for these measures. According to NATO STANAG 4154, a value of one MII per minute is chosen because it represents a reasonable level of risk for many shipboard tasks (NATO 1997). Crossland & Rich (2000) also state that deriving performance from MII incidence is strongly linked to the shipboard task being assessed in two ways: the level of acceptable number of MIIs and the value of tipping coefficients. As an example, the number of acceptable MIIs per minute during a watchstanding task will be higher than the level for a person undertaking a weapon reloading task. Similarly, the tipping coefficient for a person standing during watchkeeping will be different than the same person carrying a 40 lb (18 kg) load.

Table 6 contains the current roll/pitch angle and horizontal/vertical acceleration limits in use by the U.S. Navy and U.S. Coast Guard in addition to the MSI and MII criteria presented above. (Note that the USN and USCG limits are equivalent, but expressed in different units—root mean square [RMS] and significant single amplitude [SSA]).

Faltinson (1990) also presents general operability limiting criteria for ships from a different perspective. Here, these limits are presented as functions of ship type or the nature of the work conducted on the ship. Table 7 illustrates the differences in criteria among merchant ships, naval vessels, and fast small craft. Table 8 indicates how ship motions affect humans' ability to perform various work as previously discussed, and also illustrates the requirement for passenger and cruise liners to minimize motions.

Prevention

Having discussed the effects of motion sickness and their implications for personnel performance and safety, it's useful to now identify measures that may be used to reduce or moderate the effects of seasickness. Prevention may be categorized into one of several measures: pharmacological treatment, biofeedback or autogenic training, behavioral measures, adaptation, and finally, design considerations of the vessel itself.

Pharmacological

According to Griffin (1990), the two most common groups of antimotion sickness drugs are the anticholinergics and the antihistamines. Anticholinergics have antagonistic action on the parasympathetic nervous system and relax nonvoluntary muscles; they are shorter acting making them more appropriate for shorter journeys. Antihistamines include the well-known Dramamine, and there is considerable variation between individuals in their response to antihistamines. The most common side effect is drowsiness and as Dobie (2000) points out, the variability of reactions in individuals and the potential side effects of these medications may not be acceptable when the user is in control of sophisticated or potentially hazardous equipment, or making command and control type decisions.

Though not pharmacological, and in addition to being contrary to one's intuition, eating may prevent motion sickness by reducing the type of gastric motions that are typically associated with motion sickness (Uijtdehaage et al 1992). In experiments conducted by Bles et al (1991) aboard the training vessel MV *Zeefakkel,* motion sickness was reduced in an afternoon portion of a study in which the subjects had had the opportunity to consume lunch, and it was hypothesized that Uijtdehaage's explanation was at least partially responsible. It has also been found experimentally that there is no evidence that motion sickness is dependent on the time of motion exposure with respect to meal times (Alexander et al 1945, Manning & Stewart 1949). Griffin (1990) also advises that going without food for long periods can result in lessened resistance to motion and a weakened effort to adopt preventative measures. Finally, as mentioned previously, consumption of alcohol is considered a temporary predisposing factor that should be limited prior to encountering a moving environment (Guedry 1991a).

Desensitization/Biofeedback

Due to the potential problems associated with antimotion medications, a more permanent treatment may be a more

Table 6 Operability criteria (RMS = Root Mean Square; SSA = Significant Single Amplitude; SSA = 2 × [RMS])

	NATO STANAG 4154 (U.S. Navy)	U.S. Coast Guard Cutter Certification Plan
Motion Sickness Incidence (MSI)	20% of crew in 4 hours	5% in a 30 minute exposure
Motion Induced Interruption (MII)	1 tip per minute	2.1 tips per minute
Roll amplitude	4.0° RMS	8.0° SSA
Pitch amplitude	1.5° RMS	3.0° SSA
Vertical Acceleration	0.2 g RMS	0.4 g SSA
Lateral Acceleration	0.1 g RMS	0.2 g SSA

Table 7 General operability limiting criteria for ships (NORDFORSK, 1987)

	Merchant ships	Naval vessels	Fast small craft
Vertical acceleration at forward perpendicular (RMS)	0.275g (L ≤ 100 m) 0.05g (L ≥ 330 m)	0.275g	0.65g
Vertical acceleration at bridge (RMS)	0.15g	0.2g	0.275g
Lateral acceleration at bridge (RMS)	0.12g	0.1g	0.1g
Roll (RMS)	6.0°	4.0°	4.0°

Table 8 Criteria with regard to accelerations and roll [RMS] (NORDFORSK 1987)

	Vertical acceleration (RMS)	Lateral acceleration (RMS)	Roll (RMS)
Light manual work	0.20g	0.10g	6.0°
Heavy manual work	0.15g	0.07g	4.0°
Intellectual work	0.10g	0.05g	3.0°
Transit passengers	0.05g	0.04g	2.5°
Cruise liner	0.02g	0.03g	2.0°

plausible strategy for extremely susceptible individuals or critical personnel routinely exposed to motion provoking environments (i.e., ships). Desensitization therapy is currently used within aviation and space travel and it is based upon relieving a person's state of arousal associated with previous unpleasant responses to a provocative motion environment (Dobie 2000). Detraining one's arousal level stems from the fact that the difference between a sensitive and insensitive person is often the level of arousal evoked by exposure to the motion environment (Dobie 2000). In other words, the "resistant" individual enters the environment with zero arousal and can cope with a considerable amount of provocative stimulation before reaching his or her threshold. In contrast, the susceptible person has varying degrees of arousal based on their previous experiences, and in extreme cases may become sick before even entering the provocative environment.

In desensitization therapy, the subjects are placed in increasingly intense motion environments over time with concurrent psycho-therapeutic treatments to help allay their fears and anxiety (Benson 1999). In the Royal Air Force, it is reported that this procedure has effectively prevented recurrence of air sickness upon a return to flying duties in all but about 15% of those who have undergone therapy (Benson 1999). Griffin (1990) notes that although there is a lowering of sensitivity with repeated exposure to motion, it is not clear how much similarity is required between the various motions involved in the habituation process. In other words, according to the sensory conflict theory, habituation should occur only for a specific combination of motion signals. Thus, the optimum desensitization program would entail identifying the appropriate combinations of stimuli that would vary between problem environments, and then exposing the individual to these combinations.

Biofeedback (also known as autogenic feedback) training is a relatively new, yet effective, approach in the treatment of motion sickness. Using this technique, the subject learns to acquire voluntary control over certain autonomic responses that characterize motion sickness. This allows them to attenuate at will the whole symptom complex, increasing their tolerance to the provocative motion. The technique involves both visual and auditory feedback of several autonomic responses (e.g., heart rate, respiration rate, blood volume, and galvanic skin response) that occur during the onset of motion sickness. Subjects are taught to control some of the responses or even reduce them (Stott 1991). The U.S. Air Force employs biofeedback along with desensitization and Jones et al (1985) reported a 79% success rate among 53 aircrew treated for airsickness, while Benson (1999) indicated a 40% success rate in aircrew returning to flying duties. Dobie (2000) highlights that the real value in this treatment lies in the long-term protection remaining with the individual long after training has ceased.

Behavioral

As previously discussed, a variety of behavioral measures can be undertaken to avoid or moderate the onset of seasickness. It is well known among seafarers, that a common remedy for seasickness is to situate oneself above deck or to gaze through a porthole to observe a steady horizon. This provides a stable visual reference that helps to reduce the visual-vestibular conflict associated with motion at sea.

Wertheim (1998a) remarks that continuous alignment of one's stance with the vertical may provide beneficial effects to motion sickness prone individuals. In doing so, it would provide an optic flow across the eyes that was consistent with the motion of the ship; however, he also acknowledges that this is merely a speculative measure, and it would require a kind of balancing act that makes the body (and head) move quite strongly relative to the walls of the cabin (Wertheim 1998a).

The following measures can moderate motion sickness. They may not, however, be the most practical solutions for operating personnel aboard a ship. Keeping one's head movements to a minimum results in a reduction of the complexity and magnitude of inputs to the vestibular system and reduces the probability of moving the head to an especially provoking alignment (Bittner & Guignard 1985). Adopting a recumbent posture is also helpful in reducing motion sickness incidence. Stott (1991) concurs that an oscillatory stimulus is best tolerated in a posture which requires a minimum of postural regulatory activity in order to maintain it, i.e., lying down. Both of these measures, while potentially effective, may have limited applicability on board a ship where full activity of every person is generally required for complete operational effectiveness.

Adaptation

As Benson (1999) states, the most potent therapeutic measure is adaptation to the provocative motion. This is "nature's" own cure and is the preferred method of preventing sickness. Adaptation formally refers to the increase in tolerance to a nauseogenic stimulus that occurs over a period of several days or even weeks of repeated exposure (Stott 1991).

However, as discussed earlier, there is wide variation among individuals in the time it takes to adapt and within a relatively small percentage (about 5%) of people, adaptation never occurs.

Design considerations

Currently, techniques for predicting ship motions from a given sea state (e.g., wave spectra) and the vessel form (e.g., hull lines) allow effective assessment of the relative nauseogenic properties of various vessels and different sea conditions. Although more accurate information could be obtained by measurement, the diversity and unpredictability of sea and weather causes variation among tests on different occasions. These measurements and predictions of ship motion can then be used to assess the capabilities of alternative designs.

As an illustration of the recent advances in seakeeping technology, work conducted by Bales (1980) related seakeeping performance to hull form parameters of destroyer-type ships. His efforts resulted in a rank estimator of seakeeping performance that could be used to quantitatively assess the merits and consequences of various hull forms in terms of vertical ship motions. By analyzing a large database of selected seakeeping responses for various ship speeds and wave periods, he was able to rank 20 frigates, destroyers, and cruisers on the basis of the averaged responses. Then, using regression analysis, Bales developed a rank estimator ($\hat{R}$) in terms of six underwater hull form parameters for vertical plane seakeeping performance. This estimator yields a ranking number between 1 (poor seakeeping) and 10 or higher (superior seakeeping) and has the following form:

$$\hat{R} = 8.42 + 45.1\,C_{WPf} + 10.1\,C_{WPa} - 378\,T/L + 1.27\,C/L - 23.5\,C_{VPf} - 15.9\,C_{VPa}$$

where

C_{WPf} = waterplane coefficient (forward)
C_{WPa} = waterplane coefficient (aft)
T = draft
L = length
C = distance aft of forward perpendicular where hull begins its rise from baseline to stern
C_{VPf} = vertical prismatic coefficient (forward)
C_{VPa} = vertical prismatic coefficient (aft)

Here, the waterplane coefficient and the vertical prismatic coefficient are expressed separately for the forward and the aft portions for the hull. Since the objective for superior seakeeping is high $\hat{R}$, high C_{WP} and low C_{VP} corresponding to V-shaped hulls, can be seen to provide improved vertical plane seakeeping. Note also that added waterplane forward is about 4.5 times as effective as aft and lower vertical prismatic forward is about 1.5 times as effective as aft in increasing $\hat{R}$. Thus, V-shaped hull sections forward provide the best way to achieve greater wave damping in heave and pitch and improve vertical plane seakeeping. Low draft-length ratio T/L and keeping the hull on the baseline well aft to increase the cut-up-ratio C/L also improve vertical plane seakeeping. This logic guided the shaping of the DDG51 hull that has superior vertical-plane seakeeping performance compared to the earlier DD963 hull form.

This approach to seakeeping in the parametric design phase of a vessel is discussed to demonstrate the important ship characteristics and what is required to include motion sickness criteria into the design process. A similar analysis could be conducted to create a comparable "motion sickness rank estimator," which does not yet exist. Using this estimator, the motion response of vessels would be analyzed not only in terms of vertical-plane motion, but also with respect to roll motions. Underwater hull form characteristics including stabilizing devices would be included to define those qualities of a vessel hull and design that minimize motion sickness.

Trends in incorporating MSI and MII criteria into the early design phase are already in progress. The current version of the Navy's Ship Motions Program (VisualSMP) includes a preliminary output of MSI and MII (by tipping and sliding) incidence rates for given hull and environmental inputs. Though the MSI and MII calculations have not yet been fully implemented, their incorporation into the newest version of this widely used software is indicative of their trend in design.

Currently, the effects of anti-rolling devices on motion sickness incidence are not conclusive. Stabilizers such as bilge keels, anti-roll fins, and antirolling tanks are used to reduce the rolling of a ship for crew comfort, to prevent movement of cargo, improve the accuracy of gunfire on military ships, and reduce the internal stresses on a vessel. One would reasonably expect these devices to also alleviate motion sickness by reducing the motions, in addition to reducing the number of motion induced interruptions experienced. However, as Griffin (1990) indicates, there appears to be little evidence that the roll angle on ships is directly related to the incidence of motion sickness. In fact, the largest roll angles generally arise from the lowest roll frequencies and their reduction may, in some cases, increase the acceleration at slightly higher frequencies where sickness is more common. Griffin also indicates that some stabilizers tend to produce jerky and unpredictable motions, which some crews have suggested contributes to sickness rather than prevents it. Most importantly, however, is that roll stabilizers have little effect on heave and pitch and their corresponding *vertical* motion—the direction most closely implicated in motion sickness. However, roll motion does lead to vertical motion away from the center of rotation, thus in this case stabilizers would seem to reduce seasickness. This is central to the issue that Wertheim et al (1998) and Bos & Bles (2000) discussed regarding the need to more fully understand the effects of roll and pitch motions on motion sickness. For the preceding reasons, it is necessary to more fully quantify the effects of roll stabilizing devices on the incidence of seasickness.

The aforementioned seakeeping considerations focus on more traditional design measures such as hull form and ship size. However, a more thorough design will also include human factor analyses of ship arrangements and the adverse effects of ship motion on personnel and shipboard activities (Bittner & Guignard 1985). Table 9 captures the wide variety of methods that can be used to minimize the adverse biomechanical and physiological effects of ship motion on the crew.

Bittner & Guignard (1985) also evaluated two mission-critical workstations for the U.S. Coast Guard from a human factors perspective. They recognized five potential engineering approaches to enhance seakeeping through prevention and mitigation of adverse motion effects on personnel as follows:

- Locate critical stations near the ship's effective center of rotation: As previously discussed, the vertical component of motion is known to be extremely nauseogenic, and at off center locations on a vessel the rotational motion components give rise to substantial vertical displacements. Obviously, the magnitude of this motion is proportional to the distance from the center of the ship. When combined with the ship's natural heave motion, seasickness frequency can be expected to increase at these locations.
- Minimize head movements: This concept has been discussed with respect to behavioral measures; however, it

Table 9 Approaches to preventing or mitigating adverse effects of ship motion on crew (Bittner & Guignard 1985)

Approaches	Methods
A. Ship design and systems engineering	1. Hull design 2. Ship arrangements 3. Operation and maintenance of machinery and equipment 4. Motion attenuation devices (e.g., fins) 5. Vibration isolation and damping treatments 6. Isolation of special stations
B. Human factors engineering	1. Arrangement and design of crew space 2. Location and orientation of crew stations 3. Work and task design 4. Display/control design and placement 5. Optimization of ship environmental factors 6. Individual anti-vibration devices
C. Enhancing natural human resistance to motion effects	1. Optimization of work/rest and duty/leave cycles 2. Habituation and oscillatory motion training 3. Specific task training in motion environment 4. Crew selection 5. Provision of adequate sleep
D. Modifying adverse physiological reactions to motion	1. Optimization of crew fitness and morale 2. Optimization of the immediate physiologic state 3. Medication
E. Operation solutions	1. Strategic and tactical planning to minimize: a. Routing through rough motion areas b. Distance/time spent in rough conditions c. Number of units simultaneously exposed d. Necessity to resupply in heavy seas 2. Tactical maneuvering compromises of: a. Speed b. Heading c. Stopping time at sea

also relates to design considerations as well. By locating primary displays and controls on a central panel, the necessity for frequent, rapid, or large-angle head turning may be minimized, thus preventing seasickness (Guedry 1991a). Additionally, consideration should be given to methods of stowing tools and other items so that they remain within close reach. For example, picking up a dropped item such as a pen requires large and complex head movements, which may provoke sickness. Work in a ship motion simulator conducted by Wertheim (1998a) revealed that subjects required to carry out various tasks involving bending down to pick objects up had higher incidences of seasickness than those who were simply seated.

- Align operator with a principal axis of the ship's hull: Because motion sickness is amplified by complex or off-axis angular motion inputs to the vestibular system, alignment with the ship's longitudinal axis is preferred over a transverse orientation, and both of these are preferred over diagonal or off-axis orientation.
- Avoid combining provocative sources: Current literature indicates that multiple provocative sources tend to be additive. Therefore, a variety of visual distortions can be expected to combine with ship motion to increase the likelihood and severity of seasickness. Also, as discussed earlier, predisposing conditions such as disordered sleep, hangovers, illness, and medication can contribute to the onset of motion sickness. In terms of design considerations, optimizing the layout of sleeping quarters may improve sleep during rough seas and would be expected to reduce seasickness development. The design of visual display terminals also has important implications in the onset of motion sickness and warrants attention during the design process.
- Provide an external visual frame of reference: This has long been recommended as an effective method to counteract the effects and onset of motion sickness. Behaviorally, this has been discussed in terms of viewing the horizon from above deck or through a porthole. In terms of ship design, the use of an artificial horizon projected within a workspace has been studied and found to be effective. Rolnick & Bles (1989) used a rapidly rotating mirror that moved in synchrony with the ship's pitch and roll movements to project an artificial horizon to the bulkheads of a ship's cabin. They found significant decreases in relative motion sickness and decrements to well being among the 12 subjects used for the study. When compared with a closed cabin window cabin condition, the benefits of the artificial horizon are obvious. Figures 15 and 16 illustrate these results. Studies aboard the MV *Zeefakkel* by Bles et al also implemented an artificial horizon in which a stabilized light was projected to the upper half of a cabin within the ship. It was found that 85% of the 17 subjects reported the artificial horizon as beneficial to well being (Bles et al 1991).

Noting that "cold" sweating (sweating occurring without an adequate thermal stimulus) is a frequent effect of motion sickness, Griffin (1990) also includes providing ample ventilation of cool, fresh air to make the sufferer more comfortable, and to aid in the fight against nausea and vomiting.

Though some of the above treatments are rooted in science, there is certainly room for doubt with others. In the case of motion sickness, however, the placebo effect cannot be overstated. Because motion sickness partly involves cognitive processes, any measure that is *expected* to help often has beneficial influences on the incidence of sickness in individuals. In other words, simply being told that a particular action

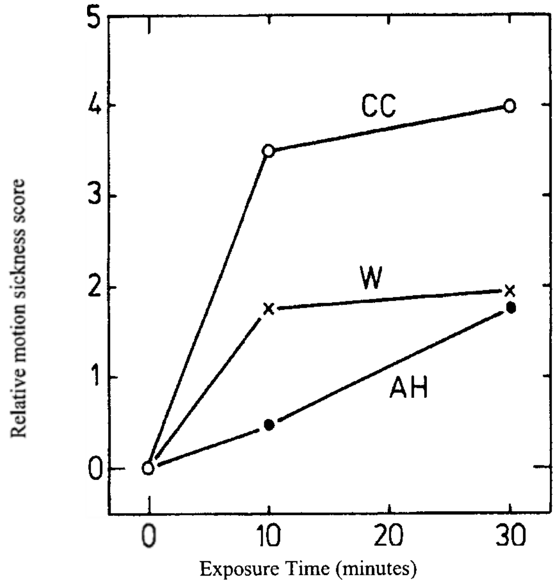

Fig. 15 Means of relative motion sickness score for experimental conditions Closed Cabin [CC], Artificial Horizon [AH], and Windows [W] (Rolnick & Bles 1989)

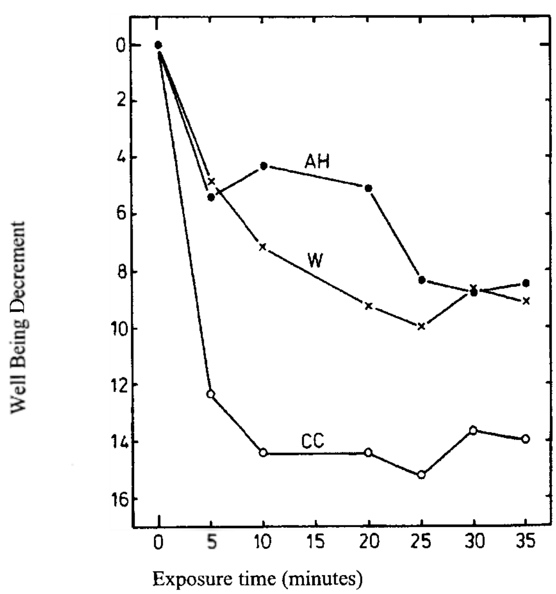

Fig. 16 Means of relative well-being decrement (with reference to level just prior to motion exposure) as a function of exposure time for experimental conditions Closed Cabin [CC], Artificial Horizon [AH], and Windows [W] (Rolnick & Bles 1989).

or treatment will help often carries significant psychological benefits, in turn moderating the effects of motion sickness.

Conclusions

It is hoped that the preceding information conveys a better understanding of the mechanisms of motion sickness. Often, simply possessing a more thorough understanding of an unfamiliar or uncomfortable phenomenon imparts a level of power to the individual to control, or at least cope with, the symptoms more effectively than if very little is known about the event. An analogous situation is the common flu—it is by no means an enjoyable experience, but because people are familiar with its nature (e.g., time course, symptoms, and causes), anxiety and arousal levels are kept to a minimum and people generally "deal" with it. Put simply, "knowledge is power."

Possessing knowledge of the effects of ship motion on crew performance, fatigue, and motivation also allows us to develop new and innovative design characteristics to moderate the effects of provocative motion on personnel. This leads to enhanced effectiveness and performance of the vessel, and more importantly, to the safety of individuals and the vessel as a whole. This is especially significant in today's seafaring services where an inverse relation exists between the number of crew on board and the workload per individual. In order for the current minimal manning goals to be achieved, the human element must be designed from day one.

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