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HUMAN FACTORS ENGINEERING PRINCIPLES FOR MINIMIZING ADVERSE SHIP MOTION EFFECTS: THEORY AND PRACTICE

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ABSTRACT

As part of a wider seakeeping program conducted by the David Taylor Naval Ship Research and Development Center, two mission-critical workstations were evaluated for the United States Coast Guard (USCG). These workstations (the communications support center and the communications center) have been specifically identified by the USCG as having exceptional seasickness problems. Five potentially applicable human factors engineering (HFE) approaches to enhance seakeeping through prevention and mitigation of adverse ship motion effects, especially seasickness, were recognized and are discussed in this report in the light of observations made aboard the ship. These are: (1) locate critical stations near ship's effective center of rotation; (2) minimize head movements; (3) align operator stations with a principal axis of the ship's hull; (4) avoid combining provocative sources; and (5) provide an external visual frame of reference at stations where seasickness may seriously impair mission effectiveness. This report relates how the application of relatively simple HFE principles (ideally at the early ship design and arrangement stage) may reduce seasickness and other adverse ship motion effects and so enhance seakeeping.

INTRODUCTION

The accomplishment of naval operations in rough seas and severe weather is of growing concern [1]. In active seas, the crew must endure the adverse effects of low frequency ship motion (mainly heave, roll and pitch). The effects of hull motion on men and equipment can be exacerbated by structural shock and vibration due to slamming and compounded at some workstations by deck wetness, wind forces, and other hazards. Below deck, cramped quarters, noise, vibration, and additional environmental factors may add to the ship motion effects by contributing to cumulative fatigue and to enhanced sensitivity to motion. These factors can severely degrade both individual and group performance and impair safety [2]. Above relatively moderate thresholds (about ±4° degrees of roll), hull motion has a progressively deleterious effect upon shipboard activities [3]. Tasks are interrupted, take longer to perform or are postponed, or require extra effort or additional crew to perform them. These effects escalate rapidly as the amplitude of the motion increases until, in severe conditions (more than ±10° of roll), much ship's work may be forced to a halt [3].

Traditionally, questions of seakeeping have focused largely on major design features of ships (e.g., ship size, hull form, propulsive powers, and top hamper). This scope, however, may usefully be broadened to include human factors analyses of ship arrangements and the adverse effects of ship motion on personnel and shipboard activities. Such features as the location and arrangement of workstations may influence combat effectiveness as much as major ship design features. This report considers human factors engineering (HFE) principles for enhancing seakeeping through the prevention and mitigation of adverse ship motion effects in general.

However, this project was commissioned primarily to address motion sickness and related effects at two specific workstations.

SHIP MOTION EFFECTS

The best known result of ship motion is seasickness. Motion sickness, including seasickness, may be defined as a constellation of symptoms and signs caused by exposure to low frequency (below 1 Hz) passive oscillation or perceptually incongruous acceleration (e.g., apparent visual motion without physical movement) [4,5]. Common symptoms and signs of motion sickness are nausea, headache, pallor, sweating, dizziness, lassitude, drowsiness, lack of concentration, and severe loss of motivation, although no one of these effects is invariably present [6]. The same syndrome is recognized by other names in other contexts (e.g., airsickness in aviation).

Motion sickness is distinguished from mechanical motion effects by its physiological character and associated deleterious effects upon thinking and motivation [6,7]. Motion sickness is also unlike the direct mechanical effects of ship motion in its time course. Mechanical disturbance is immediate and persists only while the motion persists. Motion sickness, on the other hand, takes time to develop and its consequences may persist long after the provocative motion has abated [8]. Also differing from mechanical disruptions, some motion sickness effects (e.g., debilitating nausea and vomiting) usually decline with continuing exposure (habituation). However, other motion effects, including chronic fatigue, lassitude, alterations in postural function (e.g., unsteadiness of stance or gait), impaired motivation, and difficulty in concentrating, may continue for weeks, if not indefinitely [7,9]. This condition, which has been termed the "sopite syndrome," may have long-term, continuing effects on crew performance in rough seas.

APPROACHES TO MINIMIZING ADVERSE MOTION EFFECTS

A wide variety of methods have been proposed for minimizing the adverse mechanical and sickness effects of ship motion on crew. Table 1, which is based upon concepts reviewed by Guignard [10], provides a synopsis of such methods categorized by general approach. Two such approaches are potentially applicable to ship design and arrangements: (a) ship design and systems engineering and (b) human factors engineering. Application of the second of these toward minimizing motion sickness is the specific concern of this report. In addition to these basically engineering methods, other

TABLE 1. Approaches to preventing or mitigating adverse effects of ship motion on crew.

Approaches	Methods
A. Ship Design and Systems Engineering	1. Hull Design 2. Ship Arrangements 3. Operation and Maintenance of Machinery and Equipment 4. Motion Attenuation Devices (E.G., Fins) 5. Vibration Isolation & Damping Treatments 6. Isolation of Special Stations
B. Human Factors Engineering	1. Arrangement and Design of Crew Space 2. Location and Orientation of Crew Stations 3. Work & Task Design 4. Display/Control Design & Placement 5. Optimization of Ship Environmental Factors 6. Individual Anti-Vibration Devices
C. Enhancing Natural Human Resistance to Motion Effects	1. Optimization of Work/Rest & Duty/Leave Cycles 2. Habituation & Oscillatory Motion Training 3. Specific Task Training in Motion Environment 4. Crew Selection 5. Provision of Adequate Sleep
D. Modifying Adverse Physiological Reactions to Motion	1. Optimization of Crew Fitness & Morale 2. Optimization of the Immediate Physiological State 3. Medication
E. Operational Solutions	1. Strategic and Tactical Planning to Minimize: (a) Routing Through Rough Motion Areas (b) Distance/Time Spent in Rough Conditions (c) Number of Units Simultaneously Exposed (d) Necessity to Resupply in Heavy Seas 2. Tactical Maneuvering Compromises of: (a) Speed (b) Heading (c) Stopping Time at Sea

treatments (Table 1, C-E) extending human factors approaches may be applied when engineering solutions are ineffective, inapplicable, uneconomic, or require augmentation. Table 1 is presented here to provide the broad context of this report.

Purpose

The two main goals of this report are: (1) to present a set of five HFE principles for minimizing adverse ship motion effects (primarily motion sickness) and (2) to illustrate their potential application aboard ship. The latter has been accomplished by an analysis of two contemporary workstations aboard a United States Coast Guard (USCG) cutter where substantial motion sickness problems have been encountered. The purpose of this effort is to draw attention to the potential benefits of applying HFE principles to naval architecture and ship arrangements to enhance operational performance.

HUMAN FACTORS ENGINEERING PRINCIPLES FOR MINIMIZING MOTION SICKNESS

Five principles for preventing or reducing motion sickness and its effects on crew performance are described in this section. The basis for each principle is outlined and applications are discussed.

Principle I. Locate Critical Stations Near Ship's Effective Center of Rotation

Basis.

The combined nauseogenic effects of heave (0.25 Hz; 0.11 g rms), pitch (± 15°), and roll (± 15°) have been shown to be of the same magnitude as heave action alone when seated operators, with their head movements restricted, are located near the center of rotation [11,12]. However, at an off-center location, the rotational motion components give rise to a substantial vertical displacement (effective heave) component. The magnitude of this component is proportional to distance from the center of rotation, in accordance with the principles of leverage. Combined with ship heave this added heave component due to rotation may be expected to increase the frequency of sickness over that for ship heave alone [12,13]. Several observations under operational conditions substantiate these scientific findings. Differences in resultant ship motion in the same sea conditions have been shown to have significant seakeeping implications [14].

Comments.

For use in comparative evaluations, a relative motion sickness index (RMSI) may be estimated for various locations in a ship using a four-step procedure. First, the coordinates of a location of interest (X_b, Y_b, Z_b) are identified relative to those of the ship's effective center of rotation (0,0,0). Second, the motion time-course for a given ship, speed, heading and sea state is specified for the ship's effective center of rotation. This time-course ($t = 1, \ldots, T$) will be sufficiently described by roll (θ_t), pitch (ϕ_t), and heave (Z_t) components in most cases. Third, transformation using rigid body mechanics is used to estimate the heave experienced at the selected location. For roll and pitch less than about ±20° (±0.3 radians), the instantaneous heave displacement (Z^*_t) in appropriate units (e.g., meters) at any time (t) may be approximated by:

$$Z^*_t = Z_t + \phi_t X_b + \theta_t Y_b + (1-\theta_t^2/2)(1-\phi_t^2/2)Z_b \qquad (1)$$

where X_b, Y_b, and Z_b are location coordinates in the selected unit and θ_t and ϕ_t are in radians. This small angle approximation is a modification of one suggested by L.S. Lustick (personal communication, 1984). Lastly, the time-course of Z^*_t ($t = 1, \ldots, T$), must be analyzed spectrally. The RMSI is defined by the integration of the product of the (Z^*_t) power spectrum and the inverse of the 4-hour motion sickness index (MSI) function described by McCauley and Kennedy [15].

The RMSI may be applied for the estimation of relative motion sickness incidence at various vessel locations. Preliminary reports by D.P. Hansen (personal communications, 1982, 1983) and Baitis et al. [2] indicate that the 2-hour MSI of McCauley et al. [12] correlates with observed incidences of motion sickness at sea. However, the 2-hour MSI can underestimate the absolute incidence because personnel stand 4-hour or longer watches at sea. The RMSI is based on the 4-hour MSI to compensate for this underestimation.

Principle II. Minimize Head Movements

Basis.

Head stabilization (i.e., reduction of both voluntary and passively induced head motion) has long been reported to reduce motion sickness, with degree of sickness reduction being correlated with degree of stabilization [5,9,16]. This effect results from reduction of the complexity and magnitude of inputs to the motion-sensing organs of the inner ear (vestibular system). In addition, head stabilization reduces the probability of moving the head to an alignment which is particularly provoking (see Principle III) and provides for more constant sensory inputs (which enhances habituation) [17].

Comments.

Minimization of head movement requires careful design of workplace configuration. Primary displays and controls, for example, are best grouped and located on a central panel to minimize the necessity for frequent, rapid or large-angle head turning. Multipurpose display-control systems may be recommended for this purpose, and guidance for their design may be found in HFE handbooks, e.g., [18]. In addition to display and control location, consideration should be given to methods of stowing tools and other items so that they remain within close reach (i.e., not requiring bending or twisting at the waist). Picking up a dropped item (even a pencil, for example) requires large and complex head movements which may needlessly provoke sickness. Head stabilization for seated operators may be promoted by head rests and seat design features. Consideration should be given to seat and workplace design for comfortable, long-term sitting and, consequently, minimization of unnecessary body movement due to restlessness. A number of reviews discuss workplace features that promote both productivity and long-term comfort, e.g., [19].

PRINCIPLE III. ALIGN OPERATOR WITH A PRINCIPAL AXIS OF THE SHIP'S HULL

Basis.

Motion sickness development and related effects (e.g., disorientation and vertigo) are exacerbated by complex or off-axis angular motion inputs to the vestibular system, particularly when head movement is unconstrained [5,20,21,22]. Operators may lose gaze-stability and miss visual signals if vestibular disruption is sufficiently severe [23,24]. Alignment with a principal axis of the vessel (preferably the longitudinal axis) may be expected to result in lessened motion sickness effects and improved performance.

Comments.

A forward-facing orientation along a ship's longitudinal (X) axis has been suggested as less provocative than a transverse (Y) orientation [6], and either is preferable to a diagonal or off-axis orientation. The object of a forward-facing orientation is to minimize head movements across the plane of primary rotation. Maintaining the operator's orientation along the principal axis will also minimize passive head movements (Principle II).

PRINCIPLE IV. AVOID COMBINING PROVOCATIVE SOURCES

Basis.

Reason and Brand [6] have summarized research indicating that multiple provocative sources tend to summate. Hence, a variety of visual distortions and related effects leading to perceptual ambiguity or conflict [25] may be expected to combine with ship motion to increase the likelihood and severity of seasickness. A number of other predisposing conditions (e.g., disordered sleep, hangovers, illness, medication, and exposure to toxic substances) may also be expected to contribute to the development of motion sickness [5]. The summation of effects is consistent with current, widely accepted perceptual conflict theories of motion sickness [26].

Comments.

Kennedy and Frank [5] have noted that sleep loss may be expected to contribute to motion sickness. This is because of the deleterious effects of sleep loss on vestibular (inner ear) adaptation to motion, namely, increased sensitivity and decreased recovery rate [27]. These findings have been confirmed by observations made by others during United States Navy and Royal Navy operations (A.E. Baitis, personal communications, 1983, 1984; J.W. Young, personal communication, 1983). Optimizing the design and location of shipboard sleeping quarters facilitates sleep during rough sea passages and may be expected to retard the development of seasickness.

Visual display terminals (VDTs) frequently exhibit design features that lead to visual discomfort and perceptual disturbances. Visual distortions or ambiguities are particularly likely to induce sickness when motion is involved [6,25]. Smith, Cohen, Stammerjohn and Happ [28] have presented data which suggest development of a syndrome resembling motion sickness with intensive use of VDTs at stationary workstations. The rapidly proliferating use of visually coupled systems at workstations may be expected to intensify this problem in ships.

PRINCIPLE V. PROVIDE AN EXTERNAL VISUAL FRAME OF REFERENCE

Basis.

Visual fixation on an external point or frame of reference has long been recommended as an effective way to reduce motion sickness. Reason and Brand [6], in particular, have suggested fixating on the horizon or some visible landfall. This fixation, they conjecture, is helpful because it reduces involuntary head motion and avoids discordant sensory inputs which are more prevalent when gaze is uncontrolled. Alternatively, it may be conjectured that an external frame of reference provides the basis for the development of a predictive mental model of motion. Consequently, the presence of an external reference can reduce perceptual conflict and promote adaptation to motion. Both hypotheses have led to the suggested use of artificially generated (displayed) external reference frames where views of the outside world are restricted or absent. However, this approach has not yet been implemented aboard ship.

Comments.

A number of alternative display systems may provide effective external frames of reference. The Malcolm horizon [29] offers a relatively simple approach to providing a stable, horizontal reference frame, which may be displayed either in the line of regard or in the peripheral field of vision. Contact analog display (CAD) devices provide a comprehensive external reference which is analogous to that seen under ideal visual flight conditions (at least 10 km visibility) [30].

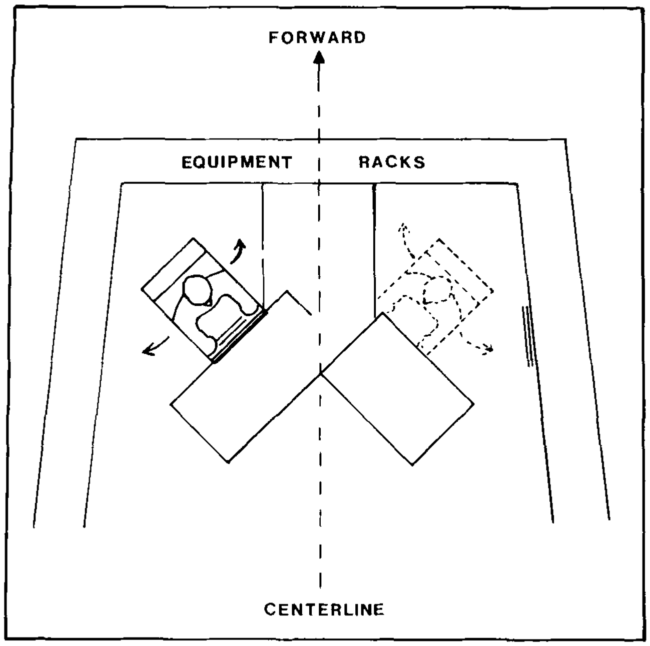

Figure 1. Diagrammatic plan (not to scale) showing approximate relationship of radio operators' stations to the ship's centerline and forward section of the communications center. (Note that the operators frequently stand up and twist around in their seats to attend to equipment in the primary workstation or surrounding racks. See photographs in Figure 3.)

Whatever system is used, care must be taken to avoid perceptual conflict problems such as those experienced in aircraft simulators [5,31]. The Malcolm horizon may be recommended for evaluation because of its simplicity and potential adaptability to workspaces of widely varying size and geometry. Contact analog devices, however, where feasible, are expected to be more effective in reducing vertigo and motion sickness, based on previously summarized research [32].

EVALUATION OF WORKSTATIONS ABOARD SHIP

Two workspaces were evaluated aboard the medium endurance United States Coast Guard Cutter *Bear* (WMEC-901), namely, the communications support center (CSC) and the communications center (CC). This evaluation focused on motion sickness as part of a larger seakeeping project [33] coordinated for the USCG by the David Taylor Naval Ship Research and Development Center (DTNSRDC). The CSC and CC workspaces had been identified by the ship's commanding officer as having relatively high incidences of motion sickness. Supporting this assessment, it was noted that almost 100% of the personnel in these spaces were provided with requested medications (vice 60% for the crew overall) during the 10-day deployment. Within each workspace, a workstation was selected for evaluation based upon officer and crew judgments that it was the "greatest motion sickness problem area." Implicit in these selections was the requirement that the identified workstations were critical to the mission of the ship. Workstations selected for evaluation were operator's station one (OS1) in the CC and the chart table in the CSC.

OPERATOR'S STATION ONE IN THE COMMUNICATIONS CENTER

This workstation is evaluated in three steps. First, location, orientation and other salient features are reviewed. Second, a critique compares these features with the five HFE principles developed earlier. Third, possibilities for redesign are briefly considered.

Salient Features.

Figures 1 and 2 illustrate the orientations of OS1 and its operator. Figure 2 shows a standing operator at OS1 seen from aft; he and the station are at a 45° angle relative to the ship's longitudinal axis. The vertical beam seen toward the right side of this picture is on the centerline (OS1 is just off the centerline). Figure 3 illustrates the variety of positions adopted in performing various communication duties. The upper left panel (A) shows the usual working position which is frequently maintained for several minutes at a time. Not shown here is the VDT which the operator is viewing or the glare from its screen reflected from overhead lights. The remaining panels (B-D) show typical positions adopted while turning to see displays or to reach for controls. Not illustrated are occasional extreme reaches made while standing or control adjustments made after turning toward and reaching past the photographer's position.

Figure 4 illustrates the relative locations of the CC and CSC within the ship. Examining this figure, it may be noted that OS1 is located near the forwardmost part (frame 50) of the CC which lies between frames 48 and 78. Moreover, this station is level with, but far forward of, the effective center of rotation (level 3, frame 120). OS1 may be characterized as facing aft and oriented off the major axes, having noncentralized controls and displays, and being located far forward of the ship's center of rotation.

Figure 2. Standing OS1 operator as seen from aft and about on centerline.

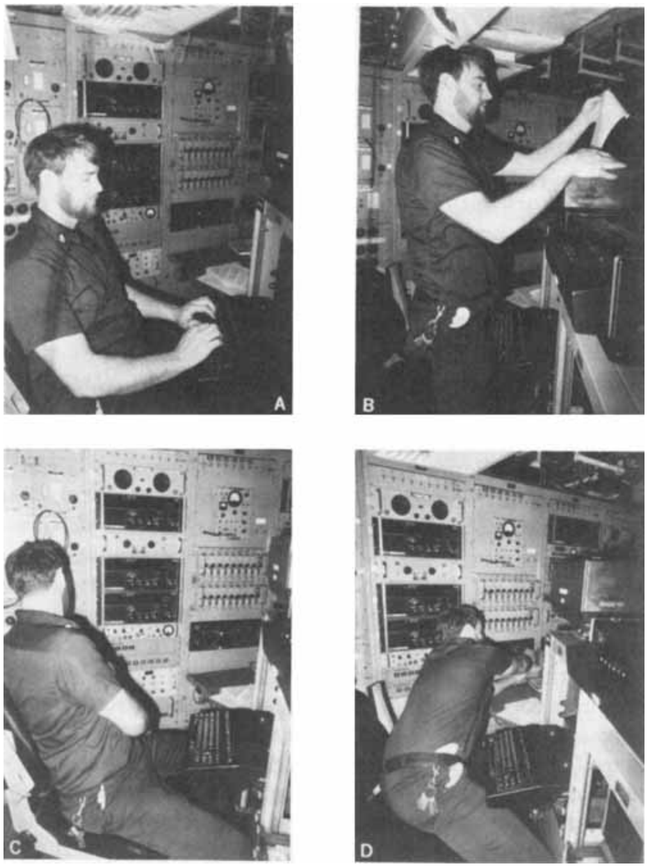

Figure 3. Various positions assumed by OS1 operator in the communications center.

Critique.

The configuration of OS1 is at variance with most of the HFE principles reviewed earlier. In particular, Principle I (location) is compromised by the forward location of the station. In addition, Principles II (minimize head movements) and III (alignment with principal axis) are violated respectively by the extensive turning and reaching needed to work at that station, and by the off-axis, aft-facing position of OS1. Principle V is violated by the absence of a stabilizing visual frame of reference. Only Principle IV (avoiding combinations of incidental provocative environmental factors) was not specifically violated, so far as we were able to observe in the present evaluation. However, the glare from the operator's VDT could possibly have been such a factor, albeit a minor one. The troublesome incidence of motion sickness currently experienced at OS1 might be reduced significantly if the deficiencies in arrangement of this operator station were remedied.

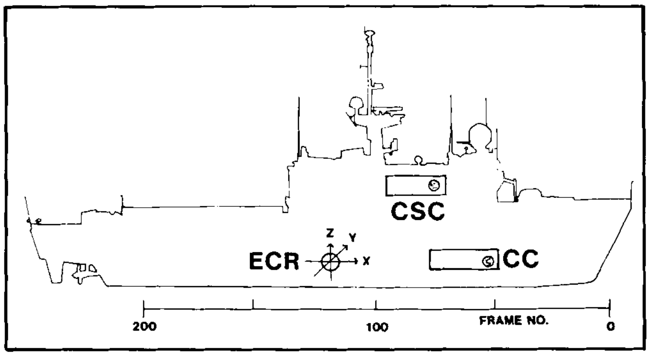

Figure 4. Relative locations of the communication support center (CSC), communications center (CC), and effective center of rotation (ECR).

Redesign Possibilities.

Principle I would suggest moving OS1 (and OS2) aft as far towards frame 78 as possible. Such a relocation would reduce the effective heave motion components by an estimated 33%. It follows from Principles II and III that it would be beneficial to reorient the stations to a forward-facing alignment along the centerline and also to use multipurpose consoles for single panel integration of important or continuously monitored displays and controls. Further, the application of Principle IV would suggest elimination of the VDT glare problem by relocating lights, use of a glare mesh or shield, or a combination of these approaches. Lastly, Principle V would suggest the possible introduction of artificially generated external reference systems to reduce motion sickness.

CHART TABLE IN THE COMMUNICATIONS SUPPORT CENTER

Evaluation of this workstation follows the same three-step procedure as described for OS1 and compares these features with the five HFE principles outlined earlier.

Salient Features.

Figures 5 and 6 depict the relative location of the chart table within the CSC. Figure 4 shows the location of the CSC within the ship. Located at level 02, well above the effective center of rotation in pitch, the chart table is close to the centerline in the forward section (frame 75) of the CSC (which occupies the space from frames 70-90). Figure 5 shows various views of this station and other nearby stations. Looking aft, the first panel of this figure (A) shows the operator, at a 45° angle relative to the centerline, consulting a manual under bright light conditions. During navigation, this is a typical posture, but the operator's stance is constantly changing, while scales are read and plot lines are drawn. Under night vision conditions, the lights visible in the upper corners of Figure 5 (Panel A) provide red light and, for color-coded charts, white light, which is provided from an unshielded fluorescent tube. The user of the table must, under night conditions, continually adjust his body and charts so as not to block these lights. The VDT, mounted above the far left corner of this table and well above eye level, displays computer-generated navigational information. The second panel (B) of Figure 5 shows a view of this station as seen from port to starboard.

The chart table has no provision for holding navigation and other implements. Users have reported enhanced motion sickness while picking up items which have fallen from the table under rough sea conditions. Panel (C) of Figure 5 shows a view of the chart table and adjoining radar station (port side). This radar station provides locational and track information which is integrated at the chart table. The chart table may be characterized as being located forward of, and well above, the ship's center of rotation, and requiring aft-facing body orientations and postures which are continuously shifting and are frequently off the major axis.

Critique.

The chart table workstation does not conform to the principles stated earlier. Principle I (location) is compromised by the forward and high location of the station. Principle II (minimize head movements) is compromised both by the locations of the night lights and the lack of fixtures to hold navigational tools. Principle III (orientation) also is compromised by both the night light placement and the aft-facing orientation of the operator. Further, Principle IV (avoid combining provocations) is compromised by the night lights because bare fluorescent lights are reported to provoke nausea. Last, Principle V is not followed because an appropriate visual reference is not provided.

Figure 5. Three views of the chart table in the communications support center: looking aft (A); toward starboard (B); and port (C).

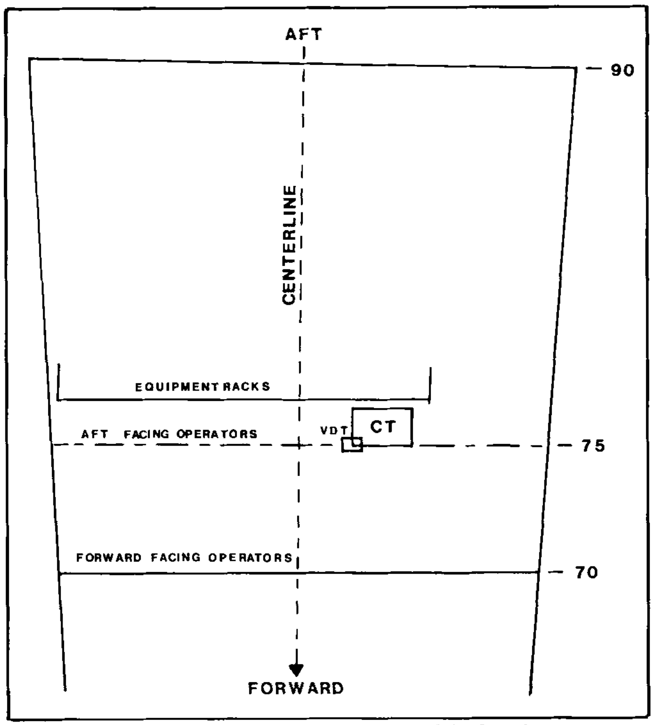

Figure 6. Diagrammatic plan (not to scale) showing approximate position of the chart table (CT) and overhead visual display terminal (VDT) in the communications support center.

Redesign Possibilities.

To adopt Principle I, the chart table conceivably could be moved aft toward frame 90 from its present position at frame 75. This would reduce by approximately 33% the effective heave component due to the ship's rotation in pitch. Moreover, the radar station would benefit from relocation because of its association with the chart table. Adopting Principle II, the night lights could be replaced by overhead directional (red-white) lights. Fixtures or retainers for navigational tools could be fitted to the table, thereby reducing head and body movement and the likelihood of seasickness. Application of Principle III would suggest that the chart table be turned round so that the user would face toward the bow. The need to shift position would be reduced by placing the night lights as described. Further, Principle IV would suggest using incandescent lights in place of the unshielded fluorescent lights. Lastly, Principle V would suggest the use of artificial visual frames of reference for possible reduction of motion effects.

SYNOPSIS

This evaluation suggested how the application of relatively simple HFE principles may reduce seasickness and enhance seakeeping capabilities. Analogous principles for minimizing mechanical interference and related performance-degrading effects can be recognized but are outside the purview of this report, as are several other broad approaches to preventing or mitigating adverse effects of ship motion on crew (Table 1). The present report was aimed at the potential benefits that may result from applying HFE principles to reduce motion sickness and its effects. As illustrated in this report, five HFE principles may be applied to the redesign of mission-critical workstations with histories of excessive motion sickness. Not all redesign possibilities may be feasible in an extant vessel such as the USCGC *Bear* because of overriding practical or budgetary considerations. For example, the costs involved in physically relocating workstations or integrating displays and controls into a single panel may be prohibitive. These and other design possibilities might have been feasible during the early stages of ship planning and design. Because of its potential for reducing ship motion effects, the application of HFE is recommended during initial planning of ship arrangements and design of workstations aboard new classes of vessels.

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