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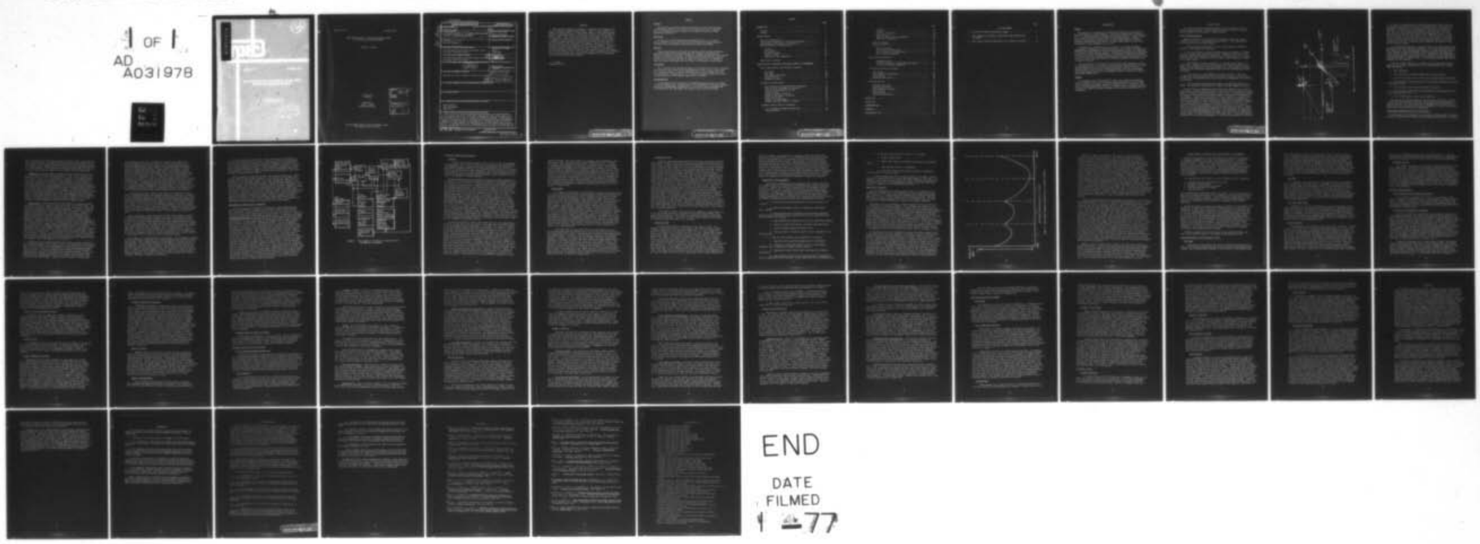

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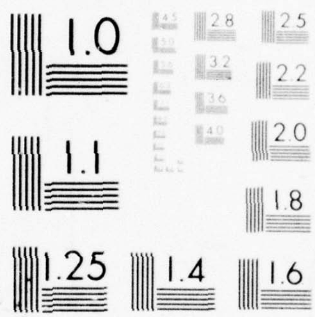

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SHIP MOTION EFFECTS IN THE HUMAN FACTORS DESIGN OF SHIPS AND SHIPBOARD EQUIPMENT

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SHIP MOTION EFFECTS IN THE HUMAN FACTORS DESIGN OF SHIPS AND SHIPBOARD EQUIPMENT

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Ship motion can seriously degrade task performance even when personnel are not actively sea sick. This report demonstrates that motion effects can be considered in the design of ships and shipboard equipment. Design guidelines are provided for use in the human factors design of ships and shipboard equipment to help minimize the degradation of task performance due to ship motion. Background material on the mechanisms by which motion affects personnel is also provided as an aid to the human factors engineer in performing his design function.

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FOREWORD

This study was conducted in support of Exploratory Development Task Area ZF55.521.022; Manned Systems Design. NPRDC has been engaged in a number of support projects for new design ships, including the Advanced Hydrofoil, Amphibious Assault Landing Craft (AALC), and Landing Vehicle, Assault (LVA). These efforts have ranged from dealing with problems of personnel selection and training through development of test plans to measure the effectiveness of personnel in performing their functions. In addition, NPRDC has been engaged in research into the problems of human performance under difficult environmental conditions as part of the study of problems of measuring critical task performance. This dual approach has made it possible for the Center to look at the problems of task performance under conditions of ship motion from both the design and research points of view. The resulting report provides what is believed to be the first design guide specifically dealing with the performance problems associated with ship motion.

J. J. CLARKIN
Commanding Officer

SUMMARY

Problem

Ship motion can seriously degrade performance on many tasks even when the personnel exposed to the motion are not actively seasick. Presently, ship and equipment designers consider this problem to be beyond normal engineering solutions.

Objectives

The purpose of this research and development effort is to provide design guidelines for use by human factors personnel and design engineers concerned with the problems of ship motion and human performance.

Approach

Design guidelines were developed by matching defined design problems in performance under motion conditions with the available experimental and theoretical research literature. Knowledge of design problems has been obtained during the Center's participation in ship design programs and the extensive review of the literature has been a result of research into the problems of task performance measurement and the effects of environment on performance.

Conclusions

It is concluded that appropriate human factors design can be used to minimize the effects of ship motion on task performance, but that there is great need for a research program to develop additional data on the problems of motion and performance. The application of such data to shipboard design will result in improved mission effectiveness under motion conditions.

Recommendations

An integrated research program is recommended to develop data in a number of motion-related areas. Additionally, it is recommended that the Navy generate appropriate implementing documentation to ensure that motion considerations are addressed in the development and design of ships and ship systems.

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INTRODUCTION

Problem

The effects of ship motion on personnel have received little attention from ship/shipboard system designers. This may be because the most obvious effect of ship motion--motion sickness (also called kinetosis or seasickness)--is not usually considered controllable by engineering means. Further, it is frequently assumed that personnel not showing outward symptoms of motion sickness are performing their tasks at or near normal levels of efficiency. Unfortunately, this assumption is not true.

The problems of ship motion are not trivial. In a recent workshop (June 1975) on "Seakeeping in the Ship Design Process," VADM R. E. Adamson, Jr., COMNAVSURFLANT, described the difficulties encountered during fleet exercises as a result of North Atlantic weather. Personnel performance was a significant problem, and injuries were experienced in the weather conditions encountered. In the report of this conference (Seakeeping in the Ship Design Process, 1975), an entire section (4.4) was devoted to outlining problems and research needs relating to personnel.

The difficulties of predicting and controlling human responses to motion are increased by the lack of data on the ship motion characterisitcs of existing displacement hulls, and the major differences in motion that will be characteristic of the variety of high-speed vessels now under development. This makes detailed prediction of performance effects of motion for specific ship designs impractical.

Purpose

The purposes of this research effort were (1) to identify the general types of motion effects, (2) to develop design guidelines for use by human factors personnel and design engineers concerned with the problems of ship motion and human performance, and (3) to indicate areas of research which may increase our presently limited knowledge of the relation between motion and performance.

MOTION EFFECTS

This section provides background material on the mechanisms by which motion affects personnel. Material included should be an aid to the human factors engineer in performing his design function.

Physical Characteristics

Adequate definition of the ship motion stimulus to which the person responds is critical to understanding motion effects. Such specification is often difficult for several reasons.

1. The motion must be defined in terms of three distinct coordinate systems: earth, ship, and human body.

2. The ship and body coordinate systems involve six degrees of freedom of motion--three linear and three rotational. Impulsive loads due to slamming may require differential consideration, even though they can be analytically resolved into components of the six axes. Earth reference is handled in a simpler manner.

3. Ship motions, although continuous, are usually neither smooth nor symmetrical. Rather, they are often irregular in frequency, amplitude, and phase, and are asymmetrical about one or more axes. The presence of impulse loading further complicates physical analysis by usual time/frequency domain techniques.

4. Ship motions are time dependent and highly variable. Long-term averages may simplify analysis into the statistical values of "sea states," but they are not compatible with the much shorter physiological time constants of the human.

5. Ship motions interact with both sensory and motor functions of the human. The resulting interactions are complex, and only roughly understood.

Since the three coordinate systems involved (see Figure 1) do not have a common point of origin, the description of motion as it affects man is complex. People are normally oriented towards the earth g vector. Learning neurological function and the related muscle control based on the g vector orientation is, for example, a significant factor when a child is learning to stand and walk. Disturbance of this learned orientation is a major factor in causing motion effects on performance. Ship motion can be considered to be measured relative to the earth g vector as a set of deviations from the rest position. Normally these measurements are related to the center of gravity (CG) of the ship. However, it is rare that personnel in the ship are located at the CG. Therefore, the motions experienced by personnel are different from those described for the ship--sometimes radically different. This difference is complicated by the fact that during maneuvers some ships may rotate about the hydrodynamic center (center of lateral resistance) rather than the CG. This superimposes a secondary set of ship motion parameters on the motion experienced by personnel.

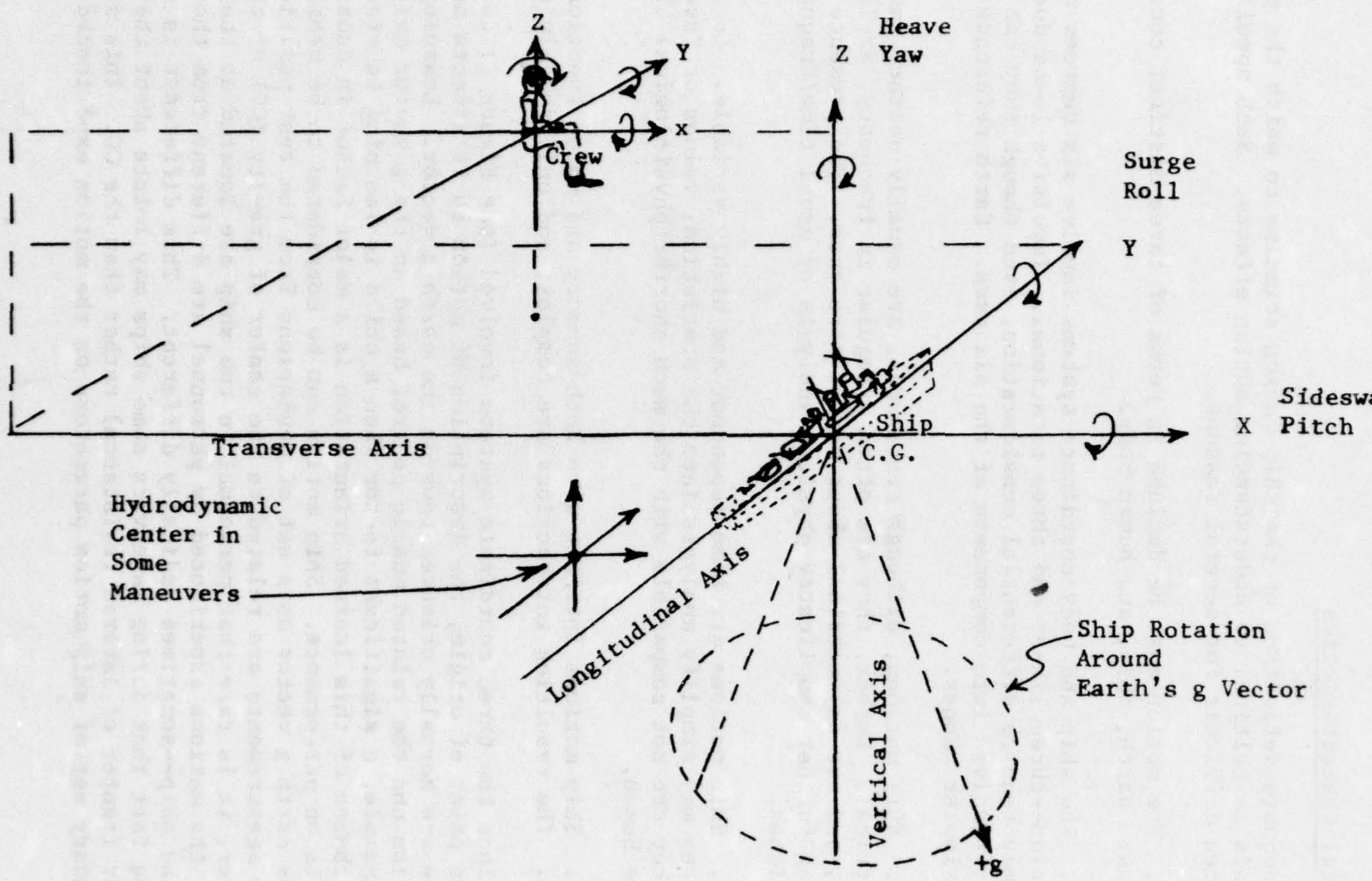

Figure 1. Ship and crew motion coordinate systems.

The above is a simplified description of the complexities of describing personnel experienced motion in a displacement hull. High speed non-displacement vehicles such as planing hulls and hydrofoils are generally different. In the case of the planing hull, the rotational axis pivot point near the stern becomes more significant when on plane. The lever arm distance to the rotational pivot affects damping of motion in a very different manner than for displacement hulls. For hydrofoils, it is difficult to locate a classical center of gravity when on foil. The presence of multiple points of interaction with the sea, plus the effect of wave encounter with the hull in high sea states, makes the description of the motion even more complex.

It is generally agreed that all ship motions are not equally significant physically or in their effects on personnel. Roll, pitch, and heave are the most significant, with yaw sometimes important. In most cases the translational motions of surge and sidesway are relatively small and unimportant to the physical analysis of the ship motion. However, in the translation of position from the CG to another part of the ship, the relative importance of a given motion may be shifted, and it is this modified stimulus that affects personnel at that location.

A ship in a seaway responds to a number of factors which determine its motion and which make analysis based on "sea state" insufficient. Among these factors are:

1. Ship dimensions.

2. Hull form and, for nondisplacement ships, operating mode.

3. Location of CG and center of bouyancy, including weight distribution.

4. Ship speed and relative heading to seas--usually expressed as frequency of encounter of seas.

5. Wind velocity and ship wind resistance (sail area).

6. Wave steepness and breaking characteristics, including modifications due to being near the coast.

7. Use of stabilizers or other motion modifiers.

The best way to determine motion at any point is to measure it. This is a relatively straightforward procedure, and the necessary instrumentation is readily obtained. Yet, even though this measurement tells us the motion to which the body of a person at that point is exposed, this may not be precisely the motion to which the person is responding.

<u>Physiological Responses to Motion and Vibration</u>

The response of the human body to ship motion is complex, and it is often difficult to differentiate between this response and the response to vibration.

This is especially so since the two types of stimuli tend to occur together, and responses overlap. To clarify the differences for the purposes of this discussion, the following definitions are given, with the recognition that, for physical signal analysis and other special purposes, there are other preferred descriptions. The following are designed to emphasize the nature of the motion and vibration stimuli as they interact with the human body.

Vibration is structure-borne oscillatory motion transmitted to the body by direct contact with the vibrating surface. This motion is usually independent of any motion of the structure as a whole. The frequency range of interest is from 1 Hz to about 200 Hz. Vibration is usually normal to the plane of the oscillating surface, and amplitudes are not large. Any rotational components are usually introduced by body position relative to the vibrating surface or by exposure to two or more translational vibrations at the same time. The primary mechanism by which vibration affects the body is by direct transfer of energy to the tissues. At higher levels and at lower frequencies, this may result in secondary effects on the nervous system similar to those generated by ship motion. The human body has whole body resonances and major component (e.g., the head) resonances in the frequency range of approximately 4 Hz to 60 Hz (von Gierke, 1965), with the effects of vibration at these frequencies being increased accordingly. At or near resonance, physical damage to body organs is most likely to occur.

Ship Motion is normally generated by the platform or structure moving as a whole, along one or more of the translational or rotational axes. Most commonly the motion is complex, involving at least three axes of motion and having both rotational and translational components. Frequency is usually below 1 Hz and seems to have little effect (in the shipboard situation) for components below 0.02 Hz. There is relatively little direct transfer of energy in the manner of vibration; however, the large amplitudes often associated with ship motion can create other mechanical problems such as having difficulty in staying in one place or in controlling hand and arm movements. Although the motion is usually oscillatory, it is not symmetrical or precisely repetitive in form. The primary motion effects are neurological and are mediated by a complex system involving muscle position sensors, vision, and, most of all, by a complex sensing mechanism called the labyrinth or vestibular system. This system, located in the inner ear, has direct sensors for linear and rotational motion. This mechanism will be discussed in more detail later in this section. The effects of motion exposure involve a number of physiological systems. The more extreme effects of overt motion sickness are well known. The symptoms include pallor, sweating, nausea, and vomiting. The effects on performance prior to overt motion sickness are less well known and represent a major consideration of this report.

In addition to the motions described above, there is another type which has received relatively little notice. This is the repetitive, short-duration, high-amplitude impulse, often represented in the shipboard situation by slamming. The lack of attention to the impulse problem has apparently stemmed from two factors. First, the impulses can be analyzed for their physical components as if they were brief ship motion excursions similar to the oscillatory motions. Second, in the relatively high sea states in which they usually occur for displacement hulls, their effects are difficult to differentiate from other motions. However, there is reason to believe that, physiologically, there is a difference in response to an impulse (or series of impulses) relative to that for the oscillatory ship motion. This difference may be of great significance for nondisplacement hulls, since, for many of these hulls, there is a relatively small oscillatory motion in a given sea state, but a larger amount of slamming. This is typical of hydrofoils and planing hulls, both of which show relatively less rotational motion but more slamming when in the nondisplacement mode. Since the new hull designs call for higher speed than conventional hulls, the effects of slamming can occur at lower sea states and with higher frequency of encounter. In the case of surface effect ships and air cushion vehicles, there is a pressure pulse generated underneath the hull as waves are overridden. Although this pulse may have some of the characteristics of a slam, it may be propagated more vertically and may be in addition to the horizontal (surge) components of the slam itself. At present, there are no shipboard data on the effects of slamming on personnel performance and only one recent laboratory study (Wolk & Tauber, 1974) on the subject.

The mechanisms by which these motions affect the human are not fully known. As mentioned above, the vestibular system, or labyrinth, is central to the physiological response to motion, but the manner in which this system interacts with other body systems to generate the responses (including the symptoms of motion sickness) is not known in detail. The vestibular system is a sensory system that is, in some respects, similar to vision or taste or other senses. It is concerned with sensing the motion of the body through space and position in space. There are two major components of the vestibular system, the semicircular canals and the otoliths. There is a complete system in each ear, with the semicircular canals in mirror image position on each side.

Three semicircular canals are present on each side, arranged in nearly orthogonal relationship along the three major axes. The physical stimulus of the canals is acceleration. However, the output neural signal is proportional to velocity, indicating that there is an integration in the nervous system. The mechanics of the semicircular canals have been studied in detail, and differential equations of motion for the system have been written (Mayne, 1965; Jones & Spells, 1963; Van Egmond, Groen & Jongkees, 1949). It is important to note that, in the real world, it is not possible to excite only one canal. To do so is difficult even in the laboratory, as the canals are not exactly orthogonal or exactly oriented to the body axes. Under conditions of ship motion, all six canals are usually generating signals.

Two otoliths are located adjacent to the canals. The "operational elements" are small bony masses suspended in a jellylike membrane that includes sensory cell endings. These endings respond to displacement of the body as the differential mass of the otoliths relative to the membrane causes distortion of the membrane. The two otolith structures--the utricle and the saccule--are located in two different vertical planes. Neural signals from the otoliths have been shown to be proportional to velocity although the input is displacement. In this case and in opposition to the canals, the otoliths are differential detectors. One author (Lowenstein, 1974) describes the otoliths as working as differential density accelerometers.

The visual system and visual-motor system (the muscles controlling eye movement) are both affected by motion. Generation of the eye rotation movement called nystagmus is apparently primarily dependent on canal function, but otoliths can generate a perceptual change in apparent position of external objects (the oculogravic illusion). Since nystagmus is apparently at least partly intended to stablize images on the retina for perceptual control, the two systems are involved in visual perception and are important to the motion effects on visual perception tasks.

There is extensive interaction between the vestibular system and a number of other physiological systems (Figure 2). This interaction includes both signals from the vestibular system to the other systems and signals from the periphery to the vestibular system. The visual and muscular systems are the most important of the interactive systems. Complex feedback loops are operative in which signals flow both ways, using both direct and indirect pathways. The direct connections are fairly well understood as to function. However, although a number of connections for the indirect paths have been identified either partially or completely, there is much doubt as to their functional significance. The effects of motion on performance and the symptoms of motion sickness must involve intermediate connections, probably central in nature, but many are presently unidentified. The large difference among individuals in their responses to motion may well be tied to these interactions. Dealing with the individual difference problem is beyond the scope of this report.

Relationship of Ship Motion to Vibration

Unlike ship motion, the effects of vibration on task performance have been studied extensively, and many of the effects are well known (Collins, 1973 and others). Two excellent reviews of the research on vibration are the 1969 study by Bender and Collins and the National Institutes of Occupational Safety and Health report (Wasserman and Badger, 1973). In addition, the Shock and Vibration Bulletin series published by the Naval Research Laboratory is an on-going source of recent research, including that on the effects of vibration on personnel. In their review, Bender and Collins (1969) briefly examined the question of low frequency vibration and stated: "At low frequencies (.05 - 2 Hz.), the data are so disperse that we are unable to establish any meaningful criteria." In the intervening years, there has been little reason to change this statement. Unfortunately, the few studies that have been performed have been conducted under specialized conditions that cannot readily be generalized. However, as the frequency decreases, the effect of vibration is reduced, with the energy transfer decreasing (for a given amplitude of vibration). As a result, the neural effects of ship motion become dominant. In this crossover region, there are undoubtedly interaction effects of interest, but there are no data on this subject. The interaction of motion with higher frequency vibration is probably of greater significance to task performance than the interaction with low frequency vibration. This is due to the greater effect of the higher frequency vibration as a task degrader and the probability that the interaction with motion will tend to summate the effects of each. This type of interaction occurs in varying degree where other pairs of environmental factors are involved (such as vibration and noise--see Harris & Sommer, 1971), and probably applies to the motion-vibration interaction. Since both motion and vibration are present in the ship environment, it is probably safe to assume that the performance decrement will be more severe than in isolated laboratory studies of either factor individually.

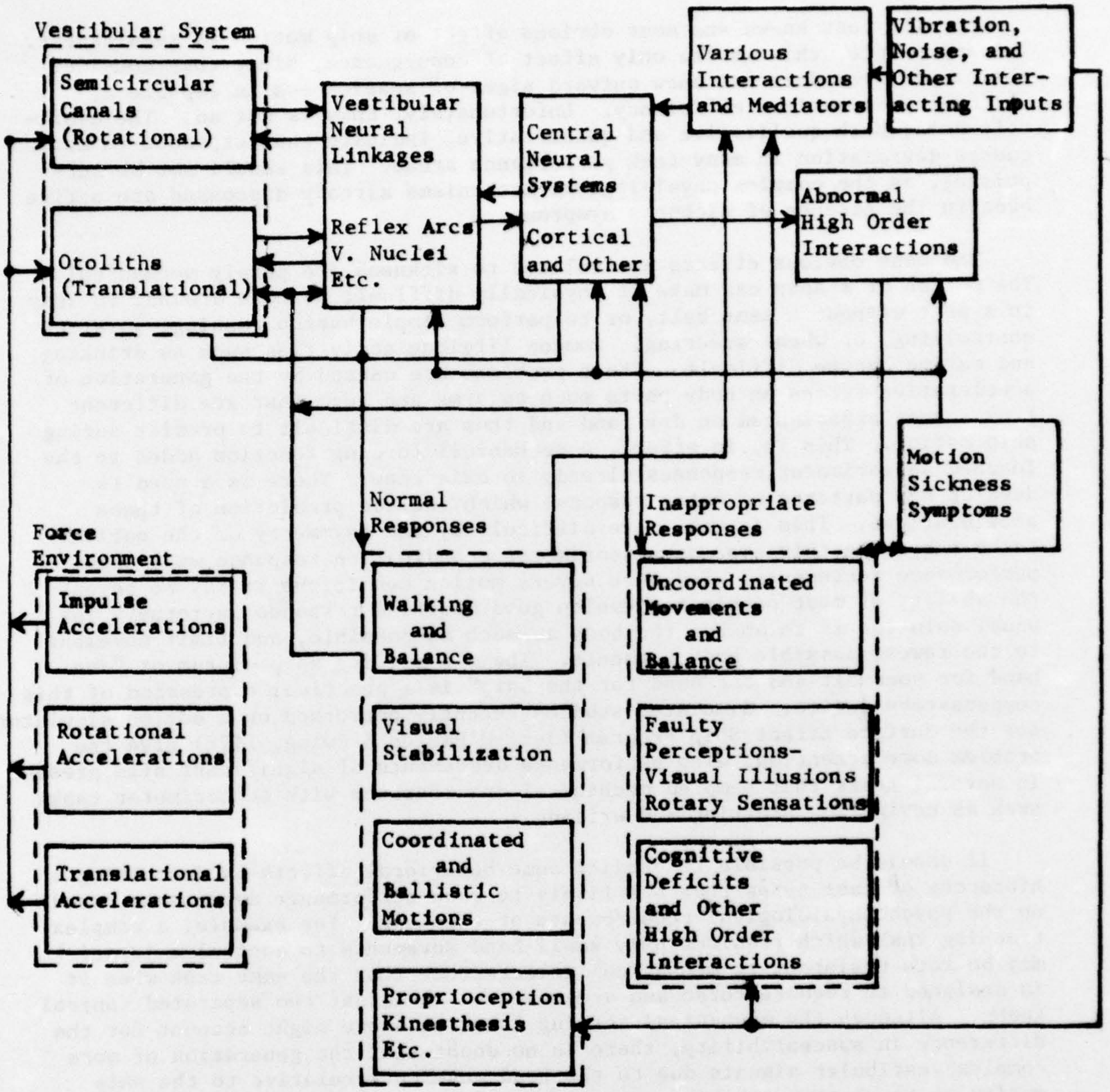

Figure 2. Flow diagram of vestibular interactions with the body and environment.

Behavioral Effects of Ship Motion

Overview

The best known and most obvious effect of ship motion is seasickness. To many people, this is the only effect of consequence, since they consider that anyone who does not show outward signs of seasickness is capable of performing at maximum efficiency. Unfortunately, this is not so. The available data, both qualitative and quantitative, indicate that exposure to motion causes degradation in many task performance areas. This should not be surprising, as the complex physiological mechanisms already discussed are active even in the absence of sickness symptoms.

The most obvious effects not related to sickness are purely mechanical. The motion of a ship can make it physically difficult to move around, to stay in a seat without a seat belt, or to perform simple button pushing, joystick controlling, or wheel steering. Common lifelong activities such as drinking and eating become difficult. These problems are caused by the generation of accelerative forces on body parts such as arms and legs that are different from forces experienced on dry land and thus are difficult to predict during ship motion. This is, in effect, a mechanical forcing function added to the learned sensorimotor responses already in existence. There is a need to develop new patterns of motor response which include prediction of these accelerations. This is made more difficult by the asymmetry of the motion. Tasks requiring this type of sensorimotor coordination response will show performance decrements. For more severe motion conditions it may be beyond the ability of most people to develop good modified response patterns. The usual solution is to anchor the body as much as possible, and limit movement to the fewest possible body segments. The old sailing ship dictum of "one hand for yourself and one hand for the ship" is a practical expression of this compensatory device. Simulator studies recently performed on a motion simulator for the Surface Effect Ship Program (Jex, O'Hanlon & Ewing, 1976) give the problem some attention, with performance decrements of significant size present in several tasks that sampled mechanical interference with sensorimotor tasks such as navigation plotting and writing.

It should be possible to predict some behavioral effects by describing a hierarchy of task types that are likely to show performance decrements based on the psychophysiological requirements of the task. For example, a complex tracking task which requires only small hand movements to control a joystick may be more resistant to mechanical interference than the same task when it is designed to require torso and arm movement to adjust two separated control knobs. Although the mechanical forcing function alone might account for the difference in susceptibility, there is no doubt that the generation of more complex vestibular signals due to the head movements relative to the ship motion in the latter tracking arrangement is also involved, and probably reinforces the mechanical effect. In general then, if the simple assumption is made that greater involvement of vestibular function implies poorer operation of the related systems, we could predict that tasks which involve those physiological systems which are known to be linked to vestibular responses should show effects of motion sooner than others. However, this isn't always the case. The complex feedback systems of the nervous system can utilize both vestibular signals and the other related system signals to counteract the effects of motion. There are limits to the compensatory capability of these feedback systems. When these limits are exceeded, rapid breakdown of task performance using the physiological system involved can occur. Further, the simple linear assumption is difficult to integrate with the existence of substantial differences in individual response to motion, as the range of physiological responses such as nystagmus does not always correlate well with the range of variability of a behavioral response to ship motion. This complexity of the vestibular-related systems makes the prediction of motion effects more difficult. It is necessary to consider not only the level of motion but also the characteristics of the motion in terms of components and relative magnitudes. The presence of vibration and noise tend to generate interactions which can affect task performance. With these caveats, and the recognition that specific conditions can modify the general predictions, the following are presented as probable response problem areas due to the presence of ship motion.

Visual Tasks

Two types of visual tasks are candidates for significant motion effects. The first is the visual task that involves complex perceptual processing, such as target search and detection on a CRT, especially at low signal to noise ratios or in cases where jamming or other competing stimuli are involved. Vibratory stimuli have been shown in many studies to reduce visual acuity and other aspects of visual performance required for search or fine perceptual distinctions. In the Soviet literature (Parin, 1964), there are data on brief angular accelerations of the appropriate frequencies which also show decrements in visual acuity. However, acuity is not the only visual factor, as shown in a study by Guedry and Holmes (1972), in which sequences of digits had to be located and identified under conditions where acuity was not degraded to the point of making the digits unreadable. Error was attributed to the requirement to control visual scanning superimposed on nystagmus and on vestibular-imposed errors in spatiotemporal relationships. In effect, the visual perception task became too complex and subject to interference in correlating the conflicting spatial signals relating to the motion and the display, thus decreasing the ability of the viewer to perform his task. This implies that complex and/or multipart tasks requiring sharing of visual perception are likely to be motion sensitive.

The second type of visual task likely to be most affected is the multiposition monitoring and reading task. This is typified by tasks such as monitoring engine meter boards. The mechanisms involved in generating problems are somewhat similar to those of the CRT task just discussed, but an added element is present. In CRT work, the head remains relatively unmoving as attention is focussed on a small area while monitoring large boards requires movements of the head relative to the body and to the imposed motion. This additional motion creates additional vestibular stimulation. In numerous studies, (e.g., Guedry, 1965 and others) it has been shown that in the most severe case, where head motion is orthogonal to the direction of body motion, Coriolis forces are generated in the canals which can cause motion sickness very rapidly. In the shipboard case, the head motion may not be at the optimum angle to generate the strongest Coriolis effect most of the time, but its cumulative effect is likely to be significant.

Psychomotor Tasks

Both the visual/perceptual aspects and the motor interference problems make fine-grain manual control and tracking tasks potential problem areas in performance. In these tasks there is an added component that may be of significance, although direct evidence as to its contribution has not been obtained. This component is the presence of learned perceptual-motor response patterns based on the existence of sensorimotor feedback loops (Norman, 1974). Since these patterns were learned under conditions in which the spatiotemporal relationships and force environment were different from those existing on the moving ship, it is necessary to relearn them. In many such learned patterns, including the examples given earlier of eating and drinking, ballistic movements of the body are an integral feature (Hartson, 1939). Since such movements require prediction of the force environment effects on the moving part of the body, ship motion is highly disruptive because it is not usually fully predictable over the short times associated with body motions. Also, the probable relearning required involves replacing the ballistic movements with continuously controlled movements. This may contribute to the fatigue associated with ship motion, as it has been shown by EMG recording that ballistic movement of the muscles is less fatiguing than nonballistic movement (Hartson, 1939). An additional factor of potential significance is that many motor tasks that are learned initially as visual-motor tasks transfer the feedback function to the muscle sensors (proprioceptors) in whole or in part, once the behavior is well learned. Walking is a good example of such behavior, even though the visual part of the loop is not completely removed. In walking, the normal movements of the legs are primarily controlled proprioceptively, while the visual function is concerned with spatial relations of foot placement such as obstacle detection.

In the Surface Effect Ship studies (Jex, O'Hanlon, & Ewing, 1976), one of the few studies conducted to examine complex tasks quantitatively under ship motion conditions, it was found that tracking performance deteriorated during motion conditions. Difficulty in other complex tasks such as walking and eating has long been known to be a problem.

Cognitive Tasks

Another task category of importance is the cognitive task. This category is comprised primarily of "thinking" tasks such as decision making, planning, analysis of data, and mental computation. It also includes the ability to concentrate or maintain attention to a task. Quantitative measurement of such tasks is almost always more difficult and complex than for most sensorimotor tasks. (See Collins, Crampton, & Posner, 1961 for a typical study.) The inputs and outputs are less clearly defined, and the process itself may be poorly understood, making it difficult to establish criteria and to develop measures of performance and test materials. The evidence for motion effects on cognitive function is less direct than for the other categories discussed so far. The neuroanatomy and neurophysiology data in this area are more limited and, to some degree, inconsistent. The extent to which the vestibular system has cortical connections and the functional relationships are not clear. The common anecdotal evidence is not very useful in the cognitive area, as cognitive defects are likely to be unobservable by the person affected, as well as by others. The possibility of cognitive effects as second-order effects is also present; that is, the vestibular-related systems may interact with some system that is not normally involved and this interaction affects cognitive task performance. Such derived or second-order effects are purely speculative, as no direct evidence exists as to their presence. At most we can say that since there are second-order effects in motion sickness such as sweating and nausea, a second-order effect involving cognitive function is not unlikely. The Surface Effect Ship Studies (Jex, O'Hanlon, & Ewing, 1976) found decrements in some tasks containing a cognitive component, such as navigational plotting and cryptographic encoding/decoding. However, since these tasks also involved mechanical performance, there is no logical reason for assigning the performance decrements to cognitive functions.

Hierarchy of Task Components

As the above examples show, many shipboard tasks involve more than one parameter that must be evaluated in determining the probable sensitivity to motion. Further, the relative contributions of the parameters can vary with the specific motion of a given platform under particular sea state conditions. Our present knowledge of how these parameters interact makes it unrealistic to attempt detailed quantitative predictions of motion effects on specific task performance. However, based on the available data, the following guidelines as to characteristics of tasks and possible motion effects are useful as a general guide for ships with multidimensional motions.

1. A task will show strong susceptibility to motion effects if it involves:

   a. Whole body movements subject to mechanical interference (e.g., walking).

   b. Complex sensorimotor performance which involves previously learned ballistic movements or motor patterns that are not synchronous with the ship motion (e.g., eating).

   c. Head movements that generate Coriolis-type vestibular responses.

   d. Complex perceptual processing, especially involving vision.

   e. Cognitive tasks combined with motor output.

   f. Tasks performed in locations where no visual reference to the horizon exists.

2. A task will show moderate motion effects if it involves:

   a. Cognitive tasks requiring extended time of performance.

   b. Sensorimotor tasks that require only small body segment responses (e.g., tracking with finger-operated control).

   c. Sensorimotor tasks learned under less severe, but similar ship motion.

   d. Simple sensory detection tasks where mechanical interference is not a significant factor (auditory function apparently has an advantage here).

3. A task will show less motion effect if it involves:

a. Verbal communication.

b. Simple motor tasks not involving fine control (two position switch).

c. Body and head movement are minimized.

d. Tasks which have been practiced extensively (overlearned) and which are not in group 1 above.

It must be emphasized that the above listing is not rigid. Specific ship motion characteristics can cause significant changes in the order. For example, a ship subject to heave motion only should generate less mechanical interference than one with multidimensional motion, and should cause less problems in walking or other sensorimotor functions.

Habituation to Motion

The term "habituation" is usually used to refer to a reduction in the response to a stimulus over time. Habituation to ship motion occurs under most conditions. It is most obviously evidenced by the reduction and disappearance of motion sickness symptoms after continued exposure. Although the mechanisms underlying habituation are not fully known, there are characteristics of habituation which are significant and worth examining.

Habituation can be considered as a highly specific and specialized form of learning by the neuromotor systems. It is probably most similar to the type of learning called conditioning as it shares some of the characteristics of conditioning, including its great specificity of relationship between stimulus and response, limited ability to generalize to other stimuli, and some aspects of habituation loss (extinction) and reacquisition. The review by Collins (1974) emphasizes the specificity of habituation. This specificity is important in that it helps account for the fact that people who have habituated to a given ship motion may be affected again if the ship motion changes significantly. Vision plays a significant role in habituation to motion. It has been frequently demonstrated (see Collins, 1974) that visual access to a fixed external reference reduces motion-related responses such as nystagmus and enhances habituation. In the absence of fixed external reference, motion effects are more resistant to habituation and may have an earlier onset after start of exposure to motion.

In relating the effects of habituation to task performance, remember that, as for other aspects of motion exposure, the absence of overt motion sickness symptoms does not necessarily indicate that no motion effects are present. Consider a hypothetical scenario (Figure 3) in which a ship leaves port, travels for a few days in light to moderate seas on a constant course (call this part A) and then changes course and speed to avoid a storm moving toward the ship, with increasing motion due to higher speed and the presence of a heavy swell from the storm (part B). The wind increases and, after a day, there is a large confused sea due to the difference in direction between the storm swell and the increasing wind waves (part C). During this part of the trip, ship speed is decreased, but the ship motion is large and irregular, including considerable slamming. The final part of the trip (D) has decreasing seas and swells for the 2 days to port, with higher ship speed and a constant course maintained.

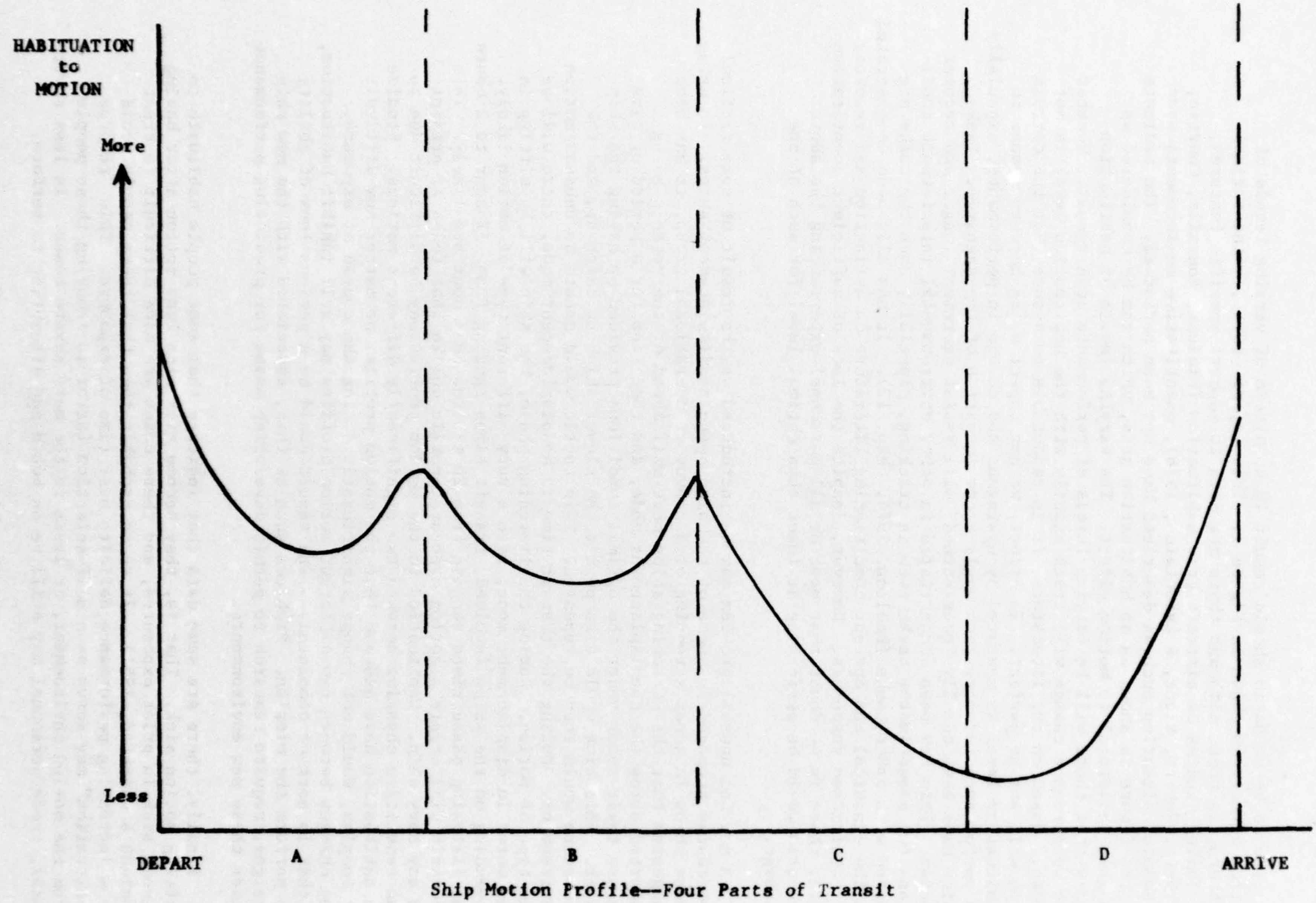

Figure 3. Ship transit scenario--habituation as a function of motion.

The above scenario should result in a pattern of varying levels of motion effect, as shown in Figure 3. This is, of course, a theoretical pattern, in that, although there are data to support specific features, including studies of aircraft crew habituation (Pialoux, Fontelle, Courtin, Gilbert, Robert, Blanc, & Lafontaine, 1976), quantitative measurements over a complex situation such as described have not been performed. The ordinate of the figure is shown as an habituation axis, which can be considered as roughly reciprocal to motion effect. The varying levels of habituation imply that there will be varying levels of performance as a result. Whether the performance change will track exactly with the habituation level is not known. Based on the literature, it is reasonable to assume that the correlation will not be perfect. In effect, we can expect a lag between change in habituation level as measured by nystagmus and change in performance, expecially in performance recovery such would occur in part D of the scenario. Tasks which have been heavily "overlearned" will resist decrement longer and recover sooner. This has been demonstrated in other environmental interference conditions for sensorimotor tasks such as tracking, especially when the tasks are shared with other tasks (Poulton, 1974, Chap. 12). It has also been demonstrated in the classical and operant conditioning literature on extinction and recovery of conditioned responses. However, despite the lack of sufficient quantitative data, there is no doubt that most or all personnel experiencing the above scenario would be performing at lower than optimal level for much of the passage.

A new and unusual problem may be introduced as the result of some tactical procedures proposed for some of the high speed nondisplacement ships. In using these ships in sonar screening of a convoy or operational group, it has been suggested that the screening ships move well ahead of the vessels being escorted using the nondisplacement mode, and then stop for a period of time to use their sonar under the optimal conditions provided by having the ship quiet. This time would also permit the slower ships to catch up, and the procedure would then be repeated. This tactic would create an unusual motion environment. During the transit time in nondisplacement mode, there will be one type of motion. During the listening phase, the ship will be sitting in the water in displacement mode, with a very different type of motion likely. Depending on the ships involved, transit times ranging from 1/2 hour to 2 hours and listening phase times ranging from 20 minutes to 1 hour are likely. This scenario will create a motion exposure profile unlike that found at present on any Navy ship. Habituation to the motion profile may be difficult due to the repetitive changing between two significantly different motions. Studies on habituation have assumed that the motion profile, no matter how difficult or complex, would not change significantly during the course of exposure. The changes between two different motion profiles may well inhibit habituation, either in part or completely. The result could be a serious loss of ability to perform the mission. Problems such as this, associated with the new ship designs, require research to permit developing means for predicting performance under these new environments.

Finally, there are some data that indicate that some people habituate to getting motion sick. That is, they become sick with less motion after having become sick in prior exposures, and these cases are more difficult to treat (Boland & Grinstad, 1951). It seems probable then that these people would show increasing performance deficits over time of exposure. This "reverse habituation" may serve as a self-selection factor in removing these people from the motion environment, at least in the more severe cases. In less severe cases, these personnel may still be on board and attempting to perform.

DESIGN FACTORS TO MINIMIZE SHIP MOTION EFFECTS ON PERFORMANCE

This section discusses factors that should be considered in the design of workspace, equipment, and tasks. This discussion is not a substitute for thinking about or understanding the problems involved. It is not a mechanical crutch. Rather, it is intended to serve as a mnemonic device and aid to ship and system design and to assist in the organization of data and the evaluation of design tradeoffs. Use of this material in applying the principles of response to motion to good human factors design, particularly when used in consultation with the appropriate hardware engineers and ship designers, should help to minimize the effects of ship motion on task performance.

The considerations are divided into the following five major categories:

1. Ship Characteristics and Personnel Location
2. Workspace and Environment
3. Equipment Characteristics and Design
4. Task Characteristics and Design
5. Personnel Factors

The categories have considerable overlap in content. This is not accidental. Many of the problems encountered will be complex in nature and will have components in more than one category. Such problems may be approached in more than one way, emphasizing different aspects to achieve different goals. The overlap will help insure that consideration is given to these different approaches.

Mission and functional analysis are basic and critical to any human factors design effort, especially in the case of design relating to motion effects. The manner in which a ship is operated can be critical. As an example, some of the new nondisplacement designs have only limited endurance in that mode. To increase their endurance, they may be operated in displacement mode much of the time and in the nondisplacement mode only while performing certain mission functions. This shifting back and forth between modes will have a major effect on the motion environment of the crew and, consequently, on their ability to perform their assignments. The potential effects of frequent transitions on habituation to motion already have been discussed. The importance of evaluating the effect on the mission as indicated by scenarios is obvious. Every item in the discussion which follows must be examined with mission and equipment function in mind.

Finally, a design that works well under motion conditions should work well in the absence of motion. The reverse is not necessarily true.

Ship Characteristics and Personnel Location

Hull Type

The motion of displacement hull ships is significantly different from that of most nondisplacement hulls when operating in the nondisplacement mode. Further, since nondisplacement designs can also operate in displacement mode, the motions present in each of these modes may differ radically from each other. Personnel may therefore be required to perform their tasks under two or more radically different conditions. This may present a severe design problem since design requirements may differ for the different modes. To solve this problem, designers of equipment and tasks must consider the proposed utilization of the ship, including the extent of use of the different modes, whether specific functions will occur in one or more modes, and how frequently transitions occur from one mode to the other. Frequency of transition between modes is especially significant, as for any given percent of time using a given mode, the number of transitions can control the responses to motion and time for habituation and, thereby, the ability to perform many tasks.

Ship Size

In general, the larger the ship, the higher the sea state needed to generate large ship motion excursions. Presumably, this will hold true for both nondisplacement and displacement hulls. A patrol gunboat (PG) will be moved around much more in a Sea State 5 or 6 than will an aircraft carrier. Further, although the ability to maneuver and maintain speed as the sea state increases also relates to the ship's size, not all ships of a given size (length or displacement) will have the same or even very similar motions. Other factors, such as location of the CG, fore/aft distribution of weight, superstructure sail area, draft, and hull shape, are important determinants of the motion experienced.

Ship Operational Speed

Ship speed is a critical consideration, since it determines the frequency with which the ship encounters the wave system for any given heading relative to the seas. The nature of the encounter will generally vary with speed. For example, in a head sea, a slow ship may have lower acceleration peaks and a different profile of motion than a high speed ship that tends to slam into the seas and cut through rather than ride up wavefronts. Further, during high sea states, many nondisplacement hulls will be required to slow down and revert to their displacement mode.

Operational Area

For many ships, this question is not given enough attention. A number of ships are intended to operate along coastal waters (e.g., PG, CPIC), and others, in the open ocean. In general, the coastal designs are smaller, and the sea state conditions they encounter are quite different from those of the open ocean. For this reason, the standard sea state descriptive equations used by the Navy often are not applicable to coastal conditions since (1) the shallower water along the coast produces transitional and shallow water wave systems that tend to be steeper than those in the ocean, and (2) the height and length of waves along the coast do not correspond to those in the commonly used wind speed/fetch/time prediction tables. Further, coastal craft are not likely to encounter the massive wave systems that exist in some areas of open ocean. Since many of the smaller coastal craft are high-speed designs, the short, steep seas often encountered would tend to emphasize the presence of slamming and other high acceleration motions. Even the largest ships will show extreme motion in the conditions of a strong tropical depression or during a gale in the open waters of the Southern Hemisphere.

Personnel Location

The location of personnel in the ship is a major determinant of the motion experienced. Although the usual method of measuring ship motion is with reference to the ship's CG, the distance along the axes at which personnel are located will modify the motion significantly, especially where rotational motion is involved. Further, reference to the CG tends to ignore the fact that a maneuvering ship tends to pivot around the hydrodynamic center. In some cases, such as the planing hull, the shift of center is toward the stern when on plane, and acceleration loadings increase as one goes forward. In effect, the dynamic CG is located aft of the static CG. In selecting the location for equipment and/or personnel with critical tasks, the determination of the location of the hydrodynamic center can be an aid to minimizing effects on performance.

Workspace and Environment

Basic Workspace and Environmental Conditions

All the normal requirements for design of good workspace layout including plans for environmental control, also pertain to design for motion effects. However, the motion problem introduces additional restrictions that are not otherwise necessary. For example, good workspace layout and environmental design for use on a moving ship must also contend with ordinary problems such as limited space.

Work Area Size and Number of Personnel

The space in many ship compartments is very limited, either because of compartment dimensions, the presence of large amounts of equipment, or both. As a result, there is often a high density of personnel, which, under motion conditions, can have deleterious effects. If some of these personnel are expected to move around the space, high levels of motion can interfere with normal operations or even totally prevent operation. To alleviate this problem, it is better to lay out the workspace so that movement by personnel is not required. The benefits of having all personnel strapped in seats so that personnel motion is limited to use of seats on rails are evident. In addition, the seated individual should be maintained in a constant orientation to the axes of the ship to minimize the Coriolis effect. Head rotation can also generate Coriolis effects. In some aircraft studies, it was found that strapping the head to the seat (with a helmet) was partially successful in reducing these effects (Woods, 1967).

Crowding of personnel also can cause other problems. Maintaining adequate ventilation and temperature, and controlling other environmental factors is more difficult. The role of smell, temperature, noise, or other sensory and environmental factors as generators of motion sickness is a matter of debate. Although the primary cause of motion response is the vestibular system, there is little doubt that many other factors can modify the response for many people. To some degree, this may be because the expectation of a reaction to smell (or other factor) helps generate the response. However, the fact that autonomic responses, such as sweating, are also involved may well indicate that, once the physiological mechanisms are initiated, there is a direct sensory input modification of the motion response. For example, if one crew member does become sick and displays outward symptoms such as vomiting, this can affect other crew members. Certainly, the sight, sound, and smell accompanying such symptoms can affect both performance and susceptibility to motion. Minimizing crowding of personnel can help minimize motion effects.

Control of the Environmental Factors

Excessive levels of temperature, humidity, ventilation, noise, lighting, and odors are common in ships. Control of these factors is critical since they often pose a problem aside from any consideration of the relationship to motion, and they may increase the severity of the motion responses. Temperature and odor appear to be the most significant in subjective response to motion. However, there is no evidence that design beyond that satisfying good human factors practice and criteria is required. Rather, the involvement with motion effects should serve to emphasize the necessity of meeting the relevant criteria for temperature and ventilation. The "smelly sweatbox" environment found on some ships is an invitation to poor performance in any conditions, but when motion is involved, the problem is compounded.

External Vision

It has been known for a long time that visual reference to the horizon reduces the incidence of motion sickness. In the modern warship, this is not possible for many of the crew. Since the possibility of using an "artificial horizon" has not yet been explored, at present, access to the external horizon reference must be considered as desirable but not always possible.

Design of Operator Positions

Because of such problems as mechanical interference and Coriolis effect (discussed earlier in this report), it is more difficult to design operating positions for shipboard use than to design those for use at land-based sites. Since it is necessary to reduce the operating volume of space, dimensions for manual control, visual monitoring, and any other tasks requiring body or body segment motion must be minimized, especially if body restraints such as seat harnesses are required. It is possible to expand the effective usable space for operation by using adjustable position seating. However, in designing the seat motion, changes in orientation to the axes of the ship and its motion must be avoided to prevent Coriolis effects. Although seated operation is preferred, it is not always feasible. Where standing operation is required, the same type of volumetric limitations exist. It is necessary to provide for adequate handholds for use while operating the console or equipment and to design both the equipment and the handholds to minimize the risk of injury in case the operator is thrown around. Further, operation must be predicated based on use of one hand, since, the operator must use the other hand for a handhold. One possible means of minimizing injury potential and permitting two-hand operation is by use of a safety belt or harness, similar to those used by window washers working on the exterior of a building.

Design of Maintenance Positions

The design considerations applicable to operator positions also apply to maintenance positions, plus some additional restrictions due to the nature of most maintenance tasks. For example, many maintenance tasks require more physical mobility and activity than do many operator tasks. Under motion conditions, the maintainer may find it difficult to perform simple tasks such as pulling and replacing circuit boards, removing screws, or connecting cabling or ducting and almost impossible to perform more complex tasks. The need to move around, and to handle heavy components such as drawers of electronics can result in damage to equipment or injury to the maintainer. Avoiding such problems is a major concern in the workspace layout. While appropriate equipment design can do much to minimize the difficulties, there are also steps that can be takesn in the setup of the workspace, such as using handholds and harnesses. In addition, special attention should be paid to accessibility of equipment and components. Space must be provided to permit the maintainer to open equipment without having to stand where a drawer or cabinet door or other item can be thrown or swung against him. If at all possible, transporting items from one place to another should be avoided. If this cannot be avoided, a properly designed transfer cart, which would include such features as positive quick-setting brakes, and which would be dimensioned appropriately to the work area, is a possible alternative.

Repair Facilities

Equipment repair facilities must receive sufficient attention. Some of the special-purpose equipment that must be used--ranging from soldering irons through torches, drill presses, and pipe wrenches--is inherently unsafe in motion conditions. In general, any object that involves electric voltage, rotary motion, sharp edges, or heavy weights can be dangerous. Use of these items under motion conditions can result in injury to the user and/or damage to the item under repair. If sufficient and adequate means of holding objects being repaired is provided--such as appropriate vises, clamps, drawer holddowns, and the like--repair work can be greatly simplified and the risks of injury reduced. Unfortunately, such provision is often ignored. Maintenance under motion conditions is a difficult situation that merits much more careful attention than it has received in the past.

Design of Living Spaces

This is another design area that has been taken for granted. When personnel environment requirements are ignored in the design and placing of berthing, messing, and other living spaces, personnel may be exposed to environmental factors while off duty that can adversely affect their performance when on duty. For example, many berthing areas are exposed to motion and noise levels in excess of those recommended for long-term exposure. (The existing Navy noise standards for such areas are often exceeded; no standards have been established for motion levels.) In such cases, it is entirely likely that task performance on at least some critical tasks will suffer, and that the performance degradation will increase with the duration of the exposure. If berthing areas are located in those portions of the ship that have greater levels of motion, the performance problems may be exacerbated.

Similarly, the mess area placement should be considered in ship design. Since providing good food service under high sea state conditions is difficult in any case, it follows that placing the mess area in a high acceleration area can only worsen the problem and encourage motion sickness. Similar comments are possible about any living space use. Environmental factors, such as temperature and ventilation, must be considered both in their own right, and in regard to their contribution to motion effects. Since personnel usually spend more hours each day in living spaces than on duty, the effects of living space environment on task performance must be considered.

Walkways and Other "Mobility" Spaces

Here again, consideration is often by default. Proper dimensioning, provision of handholds, avoidance of protrusions, and other normal human factors and safety design features apply. The traditional "footprints on the wall" is not satisfactory. These spaces should not be ignored, particularly since the additional design work required is minimal.

Equipment Characteristics and Design

Use of Standard Equipment Design Data

Present human factors design guides and standards for equipment are not adequate when considering motion effects. As indicated above, there are limitations on workspace volume that restrict the use of such reference data as MIL-STD 1472B. These stricter limitations must be reflected in the design of equipment. Similarly, there are greater restrictions on the design of controls and displays and on communications than are found in the usual human factors data books. The following items will discuss some of the more important equipment design problems from the point of view of equipment design for operation and maintenance under motion conditions.

Visual Displays

The interactions of the vestibular system with the visual and oculomotor systems described earlier are critical to the design of visual displays. Such displays are the most important data source for nearly all systems that are operated by humans. Thus, in designing visual displays for use in motion conditions, consideration must be given to restraints in several parameters. These parameters are described in the following paragraphs.

Location. Because of the need to minimize head motion, primary displays of data should be located at or near the center of the field of view, and secondary displays, as near as possible to the primary display. Multiple primary displays that compete for attention should be avoided; one switchable multimodal display is preferrable so long as no data loss is experienced. In electronic equipment, this can usually be accomplished by good circuit design. When multiple displays must be used, the displays should be centrally grouped to minimize head motion.

Engine monitoring panels or other displays that are usually designed as multimeter scanning displays constitute a difficult design problem. Thus, techniques such as out-of-tolerance warning indicators, switchable meter functions, and division of the monitoring task should be considered as alternatives to the more conventional meter panel. CRT display practice is generally in accord with these recommendations. For example, most CRT monitoring tasks require concentration on a fairly small area, with minimal head movement (unless other task requirements such as control operation or communication require head motion).

Coding. Use of appropriate alphanumeric or other coding on a display can simplify the perceptual and interpretive tasks. By minimizing perceptual load, the sensitivity of the task to motion effects can be reduced. This can be accomplished in many ways, depending on the nature of the data to be extracted from the system. Properly designed go-nogo displays are excellent.

The complexity of the coding must be a major design factor. The larger the number of coding elements, the greater the perceptual and interpretive load. The use of multiple coding dimensions is frequently chosen for conditions of high data rate and/or density. There are no contraindications for this technique in the motion environment.

Relative effectiveness of alphanumerics versus pictorial symbols and/or abstract symbols represents another consideration. Since highly overlearned material is more resistant to motion effects, it appears that the alphanumeric set is the best choice. However, in some cases, an alphanumeric symbol may prove to be less desirable than a pictorial symbol, as the relation between symbol and data may be more readily overlearned and, as a result, may have higher recognition value.

Data Rate and Density. High data rates (frequently changing data) and high data density (number of data symbols per unit area of display) can both result in high error rates under motion conditions. High density often requires smaller symbol size, which may be difficult to accurately perceive under vibration or motion conditions. The Guedry and Holmes (1972) study already referenced shows how such factors as density and rate can affect symbol recognition. At the other extreme, a very low data rate can generate vigilance problems, which can be more severe than normal, due to the fatigue associated with ship motion.

Display Motion. When a display is dynamic (e.g., a television display or a moving needle), degradation can occur under ship motion conditions. This is due to the need to superimpose control of the visual image over the motions of the eye responding to the ship motion. Complex visual tasks are easily degraded. For example, in target-tracking CRT displays and ECM displays, symbolic data, which changes position rapidly, is often superimposed on the screen. Tasks involving crossing and merging tracks are difficult under any condition. Thus, when motion is also involved, errors are even more likely. Sonar "waterfall" displays develop at a slower rate, and may be less subject to motion-induced errors. Meter movements are probably least subject to the self-movement effects. Even so, design for accurate reading of moving meters is still difficult.

Signal-to-Noise Ratio and Detection. Target detection using the CRT display or the "waterfall" display is essentially a problem of finding a signal in a noisy field. The Theory of Signal Detectability, as developed for sensory processes, infers that the limiting factor in most detection situations is an internal noise level or a signal-to-noise ratio in the perceptual sensory system. Higher internal noise levels will require higher display signal-to-noise ratios for the same probability of detection. Examination of the related phenomena of vision under motion conditions indicates that the internal noise figure is higher under these conditions than under normal conditions. Even though habituation should reduce the noise level, it is likely that detection performance will be degraded by motion. For example, the recognition differential of the sonar equation will be greater under motion conditions. Although changes in the display parameters as a function of motion levels may compensate for motion effects, measurement of performance as a function of signal-to-noise ratio is difficult without the availability of a highly sophisticated experimental facility. Studies to quantify the effect of motion on detection are needed.

Color and Illumination. No data are available that indicate that task performance based on color recognition or on illumination is degraded by motion. Similarly, display illumination has not been shown to be a factor. Although human factors design standards appear to be adequate for these parameters, the extremes of the distribution in selecting parameters should be avoided, as the general visual situation is less than optimal, and some effects may exist that have not been documented.

Auditory Displays

The use of auditory displays is much more limited than the use of visual displays. As a result, auditory function under motion conditions has received very little attention. In the one direct measure of auditory vigilance (Jex, O'Hanlon, & Ewing, 1976), the results indicated some performance decrement, but there was great variability among individuals. The task investigated in the study involved both loudness discrimination and monitoring, but no attempt was made to assign decrement to either decreased loudness discrimination capability or increased vigilance "fatigue." The neurophysiology of vestibular function and its relation to auditory systems certainly indicates that the auditory function would be decreased under motion. This is important to the design of all kinds of auditory displays, including speech communications.

Most auditory displays do not involve detection of signal in noise (sonar is the big exception) but, rather, discrimination of pitch, loudness, or pattern. Where alerting signals are involved, the design problem is not too difficult, as selection of highly discriminable parameters, well above minimum levels for detection, can usually be accomplished. Where more complex data transfer is required, the problem can be much more difficult, particularly in situations where auditory pattern perception in poor signal-to-noise ratio conditions is required. For example, parameters of auditory displays involving sonar detection and classification are only partially under the designer's control. We do not know enough about the psychophysiology of auditory pattern perception to reliably predict either the detectability of sonar signals in noise or the speed and accuracy of classification under the best of conditions. When motion is superimposed on an already difficult task, it follows that performance will most likely be degraded.

In speech communications, the direct effects of motion may be less, since the language is highly overlearned in most cases. Although use of limited, standardized vocabularies for critical communications can assist in minimizing errors, some of the higher order interactions may still degrade speech comprehension. Further, attention and concentration may be degraded, with a resulting decrease in communication effectiveness. Design to minimize speech interference and to optimize intelligibility and comprehension is necessary in all cases.

Design of Controls

Mechanical interference is probably the most important motion effect in respect to the operation of control devices. This applies to both hand- and foot-operated controls, which represent the overwhelming majority of control types. Some of the more unusual types, such as head-mounted and eye-motion controls as well as muscle-tension controls, are probably at least as sensitive to motion. The key to control design is the selection of parameters that will satisfy the requirements of the equipment function and good human factors practice and that will minimize or compensate for the error inputs generated by responses to ship motion.

Control Location. The reduction of operational volume of space is of special significance in positioning controls. Ideally, the user of a control should not have to move any large part of the body to reach or use the control. If all controls could be located such that the user could rest his forearm on a solid surface such as an operator chair arm and operate the controls with his fingers, mechanical interference would be greatly reduced. However, normally users must reach, stand, bend, or otherwise move to operate much of the equipment in a ship. Location of controls to minimize body motion, as well as head motion relative to the ship, is critical. Placing controls at or near minimim separation by normal human factors standards should be avoided. Since motion effects are likely to reduce the accuracy of hand placement when reaching for a control, controls should be placed far enough apart to prevent high rates of error.

Selection of Control Type. All else being equal (it rarely is), the use of discrete state controls with detents and stops is preferable to the use of continuous controls. The fewer the number of states or positions on the control, the less the chance of a faulty setting. For example, even though there may be little functional difference between the toggle switch and the pushbutton, we may find that, for a specific panel layout, tnere is a higher chance of accidental activation of a toggle switch than of a push-button. Use of a control involving both hands, such as a wheel, is clearly undesirable. If it is necessary to use this type of control, correct location and force parameter selection can minimize the problems.

Small precision types of control are another problem. With the proper selection of control parameters and a layout that permits bracing of the forearm and hand, such controls can be very effective. On the other hand, if they must be operated at arms length and are very sensitive, the control error will be large. Motor control problems induced by motion tend to exaggerate the normal errors as well as adding those relating directly to the motion parameters. Thus, tactile coding may be less effective than normal.

Force, Damping, and Sensitivity. Selection of these parameters is a critical aspect of control design for ship motion conditions. Since the parameters best suited for use under various nonmotion and motion conditions will often be different, it would be ideal if the operator could vary the parameters as a function of ship motion. Although in some cases such capability is technically feasible, the cost and complexity factors will tend to rule it out. A useful compromise is often possible due, in part, to the fairly broad range over which many control parameters can be selected under normal operating conditions. High sensitivity, as well as use of operating forces at the low end of the range, should be avoided. Increased damping is recommended, since mechanical interference tends to cause superimposed motion on the normal control motion. By proper selection of parameters, some of this superimposed motion may be prevented from affecting the control setting.

While damping and sensitivity apply to continuous controls, the proper force and the use of good detents is important to discrete state devices. There are some advantages to using combined display/control devices such as the illuminated switch, which will be covered in the section on Panel Layout and Design. When continuous controls are needed, it is sometimes possible to provide a multiple function control, with constant parameters or with parameters selected along with the function. In general, however, the necessity to modify motor responses while under motion conditions is to be avoided.

Panel Layout and Design. The need to reduce the functional volume of operating space imposes a number of difficult tradeoff problems on the designer. On the one hand, displays and controls must be more centrally located, while at the same time, it is necessary to use larger displays and provide greater spacing between controls. This problem may be resolved by designing the system to use fewer displays and controls and/or to make use of combined display/control devices such as the illuminated switch.

Panel size is a related problem, as large panels will tend to expand the operating volume and to increase the body, arm, and head movements necessary for control. Since eye movement often follows the hand in controlling motions, especially when normal controlling motions are disturbed by the ship motion, even more risk of Coriolis effect is present. Further, since large panels may require the operator to lift his hand from the chair for control operation, either placing controls on a horizontal console surface or mounting them on the seat should provide the minimal error probability.

Panel illumination may also be a problem. In many ship functions, it is desirable to keep the panel lighting level as low as possible. However, in view of the general degradation of visual function under motion, the use of low light levels may result in higher error rates in reading gauges, meters, or other indicators.

In panel design, simplicity is always the best rule. Under motion conditions, it is even more critical.

Design for Maintainability

Maintenance of equipment under motion conditions is a difficult job at best. Such simple tasks as screw adjustment, drawer removal, and board replacement become difficult if not impossible. Safety problems arise from tasks involving the handling of heavy items or contacting electrical or high temperature points. The need for mobility, the larger number of types of tasks, and the variety of physical locations and postures required of the maintainer create both significant injury risks and opportunities for error. High component density and poor component identification are also common. Bracing points, handhold, and position locks on equipment are often notable by their absence. Maintenance under motion conditions requires much more care in equipment design than is presently given to it. The result is system downtime and impaired mission effectiveness. The following paragraphs discuss some significant design points.

Equipment Access. Access to the equipment and to components within the equipment is a problem inherent in most shipboard systems. Minimum standards for access to components are often ignored. Even when good access to the component is provided, it is often unusable because of poor access to the equipment itself. Motion increases the access problem. Even though access is partly a workspace layout problem, if recognized at the time of equipment design, it is possible to alleviate it by including such features as side or front access doors, providing larger access openings to the interior of the equipment, and by proper component placement. In regard to component placement, it should be remembered that working at arms length or in an unbalanced position is both inefficient and dangerous, and that blind access (without visual contact) to components should be avoided. With mechanical interference present, visual contact is necessary to avoid making contact with the wrong component. Turning the wrong valve or pulling the wrong circuit board will, at best, delay correcting a fault and at worst, compound the original problem. If blind access is necessary, the possible number of components to be contacted must be minimal, and tactile coding should be used.

Removal of heavy components such as drawers of electronic equipment under motion conditions creates another access problem. During these conditions, personnel cannot handle as heavy a load as under nonmoving conditions. Further, the permissible one-man weight standards are lower and, if two men are required, additional access space must be provided. The above represent only a few samples of what can be expected.

In-Place Maintenance Versus Remove and Repair. The two options available to equipment maintainers are (1) to repair primarily in place, or (2) to use the pull and replace technique, with repairs being done at the bench. In some cases, such as pipefitting, the choice is fixed by the nature of the task. In others, particularly when repairing electronic equipment, the choice depends on such factors as the availability of skilled repair technicians and replacement parts. Thus, human factors design will have to work within the framework of the various competing design variables. Often the work of the maintainer is given the least consideration of any of the design variables.

It is rare to have a system whose equipment is totally either remove and repair or repair in place. A mix is far more common. Use of aids such as built-in test and automatic fault location/isolation will be important under both conditions.

For most maintenance tasks, the workbench provides a much more controlled environment, particularly under motion conditions (i.e., if motion has been considered in the work area design). The desirability and necessity for bench repair tend to increase with the complexity and/or difficulty of the task and with the amount of test equipment and tools required. Finally, bench repair eliminates the need to transport test equipment to the (often space limited) operational area. One disadvantage of bench repair is the necessity to disassemble the operational equipment and bring it to the bench area, which potentially adds to the downtime of the system. In view of the number of variables involved, no firm general recommendation can be made. Good analysis is needed, and the right decision may have significant effects on the ability to maintain the equipment during difficult motion conditions.

Maintenance Aids and Automation. Although major advances have been made in recent years in developing aids for performing maintenance on electronic systems, the same cannot be said for mechanical, hydraulic, high pressure steam, or other nonelectronic systems. In many cases, maintenance requirements for such systems are identical to those for operational design. Unfortunately, whether for operation or for maintenance, these requirements are ignored more often than not when nonelectrical systems are designed. This is a real problem, since the risks associated with incorrect maintenance of such systems are critical. Failure of steam pressure, water pressure, and hydraulic systems not only can cause operational problems, but also are high injury risk conditions for both operators and maintenance men. Errors in preventive and corrective maintenance contribute heavily to these risks, and the presence of ship motion is an additional risk factor.

Improved maintenance aids can play a significant role in reducing these risks. In systems that include automatic fault isolation and location, repairs are accomplished by removing and replacing circuit boards or other replaceable units. The units replaced may be either thrown away or repaired at a shop facility (not necessarily on board the ship). Other maintenance aids include color coding and/or keying of connectors to prevent incorrect board insertion. Although some of these concepts can be carried over to non-automated systems, this is seldom done.

Since the chance for error is increased under motion conditions, any maintenance aid capable of reducing the chance for error should be considered in the design. Such aids include shape coding of valves or other control handles, proper location of accesses, etc.

Task Characteristics and Design

Task Design

Task design and/or selection should be modified to accommodate motion conditions, usually by reduction of task load and complexity. If this is not possible, other means such as modified task distribution and increased automation or equipment function must be considered. In any case, task design must be initiated at an early phase of the design process. Once the functional characteristics of a system are fixed and reflected in the hardware design, task design and modification are difficult or impossible. Review of the previous sections on Physiological Responses to Motion and Vibration and Behavioral Effects of Ship Motion will indicate some types of modifications that may be necessary.

Task Loading and Complexity

Modern weapons and support systems, including the ship itself, are often more difficult to operate and maintain than the older designs. As a result, the work (task) load on personnel has become more complex and demanding--in terms of both criticality and response time--and the potential for degradation of performance due to motion has increased. Perceptual overload and cognitive errors can lower the overall effectiveness of a ship in providing inputs to its operational and weapons systems, even where highly automated data systems are involved. Unfortunately, reduction in workload and complexity may be difficult to achieve in an environment which is personnel limited, and in which available personnel are functioning at below normal levels due to motion.

Complicating the situation is the problem of fatigue. For example, normal watchstanding times do not consider such factors as fatigue generated by motion, which may have a severe effect on performance of complex tasks. *To minimize the problem,* tasks must be designed for minimal complexity and for lower than maximum workload. Where critical tasks are involved, it may be necessary to design performance checks for use in detecting any deterioration in performance that could adversely affect the ship. Dividing a task load among personnel is always a consideration where task load is involved, but this may cause degradation in communication and team function, resulting in less system effectiveness than would normally be expected. Replacing personnel functions with machine functions may result in excessive equipment cost and complexity that would negate the expected gain in performance, and automation is not appropriate to many tasks requiring judgement or decision making. Task loading and complexity are among the most difficult problems facing the designer considering ship motion.

Watchstanding

Since fatigue due to motion effects is a problem, modification of the normal times for watchstanding may be required. In some tasks, such as

CRT monitoring tasks that include the search function, it may be necessary to limit performance time to a short time period. This would mean that more personnel would have to be trained to perform the critical functions. Such cross training is not often available at present (see the section on Personnel Factors). In heavy motion conditions particularly, frequent changes of personnel and rotation among tasks are required, as the limited available personnel will be further reduced by the number that are actively seasick. Distributing the critical functions among personnel may reduce the need to modify watch-standing times. This will be determined by the content of the task and its relation to other critical tasks performed by the ship during exposure to heavy motion conditions.

Design of Task Content

This is the area where much of the payoff in considering the problems of task design is found. Obviously, task content is central to the consideration of the previously discussed items. By proper shaping of task content and by selecting task components in conjunction with the equipment design, it is possible to minimize the effects of motion on task performance. For example, if the visual task can be designed to minimize perceptual loading, it will be less sensitive to motion, and the total task should benefit. If any engine monitoring task must be designed, this can be achieved by use of (1) a number of gauges or meters, whose scale values must be read individually, (2) meter tolerance bands, or (3) alerting signals. Each of these choices reduces the perceptual load in the above order. In the last case, meters need only be examined when a fault has been detected. Thus, meter reading effort and error probability are reduced to a minimum. Data complexity is not provided until the time it is actually required.

Similarly, many tasks can be simplified by examining their components. Frequently personnel will indicate that they need information that is really not of any use. This will also be true in respect to communication links and control functions. Any attempt to reduce the loading by designing the task to remove the unnecessary elements may be perceived as threatening and degrading to the importance of the work performed and to the individual performing it. Even when the designer uses great tact, this problem may occur. Unfortunately, there is no certain way of avoiding the problem. A thorough task analysis is required to make the task components both simple and valid in achieving the intent of the overall task--a superficial analysis may miss the necessity for some data or control that is used in a nonobvious manner. The practical knowledge of operational personnel can be a great assistance to the design analyst in improving existing tasks and in designing new tasks. The potential payoff in reduced motion effects is great, and worth the effort of a thorough job.

Personnel Factors

Personnel Selection

At present there is little preselection of personnel, either for sea duty or for specific tasks at sea as a function of the motion environment. A few individuals that show high susceptibility to motion after exposure may be medically excluded from sea duty. However, at present, there is no satisfactory means of determining in advance those personnel who will be most affected by motion, other than by exposing them to motion in a simulator, which is not satisfactory as a standard selection tool. While paper-and-pencil tests have had some success in predicting the susceptibility of student pilots to aircraft-induced motion effects (Kennedy, 1975), this technique has not been applied to the much wider range of personnel and environmental conditions represented by sea duty. Although it is possible that some physiological measures presently under investigation will correlate well with motion susceptibility, at present there are no good predictors of either susceptibility to motion sickness or to motion effects on task performance. Further, although it is often assumed that low susceptibility to motion sickness implies less degradation in task performance when exposed to motion, this assumption has not been proved. The result is that the designer must assume that the personnel on the ship are essentially an unselected group in terms of susceptibility to motion effects.

Shipboard Experience

Past experience of ship motion is a modifier of response, as discussed in the section on Habituation to Motion. However, experience is no guarantee that the individual is less susceptible to seasickness. For example, Admiral Lord Nelson was famous for becoming sick every time he went to sea. The designer simply cannot count on the past experience of a crewman to help maintain performance levels. Thus, experience of the crew must be discounted as a design factor.

Motion Exposure Training

It has been suggested that training personnel by exposing them to increasing levels of motion will provide protection against motion at sea. However, there is no assurance that this does in fact occur. For example, the habituation data indicates a high degree of specificity of learning. Collins (1974) found only limited benefit in reducing motion effects when personnel are transferred to a new motion environment. Thus, it appears that the use of motion training is of limited value at best and is both time-consuming and expensive.

Task Training

Training provided for the tasks performed aboard ship ranges from sending personnel to formal schools to giving them on-job training, with little or no formal instruction and sometimes only limited supervision. Even in the formal schools, the training often does not offer much assistance relative to motion-generated problems. In some schooling for complex systems, training may last 26 weeks or longer. During that time, the emphasis is usually on maintenance, much of which is performed using paper-and-pencil rather than "hands on" the equipment. Equipment operation may only receive very limited consideration during the school, even when the operator tasks are fairly complex. This type of balance is unfortunate when considering motion effects. It was mentioned earlier that tasks that have been practiced to a high degree of proficiency (overlearned) are more resistant to motion effects. This applies to both operating and maintenance tasks. "Hands on" training should be emphasized in development of system training since it will not only provide better system performance under nonmotion conditions, but also, for most tasks, may be one of the most effective means of maintaining performance during heavy ship motion (O'Laughlin, Brady, & Newsom, 1968). This practice should be maintained during the time at sea, and may be combined with the cross training discussed in the next paragraph.

Cross Training

Presently, the degree of cross training provided is limited. The Navy has, and will continue to have, only limited numbers of personnel to man its ships. If motion effects reduce the numbers due to motion sickness and reduce performance due to the lower effectiveness of those not outwardly seasick, mission capability may be reduced to a dangerous degree. Cross training of personnel on the more critical and more difficult tasks is one way to minimize the likely loss of effectiveness. Whether the cross training should be accomplished on board the ship or be done at formal schools is not covered here. The problem is finding a supply of personnel who can perform critical tasks satisfactorily under adverse conditions. Cross training can help accomplish this goal, since it permits more flexible scheduling of watchstanding and will provide a source of personnel to compensate for loss due to sickness or injury. Finally, it may provide personnel who can be used for error checking in critical tasks. The potential for cross training has not been exploited for aiding motion problems but it should be.

Individual Differences

Here is entered the Great Unknown. It is well known that individuals differ greatly in their responses to motion. Why these differences exist, and how the response can be modified by psychological or emotional variables are matters of pure speculation. In a small percentage of the population, neurological factors are responsible for their susceptibility to motion (or lack of it). Frequently, the anecdotal literature talks about how variables such as "motivation," "esprit de corps," "dedication to duty," "boredom," "interest," etc. can affect ability to perform under motion conditions. None of these vague terms really tells us anything beyond the fact that motion response can be modified by factors that are apparently internal to the individual and which are not obviously neurological. In this state of ignorance, it is not possible to design around the differences beyond the general rule that it is better to be prepared for the worst.

It is probable that there are both physiological and psychological response patterns that can account for the individual differences. The manner in which vestibular data is processed by the brain and the psychological stress associated with motion may be prime candidates but, in the absence of experimental data, it is not possible to evaluate the sources or dynamics of individual differences. The large range of differences creates a problem when attempting to evaluate the effectiveness of a design in minimizing motion effects. Grouping of data among individuals is likely to be invalid. It is better to use each subject in a validation (or other) study as his own control, with proper nonmoving baselines established, learning effects considered, and pre- and posttests used as necessary. With good baseline data under stationary conditions, relative degradation levels due to motion can be established for each individual. Until more is known about the dynamics of motion response and the interactions that account for individual differences, this will remain one of the biggest problems for the ship/system designer and researcher.

DISCUSSION

In preparing this report, the most surprising finding was the limited extent of data available. Despite the continuous exposure to motion conditions and the many problems experienced by ships at sea, there has been no organized effort or study directed at determining the effects of motion on performance. Motion data on ships is not generally available. Techniques for measuring performance in the shipboard environment are lacking, and the introduction of the new high speed, nondisplacement designs may present an entirely new set of (presently unevaluated) performance problems. One major reason seems to be a lack of communication (with some exceptions) among the different groups having an interest in aspects of ship motion. Naval architects and marine engineers consider the motion of the ship in terms of hull shape, weight distribution, stability, and other physical response parameters. Equipment designers generally lack any useful guidelines, and consider motion problems beyond engineering techniques. The medical personnel usually view the problem in terms of motion sickness and the use of drugs for its prevention and alleviation. Human factors people have seen the performance problem, but lacked data that could be interpreted in terms of human factors design. Finally, since the physiological studies of the vestibular system have been largely neuroanatomical, neurophysiological, and biomechanical in orientation, their findings are not readily applicable to operational problems or applied design.

In the absence of communication among these groups, the necessary pooling of data concerning the several aspects of the problem has not occurred. As a result, the ship commander looking for assistance in maintaining his ship's operational effectiveness in bad weather has recieved no help. The need for an integrated research program is evident. An outline of the research requirements is provided in the Recommendations section of this report.

Some reduction in the effects of motion on task performance can be achieved by good design with ship motion in mind. Greater reduction can no doubt be achieved when better data is available. At some future date, it may be possible to predict changes in performance capability as a function of the motion of a specific ship. At that point, precise "tuning" of the tasks to motion will become possible. The essential techniques necessary for developing this capability are within the state-of-the-art. With an adequate research program, the goal is possible.

In evaluating performance as it relates to design, a word of warning about the use of antimotion sickness drugs is necessary. Many of the drugs most effective in preventing motion sickness also have potential for causing serious behavioral effects (see Graybiel, Wood, Knepton, Hoche, & Perkins, 1975; Boland & Grinstad, 1951). If personnel are using these drugs, performance may suffer greatly. It then becomes necessary to decide whether the performance decrements due to motion sickness are more severe than those generated by use of drugs. Unfortunately, no data has been obtained on the severity of drug degradation on performance relative to degradation without drugs. One of the most common side effects of many motion sickness drugs is drowsiness. In the Graybiel and Wood study referenced above, one subject even fell asleep during the exposure to motion and could not complete his tests. While this may be an extreme case, the indications are that the behavioral effects of antimotion sickness drugs are significant and should be more fully evaluated.

A document such as this cannot answer all the questions regarding motion and performance that will be raised in the course of designing a ship or shipboard system. Frequently solutions to the problems will be found elsewhere, if at all. This report cannot be as complete or detailed as desired, since the basic data do not exist which would permit completeness and precision. What this report is intended to do is to provide for the first time an integrated approach to the consideration of human performance problems under conditions of ship motion. By including some of the basic physical and physiological background, as well as the behavioral material, it is hoped that the designer will have the tools to interpret the problems encountered in terms of these dynamics, and thereby obtain assistance in solving the design difficulties.

CONCLUSIONS

The conclusions to be drawn from this report and its development are simple and evident and will not require extensive discussion. They are listed below.

1. Ship motion can and does generate problems in task performance.

2. It is possible by proper design to minimize task performance degradation caused by ship motion. Hopefully this report will assist in the design effort.

3. The performance effects of ship motion have not received adequate attention from the Navy or from ship and equipment designers in the past. New ship designs are creating new motion parameter exposures and new performance problems.

4. There is a serious lack of communication among the researchers, engineers, doctors, and others with an interest in the ship motion problem. This has been a main factor in the failure to develop an integrated approach to solving the problem of ship motion effects on performance and personnel.

5. An adequately organized and funded research program is necessary to solve the problems of motion effects. While the problems of performing this research are significant, the techniques are largely within the *state-of-the-art*, and the potential payoffs are very large.

These conclusions may not represent any new conceptual breakthrough. This does not make them any less real and does not make the problem go away. Good design, backed by research, can contribute to maintaining and improving mission effectiveness under conditions of ship motion.

RECOMMENDATIONS

The most important recommendations are on the requirement for research. At present, the data base and theoretical structures regarding the effects of ship motion on personnel and performance are very weak. As a result, there is no way in which assistance can be provided directly to a ship commander in predicting performance decrements on critical tasks as a function of sea state. In fact, there are presently no reliable means of measuring such decrements in the operational system under operational conditions. In view of the potential significance of motion to mission effectiveness in present and future ships, the following recommendations are presented as a guide to improving Navy ability to predict, measure, and minimize motion effects on performance.

1. A research program should be initiated which draws upon the variety of technical groups that have an interest in ship motion and its effects, including naval architects and marine engineers, medical personnel, human factors personnel, hardware and system engineers, operational and tactical personnel, and others as appropriate.

2. This program should be managed at a level that will permit the development of an integrated approach to the problem. Extensive communication and interaction among the various disciplines involved is absolutely necessary. One of the major difficulties at present is the inability of researchers from one technical area to obtain data from another area, at the right time and in a useful form.

3. Some major technical goals for the research program include:

a. Development of a data base of ship motion data for both conventional and high-speed ships.

b. Development of techniques for measuring performance quantitatively under operational ship conditions, without undue interference with task performance.

c. Determination of the interaction effects of motion in combination with other environmental factors such as vibration, noise, and temperature.

d. Development of measures that permit prediction of individual sensitivity to motion effects as a tool for selection and for performance prediction.

e. Determination of the effects of antimotion sickness drugs on task performance.

f. Development of a predictive performance model, based on the components of motion and data on human response to motion, that can be applied in an operational situation to determine performance decrements in critical tasks under a given set of experienced motions.

g. Evaluation of the effectiveness of task and motion training, overlearning of tasks, and other methods of preventing performance decrements.

h. Provision of data to ship designers and naval architects on the types of motion to avoid in ship design to minimize motion problems from the hull response to the sea.

i. Development of personnel assignment, manning, watchstanding, and other administrative procedures to provide the best distribution of personnel in the ship for mission performance under motion conditions.

j. Development of better human factors data for task, equipment, and workspace design for the ship.

4. As the research results are obtained and put into the proper form for application, appropriate implementing documentation should be prepared to ensure that new data are considered and utilized properly and are made available to the users on a timely basis.

Implementation of the above recommendations requires a long-range effort, but the potential payoffs in improved mission effectiveness under difficult conditions are large and worthwhile. The essential state-of-the-art exists, and if the Navy makes the commitment to improved performance under motion conditions, the goals of the research effort can be accomplished.

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