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HUMAN FACTORS IN THE NAVAL ENVIRONMENT: A REVIEW OF MOTION SICKNESS AND BIODYNAMIC PROBLEMS

J. L. Colwell

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

Canada

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

9 GROVE STREET

P.O. BOX 1012
DARTMOUTH, N.S.
B2Y 3Z7

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ABSTRACT

Two types of motion-induced problems affecting human performance in the naval environment are reviewed; motion sickness and biodynamic problems. Methods for predicting the incidence of motion sickness are described and evaluated, and problems associated with modeling complex motions are discussed. References for quantifying habituation are cited and methods for defining the severity of motion sickness symptoms are described. Biodynamic problems are briefly discussed, including the low-frequency, large-amplitude problems of motion-induced interruptions (MII) and fatigue; and the higher-frequency problems of manual control and vision. Methodologies and criteria for evaluating human performance within the systems approach to seakeeping assessment are discussed and topics for future work are recommended.

RÉSUMÉ

L'étude porte sur deux types de problèmes dus au mouvement qui influence le rendement de l'homme dans un environnement naval: le mal des transports et les problèmes biodynamiques. Des méthodes permettant de prévoir l'incidence du mal des transports sont décrites et évaluées, et des problèmes liés à la modélisation de mouvements complexes sont exposés. On donne des références sur la quantification de l'accoutumance et on décrit des méthodes pour définir la gravité des symptômes du mal des transports. Les problèmes biodynamiques sont brièvement exposés; on traite des problèmes à basse fréquence et à grande amplitude liés aux interruptions dues aux mouvements (IDM) et à la fatigue, de même que des problèmes à plus haute fréquence intervenant dans le contrôle manuel et la vision. Les méthodes et les critères permettant d'évaluer le rendement humain (dans le cadre de l'approche des systèmes de l'évaluation de la tenue à la mer) sont décrites et des recommandations sont faites au sujet des thèmes à explorer au cours de futurs travaux de recherche.

Contents

NOTATION

a	vertical acceleration (m/s^2)
ACV	Air Cushion Vehicle (hovercraft)
ANV	Advanced Naval Vehicles (e.g. hydrofoil, ACV, SES)
d	dose parameter used in VI method [97]
f	frequency (Hz)
f_e	encounter frequency (Hz)
FDPB	Fatigue-Decreased Proficiency Boundary, ISO 2631/1 [76]
MIF	Motion-Induced Fatigue
MII	Motion-Induced Interruption
MSI	Motion Sickness Incidence predicted by the "MSI" method of O'Hanlon, McCauley, et al. [126, 109]
SES	Surface Effect Ship
SWATH	Small Waterplane Area Twin Hull (vessel)
t	duration of exposure, MSI method, and, in general, time
T	duration of exposure, VI method
T_o	modal period (sec)
UNREP	Underway replenishment at sea (i.e. from ship)
$\overline{VI}$	Vomiting Incidence per unit vertical acceleration, ($\%/ms^{-2}$)
VI	Vomiting Incidence predicted by the "VI" method of Lawther and Griffin, 1987 [97]
VI_{obs}	Vomiting Incidence: observed by Lawther and Griffin [96]
VREP	Vertical replenishment at sea (i.e. from helicopter)
WBM	Whole-Body Motion
WBV	Whole-Body Vibration
WF	Weighting factor used in calculating VI
ω_e	encounter frequency (rad/s)
ω_o	wave modal frequency (rad/s)
$\zeta_{1/3}$	significant wave height

INTRODUCTION

The ultimate goal of work on human performance in the naval environment is to develop methods and criteria which permit quantitative analysis of human performance and its degradation due to motion-induced problems. The vast amount of literature addressing this and related topics indicates that this goal has not yet been realized, but some contemporary methods and much of the experimental work are of direct relevance. The major purposes for this review are to identify promising methods and experimental data, and to recommend topics for future work.

This review considers two aspects of motion-induced problems: motion sickness and biodynamic problems. Traditionally, these two aspects of human performance have been separated on the basis of frequency; low frequency motions being the regime of motion sickness, and higher frequencies that of biodynamic problems. The contemporary literature shows that this is not true in the naval environment, where significant biodynamic problems are encountered at low frequencies.

The Naval Environment

For the purposes of this review, the naval environment is defined as the combination of naval population and the motions to which it is exposed. These two components may be considered as an integral unit for many purposes, but they must be considered separately when appropriate. The naval population is predominantly male and, for reasons discussed later, it is generally less susceptible to motion sickness than the general public. For any particular type of vessel, the motions experienced are the product of ocean environment, vessel characteristics, and operating procedures.

Arrangement of Review

This review is separated into four parts: Part I considers motion sickness; Part II considers biodynamic problems; Part III discusses performance evaluation and presents recommendations for future work; and, Part IV contains the bibliography.

As indicated by the table of contents for this review, the majority of effort is devoted to motion sickness. Part I introduces theories on the causes of motion sickness, identifies design standards, describes contemporary methods for predicting the incidence of motion sickness and evaluates their applicability for the naval environment, cites a large number of documents which contain useful information for modeling habituation (i.e. acclimatization), describes methods used to classify and assess the severity of motion sickness symptoms, and cites key documents on other aspects of motion sickness not of direct relevance to the naval environment.

Part II on biodynamic problems begins by discussing the "whole-body motion" (WBM) problems of motion-induced interruptions (MII) and long-term, motion-induced fatigue. These WBM problems occur in relatively large-amplitude motions, at frequencies significantly below the traditional 1 Hz division between motion sickness and higher-frequency "whole-body vibration" (WBV) problems. The sections on WBV problems identify topics of particular interest to the naval community and provide a cross-referenced listing of citations, arranged in the following categories: design standards and suggestions for their improvement; manual control; vision; subjective motion; and, ride comfort and ride quality assessment methods.

Part III discusses evaluating human performance in terms of the methodology and types of criteria that may be required. Also, a number of recommendations are presented on modifying and developing methods to model human response and performance in the naval environment, and on devising experiments and conducting at-sea observations to extend the current knowledge base.

Part IV contains the bibliography, which is separated into two sections, one on motion sickness and one on biodynamic problems. The documents in each section are ordered alphabetically, and papers which address both topics are listed in both sections. The documents are also numbered sequentially from the start of the motion sickness section through to the end of the biodynamics section. All documents are cited in the text by number (e.g. [109]), and documents of particular interest are also cited by author and year. Most, but not all, of the documents in the bibliography are cited in Part I and II.

PART I: MOTION SICKNESS

1 Causes of Motion Sickness

Theories on the causes, or etiology, of motion sickness generally agree that the primary cause is "sensory conflict", induced by one or both of the following mechanisms [139]:

1. visual-inertia conflict, where the motion perceived from visual stimuli conflicts with that perceived by the vestibular receptors (i.e. inner ear: semicircular canals and otolith organs);

2. canal-otolith conflict, in the absence of visual stimuli, a conflict in preceived motion between the semicircular canals (angular motion sensors) and the otolith organs (linear motion sensors).

In each mechanism, at least three combinations of sensory conflict exist. For example, in visual-inertia conflict, motion sickness can be induced by:

1. simultaneous but conflicting visual and vestibular information
(e.g. moving the head while wearing an optical device that distorts vision);

2. visual perception of motion in the absence of vestibular stimuli
(e.g. motion sickness in a stationary flight simulator); and,

3. vestibular perception of motion in the absence of visual stimuli
(e.g. elevator sickness).

A variety of references provide further insight on the causes of motion sickness, including: Money, 1970 [120]; Reason and Brand, 1975 [143]; Reason, 1978 [139, 140]; Oman, 1983 [129]; and Benson, 1988 [16]. Additional references of particular interest to the naval community are: Newman, 1976 [124]; Wiker, Pepper and McCauley, 1980 [174]; Muir, 1983 [122]; Thomas, Guignard and Willens, 1983 [165]: and Pingree, 1988 [135].

Before examining the contemporary literature on motion sickness, it is worth emphasizing that the effects of motion sickness on performance at sea can be minimized by proper attention to "human factors design". Newman, 1976 [124], and Bittner and Guignard, 1985 [17], discuss important aspects of designing shipboard workplaces, equipment and tasks. which are concisely summarized by five "human factors engineering principles" [17].

1. Locate critical stations near the ship's effective centre of rotation.
2. Minimize head movements (e.g. [4])
3. Align operator with a principal axis of the ship's hull
4. Avoid combining provocative sources (e.g. [36, 65])
5. Provide an external frame of reference

2 Literature Surveys, Reviews and Bibliographies

Money, 1970 [120] provides a comprehensive review of the motion sickness literature before 1970.

Muir, 1983 [122], provides a " bibliography of the research carried out since the Second World War on motion illness with particular reference to its prevention by drug treatment".

Other reviews and surveys on more specific aspects of motion induced sickness are cited in the appropriate sections of this document.

3 Standards

3.1 International Standard ISO 2631/3

International Standard 2631, Part 3 [77], hereafter called ISO 2631/3, is the ISO standard for evaluating human exposure to whole-body vibration for low frequencies, where motion sickness problems predominate. In summary:

> "This part of ISO 2631" (i.e. part 3) "covers vibration transmitted to the body in the frequency range 0.1 to 0.63 Hz. This part of ISO 2631 applies especially to discrete-frequency and narrow-banded vibration and provisionally to random or non-periodic vibrations within the specified frequency range".

ISO 2631/3 establishes limits on motion using "severe discomfort boundaries". As shown in Figure 1, these boundaries are defined by contours of RMS acceleration (m/s^2) vs. frequency (Hz), for three durations of exposure (0.5, 2.0 and 8.0 hours). Subject to other qualifications discussed in [77], these contours model the expected behaviour of "infrequent travellers" (e.g. ferry passengers). At any particular frequency and duration, the ISO contour defines the acceleration at which approximately 10 percent of the male population "will experience severe discomfort and temporary disability" from motion sickness. ISO also states, "women are apparently more prone to motion sickness than men", by approximately 5 percent (i.e. the ISO 2631/3 contours in Figure 1 correspond to 15% incapacitation for females).

Allen, 1974 [3] provides a useful summary of experiments on motion sickness before 1974, and its recommendations form the basis for much of ISO 2631/3.

Coe, 1987 [26], describes the "B&K human response meter" [23], which determines when ambient motions have provided sufficient stimuli to reach the ISO 2631/3 criteria.

Pingree, 1988 [135], discusses deficiencies with ISO 2631 for application to the marine environment. Since this standard is primarily concerned with motion sickness and/or comfort, the effects on performance are not quantified.

3.2 British Standards Institution BS 6841

The British Standards Institution BS 6841, 1987 [22], presents quantitative guidelines for estimating the incidence of motion sickness (i.e. percent of exposed population who vomit) from a parameter called the "motion sickness dose value" (MSDV). This approach is based on the "vomiting incidence" (VI) method of Lawther and Griffin, 1987 [97]. As described later in Section 4.2 of this review, this method is not well suited to the naval environment.

3.3 Military Standards

US Military Standard for human engineering design criteria for military systems, equipment and facilities, MIL-STD-1472 [168], states (in paragraph 5.8.4.1.1.4):

> "in order to prevent motion sickness, very low frequency vibration should not exceed the limits of Figure 43"

where, the "Figure 43" mentioned above defines contours of 10% sickness incidence for exposure times from 1/2 through 8 hours exposure, using the method of McCauley et al., 1976 [109]. This method is described in Section 4.1, below.

ISO 2631/1, Whole-Body Vibration

International Standard 2631/1 [76], hereafter called ISO 2631/1, is the ISO standard for evaluating human exposure to whole-body vibration for higher frequencies (1 to 80 Hz), where biodynamic problems predominate (degraded motor skills, blurred vision, etc). This standard is not of direct interest for motion sickness; however, methods defined in ISO 2631/1 for reducing complex vertical motions and combined vertical and horizontal motions are recommended for application with ISO 2631/3 (in the absence of better methods).

Von Gierke, 1975 [169], discusses ISO 2631/1, and describes preliminary work on lower frequencies which later became incorporated in the ISO 2631/3 motion sickness standard.

4 Predicting the Incidence of Motion Sickness

This section describes and evaluates the two following methods for predicting the incidence of motion-induced sickness:

1. Motion Sickness Incidence (MSI), O'Hanlon and McCauley, 1974 [126], and McCauley et al., 1976 [109]; and,
2. Vomiting Incidence (VI), Lawther and Griffin, 1987 and 1988 [97, 99].

In both cases, the incidence of motion sickness is expressed in units of percent (%), representing the percent of the exposed population which has been or is being sick, after exposure of a specified duration.

As discussed later in various sections, both methods share three significant problems for modeling the naval environment: (1) they are based on single-frequency experimental data; (2) the ameliorating effects of habituation due to long-term or repeated exposure are not modeled; and (3) the predicted incidence of motion sickness (i.e. percent vomiting) is not necessarily a good measure of human performance.

4.1 Motion Sickness Incidence (MSI)

O'Hanlon and McCauley, 1974 [126], and McCauley et al., 1976 [109], describe laboratory experiments on motion sickness in which humans were exposed to single-frequency, sinusoidal, vertical motions. The resulting empirical model introduced in O'Hanlon and McCauley, 1974 [126], and extended in McCauley et al., 1976 [109], defines a method for predicting Motion Sickness Incidence, MSI (%), from the magnitude, frequency and duration of vertical accelerations.

Following McCauley et al., 1976 [109]:

$$\mathrm{MSI} = 100\,\Phi(z_a)\Phi(z_t')$$

where $\Phi(z)$ is the cumulative distribution function of the standardized normal variable z,

$$\Phi(z) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{z} e^{-\frac{1}{2}\chi^2}\,d\chi$$

The standardized normal variables z_a and z_t' are defined as follows.

$$z_a = \frac{\log(a) - \mu_a(f)}{\sigma_a}$$

$$z_t' = \frac{z_t - \rho z_a}{\sqrt{1-\rho^2}}, \qquad z_t = \frac{\log(t) - \mu_t}{\sigma_t}$$

where a is the RMS magnitude of the vertical acceleration (g), f is the frequency (Hz) of a, and t is the duration of exposure (min). The remaining parameters are defined as follows, to fit the O'Hanlon/McCauley experimental data (i.e. references [109] and [126]).

$$\mu_a = 0.87 + 4.36\ \log(f) + 2.73(\log(f))^2$$

$$\mu_t = 1.46$$

$$\sigma_a = 0.47$$

$$\sigma_t = 0.76$$

$$\rho = -0.75$$

After manipulation, the McCauley et al., 1976 [109], method for predicting the Motion Sickness Incidence, MSI (%), reduces to the following simple equations.

$$\mathrm{MSI} = 100\,\Phi(z_a)\Phi(z_t')$$

$$z_a = 2.128\log(a) - 9.277\log(f) - 5.809(\log(f))^2 - 1.851$$

$$z_t' = 1.134 z_a + 1.989\log(t) - 2.904$$

Values of Φ for positive values of z_a and z_t' can be obtained from Figure 2, or from most standard mathematical handbooks. For negative values of z_a and z_t', the following relationship can be used.

$$\Phi(-z) = 1 - \Phi(z)$$

4.1.1 Evaluation

The MSI method is a simple and concise algorithm for predicting the incidence of motion sickness induced by exposure to sinusoidal, vertical accelerations. The method uses a statistically-based, response surface which models the laboratory observations from two landmark parametric studies on motion induced sickness [109, 126].

The MSI method forms the basis of most contemporary standards for evaluating motion sickness (e.g. ISO 2631/3 [77], and MIL-STD-1472 [168]). Provided it is used within the range of parametric variations on which it is based, the MSI method is not subject to constraints or limitations other than those inherent in the original experiments, and its merit is determined by how well it models the experimental results. The appendix summarizes calculations by the current author in which estimates from the MSI method are compared with the original O'Hanlon/McCauley experimental data [109, 126], and with at-sea observations of Lawther and Griffin, 1986 [96]. These calculations show the MSI method models these data to within an average error of 1 percent, and standard deviation of 6 percent.

Applebee, McNamara and Baitis, 1980 [6], observe that the MSI method significantly underestimates the incidence of motion sickness experienced in trials with USCG cutters; however, the current author suggests that this error is primarily due to the fact that the procedure used in [6] did not correctly model the effects of exposure duration. In brief, these trials were conducted by travelling around an octagonal course, where the length of each side of the octagon was determined by the distance covered in 30 minutes of steaming at a constant speed. The MSI predictions used in [6] are based on 30 minute exposures; however, the actual duration of exposure was very much greater. For example, the 3 to 4 hour transit to reach the trials area is not included, nor are the cumulative 30 minute increments associated with each leg of the octagon. The current author also notes that the motion environment experienced in these trials changed very rapidly (i.e. every 30 minutes), and that the trials were held over four consecutive days. Thus an adequate model of these conditions should consider cumulative exposure duration, changing motions and the effects of habituation.

Section 5 discusses using the MSI method to predict motion sickness incidence in complex motions.

Bittner and Guignard, 1985 [17], describe a method to assess the relative MSI (RMSI) at different positions in the ship, based on 4-hour MSI (to model the 4-hour watch-standing practice); however, since the MSI model used for RMSI does not consider habituation, the proposed distinction between 2-hour and 4-hour MSI predictions is somewhat questionable.

4.2 Vomiting Incidence (VI)

Recent work by Lawther and Griffin, 1987 [97], describes a procedure for estimating the incidence of motion sickness, expressed as the parameter "vomiting incidence", VI (%). This vomiting incidence is, essentially, the same quantity as the McCauley et al., 1976 [109], MSI parameter, but it is identified by the symbol VI to emphasize the difference in methodology by which it is calculated. Note that this Lawther and Griffin method is incorporated in the British Standards Institution BS 6841, 1987 [22].

Following Lawther and Griffin, 1987 [97], VI (%) is,

$$\mathrm{VI} = K\, d = \frac{30}{85}\, d$$

where K is an empirical constant and d is the following "dose" parameter which quantifies cumulative exposure to vertical accelerations.

$$d = \left(\int_0^T a_{fw}^2(t)dt \right)^{1/2}$$

where $a_{fw}(t)$ is the frequency-weighted, vertical acceleration (m/s^2) and T is the duration of exposure (s) to $a_{fw}(t)$. Thus, d has units of (m s$^{-1.5}$), and K has units of (%/m s$^{-1.5}$).

The constant value of $K = 30/85$ (%/m s$^{-1.5}$) is recommended by Lawther and Griffin [97], based on surveys of ferry passengers described in Lawther and Griffin, 1986 and 1988 [96, 98], and on earlier experimental work by McCauley et al., 1976 [109], and Alexander et al., 1947 [2].

The symbol $a_{fw}(t)$ is used here instead of the symbol $a(t)$ used by Lawther and Griffin, 1987 [97], to emphasize that the accelerations should be frequency-weighted before integration. This dose concept was described by Griffin, 1984 [60], for application to higher-frequency, whole body vibration problems, and has recently been applied to motion-induced sickness by Lawther and Griffin, 1986 [96].

Note that earlier work on frequency-domain modeling of motion sickness incidence in complex motions, described by Malone, 1981 [105] (following Jex, DiMarco and Clement, 1977 [80], and Donnelley, 1976 [37]), used a very similar approach, as discussed in Section 5 of this review.

The current author derives the following procedure for calculating Lawther and Griffin's VI using a single-frequency weighting factor.

$$d = \left(\int_0^T a_{wf}^2(t)dt\right)^{1/2} \approx \left(\int_0^T a^2(t)dt\right)^{1/2} \mathrm{WF}(f_m) \; = \; a_{rms}\sqrt{T}\,\mathrm{WF}(f_m)$$

where $a(t)$ is the un-weighted vertical acceleration (m/s^2), a_{rms} is the un-weighted, RMS vertical acceleration (m/s^2), and $\mathrm{WF}(f_m)$ is Lawther and Griffin's frequency-weighting factor (dimensionless), applied at the modal frequency, f_m, of the acceleration spectrum.

For narrow-banded motions (as defined in Section 5), this approximation should be very good, and for single-frequency sinusoidal motion, it is exact. This approximation for broad-banded motion is briefly discussed in the following section. In any case, this approximation provides a convenient simplification for describing the Lawther and Griffin VI method.

At any frequency, f, the weighting factor, $\mathrm{WF}(f)$, is defined as follows.

$$\mathrm{WF}(f) = \frac{\overline{\mathrm{VI}}(f)}{\overline{\mathrm{VI}}_{MAX}} = \frac{\overline{\mathrm{VI}}(f)}{23.0}$$

where $\overline{\mathrm{VI}}(f)$ is Lawther and Griffin's "normalized vomiting" and $\overline{\mathrm{VI}}_{MAX} = 23.0$ (%/ms^{-2}) is the maximum value of normalized vomiting. $\overline{\mathrm{VI}}(f)$ is calculated as the ratio of observed vomiting incidence, $\mathrm{VI}(f)$, to acceleration, $a(f)$.

$$\overline{\mathrm{VI}}(f) = \frac{\mathrm{VI}(f)}{a(f)}$$

Figure 3, following Figure 8 of [97][1], defines $\overline{\mathrm{VI}}(f)$ for an exposure duration of 2 hours, based on "normalized" experimental data of McCauley et al., 1976 [109]. Also, this figure shows Lawther and Griffin's frequency-weightings, defined as line-segment approximations to the experimental data [97], from which the value $\overline{\mathrm{VI}}_{MAX} = 23.0$ (%/ms^{-2}) is derived.

$\overline{\mathrm{VI}}(f)$ can be calculated as follows.

$$\overline{\mathrm{VI}}(f) = 10^{\{A\log(f) + B\}}$$

where A and B are the slope and offset of the approximating line-segments shown in Figure 3. Table 1 shows values for A and B, calculated by the current author from a re-analysis of the original data in McCauley et al., 1976 [109], using the method described above.

After manipulation, Lawther and Griffin's method [97] for calculating vomiting incidence, VI (%), reduces to the following simple equation (for single-frequency and narrow-banded motions).

[1]Section 4.2.2 describes corrections to [97] which are incorporated in Figure 3

Table 1: Coefficients A and B for Calculating $\overline{\mathrm{VI}}$

Frequency (Hz)	A (log (%/m s^{-2}) $\log^{-1}$ (Hz))	B (log (%/m s^{-2}))
0.028 to 0.105	2.228	3.459
0.105 to 0.129	0.928	2.187
0.129 to 0.270	0.0	1.362
0.270 to 0.495	-2.060	0.191
0.495 to 0.850	-3.490	-0.246

$$\mathrm{VI} = 0.0153\, a_{rms} \sqrt{T}\, 10^{\{A \log(f) + B\}}$$

where a_{rms} is the RMS vertical acceleration (m/s^2), T is the duration of exposure (s) to a, A and B are the frequency-weighting coefficients described above, f is the frequency (Hz) of a, and the constant 0.0153 is defined by the ratio $K/\overline{\mathrm{VI}}_{MAX} = 30/85 \times 1/23$.

4.2.1 Evaluation

The VI method (also used in BS 6841 [22]) is a simple, semi-empirical method for predicting the incidence of motion sickness from the magnitude, frequency and duration of exposure to vertical accelerations. It relies on two important assumptions to model human response to vertical accelerations:

1. at constant frequency, vomiting incidence is a linear function of RMS magnitude of vertical acceleration; and,
2. vomiting incidence is a linear function of the dose parameter.

As discussed below, these assumptions are not valid in the typical naval environment. The first assumption is used to "normalize" vomiting, (i.e. $\overline{\mathrm{VI}} = \mathrm{VI}/a$), and forms the basis for the empirical frequency-weighting used to calculate dose. The second assumption defines the factor K used to calculate vomiting incidence from dose (i.e. $\mathrm{VI} = K\, d$).

It is important to note that the limitations discussed below do not affect the VI method's application to the passenger ferry environment upon which it is based; however, these limitations strongly suggest that it is not well suited to model the naval environment. Also, it is important to separate the method being criticised from the data on which it is based. The Lawther and Griffin data are subject to a variety of exclusions and manipulations [96], including balancing results for sex, and excluding respondents under 15 years of age. One result is "a slight population weighting towards the higher age group (when compared with the general population statistics)". It is not clear how well these manipulated results represent the naval community; however, most empirical parameters used by Lawther and Griffin are based on the experiments of O'Hanlon and McCauley, 1974 [126].

and McCauley et al., 1976 [109]. The subjects used in these experiments are a fairly good representation of the relatively young, male naval population (not considering habituation).

Figure 4 shows observed vomiting incidence as a function of acceleration magnitude at constant frequency, for exposure duration of 115 minutes, from the O'Hanlon/McCauley experiments [109, 126]. A limited sub-set of this data is shown as Figure 3 in Lawther and Griffin, 1987 [97].

From Figure 4 (and from other [109] data at different durations), it is apparent that the first assumption (i.e. VI = $A(a) + B$) is valid for VI up to approximately 40 (%), but not higher. Kanda, Goto and Tanabe, 1977 [83], suggest a log-log relationship between motion sickness incidence and acceleration magnitude. Figure 5 shows the Lawther and Griffin frequency-weightings (dashed-line) and experimental motion sickness incidence data [109] normalized by a_{rms}, as a function of frequency, for constant accelerations. All of the data points shown in this figure are for single-frequency, sinudoidal motion, for which the single-frequency weighting approximation introduced earlier is an exact solution. The acceleration-dependent error relative to the frequency-weighting curve shown in Figure 5 suggests that the normalizing procedure does not produce a acceleration-independent parameter (i.e. vomiting incidence is not a simple, linear function of acceleration magnitude).

The second assumption identified above of a linear relationship between dose and VI is used to evaluate the empirical K factor, from which VI = $K\,d$. Figure 6 shows observed VI vs. dose for the MSI data, and includes a datum at relatively high dose (≈ 270 ms$^{-1.5}$) which is not used in [97]. The two curve-fits shown in Figure 6 are the Lawther and Griffin linear K factor (solid-line), and a non-linear curve (dashed line). The non-linear curve appears to provide a better fit to the data. This observation is further substantiated by Figure 7, which plots VI as a function of exposure duration, T, and compares observations ([109], $f = 0.25$ Hz, $a = 0.333\ g$) with the MSI and VI methods.

Another consequence of the linear K assumption is that the VI method predicts 100 (%) sickness incidence at dose values greater than 283. Observations and experiments clearly show that 100 (%) sickness incidence is rarely experienced in the marine environment, as discussed briefly in Section 8.4.

These criticisms of the VI methodology must be evaluated in terms of the method's ability to estimate VI in specific environments. The VI method works well for the relatively low dose passenger ferry environment [96, 97, 99]; however, this method significantly overestimates VI for relatively high dose values. As shown in the appendix, the VI method models the O'Hanlon/McCauley experimental data [126, 109] and at-sea observations of Lawther and Griffin, 1986 [96], to within an average error of 4 percent, and standard deviation of 8 percent. Close inspection of the data in this appendix shows error in the VI estimate increases rapidly with increasing dose. Also, note that the incidence of motion sickness is overestimated by an approximately constant value of about 4 percent for single-frequency (Tables A.1 and A.2) and broad-band motions (Table A.3). This suggests that using a single-frequency weighting procedure is not a bad approximation for "single-peaked", broad-banded motion as exhibited by the Lawther and Griffin data for monohull ferries [96, 97, 99]; however, this approach would not be appropriate for broad-band motions with widely-distributed or multi-peaked response spectra (e.g. [99, 105, 163]). Section 5 discusses predicting the incidence of motion sickness in complex motions.

The frigate/destroyer naval environment has high values of dose relative to the passenger ferry environment. Some of the more obvious reasons for this include: the relatively short duration of exposure for ferries (hours) relative to warships (days/weeks); the low acceleration magnitudes experienced on (large) ferrys relative to (small) warships (e.g. compare [96, 99] with [5, 153]); and the ferry's ability to cancel or re-route transits when bad weather threatens. Since the VI method assumes VI $\propto \sqrt{T}$, the relatively long duration of exposure on warships will produce large dose values where the assumption of linearity between VI and dose is clearly not valid. Also, it is likely that warships will experience high accelerations for which the assumption of linearity between VI and acceleration magnitude is not valid.

In summary, the VI method of Lawther and Griffin, 1987 [97], is an adequate model of motion sickness incidence in the passenger ferry and other low dose environments (where vertical motions predominate), but is not adequate for the relatively high dose naval environment.

4.2.2 Corrections to VI Method

The current author's Figure 3 differs from the corresponding Figure 8 in Lawther and Griffin, 1987 [97], for the following reasons.

1. The data of McCauley et al., 1976 [109], on which both figures are based were converted from units of gravities to units of m/s^2 using g = 9.807 m/s^2, rather than g = 10.0 m/s^2 as used in [97].
2. Comparing the original McCauley et al., 1976 [109], data with Figure 8 and Table II of Lawther and Griffin, 1987 [97], identifies the following discrepancies, noted below in the form $\overline{\text{VI}}(f) \approx$ i, where f is the frequency (Hz), and i is the value for normalized vomiting (%/m s^{-2}):
   (a) the Figure 8 [97] datum $\overline{\text{VI}}(0.167) \approx 35$ should be $\overline{\text{VI}}(0.167) \approx 27.5$;
   (b) the Figure 8 [97] data $\overline{\text{VI}}(0.18) \approx 35$ and $\overline{\text{VI}}(0.20) \approx 29$ are for a duration of 85 minutes, and so are excluded (all other data are for a duration of 115 minutes); and,
   (c) the Figure 8 [97] datum $\overline{\text{VI}}(0.50) \approx 2.2$ should be $\overline{\text{VI}}(0.50) \approx 7.5$

These differences have a small and offsetting effect on the Lawther and Griffin, 1987 [97], method for predicting VI; in fact the "corrected" Figure 3 shown here exhibits a better fit to the original approximating line-segments than the original data in [97].

These corrections are implemented for completeness, and this discussion is provided in anticipation of questions concerning Figure 3 from readers familiar with Lawther and Griffin, 1987 [97].

5 Complex Motions

The phrase "complex motions" describes a wide variety of conditions. The following definitions, consistent with ISO 2631/3, are used here:

- **single-frequency:** one, constant-frequency sinusoid;
- **multiple-frequency:** two or more superposed, constant-frequency sinusoids (implies a relatively low, finite number of waves, not broad-band);
- **narrow-band:** all significant energy occurs within a single, one-third octave band or less[2]; and,
- **broad-band:** significant energy occurs over more than one, one-third octave band.

The ISO 2631/1 and 2631/3 standards present frequency-dependent data to a basis of centre-frequencies of one-third octave bands. Depending on platform type and operating conditions, typical response spectra show significant energy over from six to more than twelve 1/3 octave bands [43, 95, 99, 278]. Thus, in terms of the above definitions, it is clear that ship motions are broad-band.

When reading the literature on human response to motion, it is important to appreciate that some references appear to consider that multiple-frequency and broad-band are synonymous; however, there are important differences. Ship motions in response to almost all realistic seaways are broad-banded, with spectral shapes varying from "single-peaked" for uni-directional, long-crested seas to evenly distributed and relatively flat response for short-crested seas with a large spreading angle. On the other hand, motions in response to seas with significant energy from two or more discrete wave systems will often be both broad-banded and multiple-frequency, with discrete peaks at different frequencies in the response spectra (e.g. simultaneous long-crested seas and decaying swells).

As described earlier, both the MSI and VI methods are closely based on the single-frequency, vertical motion experiments of O'Hanlon and McCauley, 1974 [126], and McCauley et al., 1976 [109]. In actual fact, it is more correct to regard these experiments as narrow-banded, as shown by representative spectra in Guignard and McCauley, 1982 [66], for their "sinusiodal" control motion. Thus, the MSI method should be a reliable method for predicting the incidence of motion sickness in narrow-banded, vertical motions; however, the naval environment is typically broad-banded and includes significant non-vertical motions.

ISO 2361/3 suggests that when significant non-vertical motions exist... "especially pitch and roll, it may be advisable to reduce the boundary accelerations by about 25% to maintain the same degree of protection". The current author notes that the contribution of pitch and roll to local vertical motions should be (and usually is) explictly included in all measurements or calculations of ship motion; however, the relative magnitude of non-vertical accelerations is another matter. Irwin and Goto, 1984 [75], observe (as expected) significant motion sickness and related symptoms in low-frequency horizontal motions (i.e. various combinations of surge, sway and yaw). Since vertical motions predominate in many marine environments, and motion sickness correlates well with vertical accelerations [96, 99, 174], this is not discussed further in this review, but it is clear that vertical motions are not necessary to produce motion sickness. Thus, when applying these methods to different platform types or operating procedures, the assumption that vertical motions predominate

[2]An octave is the interval between two frequencies having the ratio 2.

should be verified (e.g. lateral motions may be very significant for long-term, towed-array operations in oblique seas).

Using the MSI method to model multiple-frequency, vertical motions is discussed in a variety of sources. Guignard and McCauley, 1982 [66], describe experiments in which participants were exposed to complex, vertical motion formed by the sum of two (narrow-banded) sinusoids, which combine to form a double-peaked energy spectrum. The measured incidence of motion sickness was compared with the MSI method, and the results are summarized as follows.

> "Certain motion conditions provoked unexpectedly high MSIs compared with the control condition. It was found that R.M.S. acceleration is not reliable as the sole predictor of MSI in complex motion. Further data must be obtained before accurate prediction of MSI in broadband motion will be possible."

Malone, 1981 [105], Jex, DiMarco and Clement, 1977 [80], and Donnelley, 1976 [37], describe attempts to develop a frequency-domain model for predicting heave-induced MSI in broad band motions. A brief summary of this method is presented below, following Malone, 1981 [105].

Assuming that the heave acceleration, $\ddot{z}(t)$, can be decomposed into sine waves,

$$\ddot{z}(t) = \sum A_i(f_i) \sin(2\pi f_i t + \beta(t))$$

then it should be possible to generate an "effective acceleration", $\ddot{z}_e(t)$, for predicting MSI, as follows.

$$\ddot{z}_e(t) = \int \ddot{z}(t) \mathrm{W}(f) df$$

where $\mathrm{W}(f)$ is a frequency-dependent weighting function.

As stated by Malone, 1981 [105], "it was originally hoped that this expression (i.e. $\mathrm{W}(f)$) would provide a transformation or weighting variable which could generate a frequency-independent acceleration variable". The $\mathrm{W}(f)$ curve defined by Malone, 1981 [105], is essentially identical to the $\mathrm{WF}(f)$ frequency-weighting function described in Section 4.2, used in Lawther and Griffin's VI method [97]. This similarity is not unexpected, since both the $\mathrm{W}(f)$ and $\mathrm{WF}(f)$ curves were derived from the MSI experiments of McCauley et al., 1976 [109], and O'Hanlon and McCauley, 1974 [126].

The relationship between effective acceleration and MSI was explored using the RMS effective heave acceleration, σ_{MSI}, as follows [80, 105].

$$\sigma_{MSI}^2 = \int [\mathrm{W}(f)A(f)]^2 \, df$$

where $A(f)$ are the Fourier amplitudes of the heave acceleration.

As discussed in Malone, 1981 [105], this approach was not successful in modeling the complex-motion MSI experiments of Guinard and McCauley, 1981 [66], nor the simulated

SES complex-motion experiments described by Malone, 1981 [105] (see references [35, 37, 80, 127, 166]).

Malone, 1981 [105], also discusses the desirability of developing an "equivalent motion dose" parameter, Y,

$$Y = \frac{1}{T}\int_0^T F(\ddot{z}_e)dt$$

where T is the duration of exposure and F is some unknown function of the effective acceleration, $\ddot{z}_e$; however, the (unreported) attempts to define the function F were not successful.

The current author notes that if the Lawther and Griffin frequency-weighted acceleration, a_{fw} (see Section 4.2), is used for $\ddot{z}_e$, and $F(\ddot{z}_e)$ is defined as follows,

$$F(\ddot{z}_e) = Ta_{fw}^2$$

then Y is related to Lawther and Griffin's dose parameter, d, by $Y = d^2$.

Malone, 1981 [105], also comments on the need for more experimental work on motion sickness incidence in controlled, complex motions, as initiated by Guinard and McCauley, 1981 [66].

Smith, 1982 [160], evaluates two approaches for modeling the complex-motion experiments by Guignard and McCauley [66], discussed above:

1. an "independent-effects approach", in which the overall MSI is defined as the sum minus the product of the single-frequency MSIs
   i.e. MSI(i,j) = MSI(i) + MSI(j) - MSI(i)MSI(j);

2. a sum-of-squares approach which reduces the complex motion to a single, equivalent acceleration, a_0, at a reference frequency using frequency-dependent weighting factors, w_i, i.e. $a_0 = (w_i a_i + w_j a_j)^{1/2}$

Two variations on the last approach were considered, one using weighting factors from the O'Hanlon/McCauley (single-frequency) experiments [109, 126], and the other using weighting factors derived from the complex motion experiments being modeled [66]. Only the last approach using the complex-motion weightings is able to predict the "unexpectedly high MSIs" noted in the preceeding paragraph; however, since this method is essentially replicating data on which it is based, and since the amount of empirical data is limited, any conclusions must be tentative, at best.

A variety of authors report on efforts to improve statistical models for predicting motion sickness incidence for exposure to both single-frequency and complex waveform vertical motions, including: Burns, 1984 [25]; Mauro and Smith, 1983 [108]; and, Mauro and Smith, 1981 [107]. These papers suggest a "statistical mixture model" in which part of the population is susceptible to motion sickness after relatively short exposure and the remainder is not. The distribution of sickness (time to first emesis) of the susceptible population is best fitted by a Weibull distribution; however, more experimental data are required before significant improvements in modeling accuracy can be achieved.

ISO 2631/3 recommends using the "summed weighted" method described in Section 4.2 (note 2) of ISO 2631/1 for reducing broad-band motion to an equivalent single-frequency acceleration; however, ISO 2631/3 also notes that research into complex, low-frequency motions is very limited, and so the ISO 2631/1 method is recommended in lieu of better methods. Note that this method was devised to reduce narrow-band motions to equivalent accelerations at the centre frequency of discrete 1/3 octave bands [37, 76]. Using this method to reduce relatively broad-band motions to a single-frequency, equivalent acceleration for assessing motion sickness is not justified, especially for multiple-frequency, broad-banded motions.

5.1 Summary of Experiments

The following citations contain experimental and observational data of special interest to the naval community. Most, but not all have been cited previously.

Laboratory: [4, 35, 66, 80, 105, 109, 127, 126, 166]

At-sea: [5, 24, 72, 83, 95, 96, 98, 99, 134, 173, 172, 174, 180]

6 Habituation

Glaser, 1966 [52]; Money, 1970 [120]; and, Wiker, Pepper and McCauley, 1980 [174] provide useful introductions to the processes of adaptation and habituation. The following terminology from Money, 1970 [120], is used here.

- adaptation describes three different phenomena:
  1. the "change in response to stimuli", especially a diminution of response ("response decline");
  2. "the change in bodily mechanisms that is responsible for the response decline"; and,
  3. "the acquisition or process of acquiring the change in bodily mechanisms"
- habituation is the "acquisition or process of acquiring the adaptive change and the decrease in response".

Newman, 1976 [124], provides a good general discussion of habituation and of the hypothetical 'tracking' of habituation with a changing motion environment.

The requirement to model habituation in the naval environment is aptly demonstrated by results of simultaneous seakeeping trials with two RN frigates reported in Andrews and Lloyd, 1980 [5]. During these trials, the ship with highest observed vomiting (37%) experienced average vertical accelerations of approximately 0.125 (g) RMS at the bridge, and the ship with lower observed vomiting (26%) experienced higher average accelerations of approximately 0.160 g. This discrepancy is explained by the relative durations of exposure [5]; the ship with higher accelerations and lower vomiting was on its fourth day at sea, while the ship with lower accelerations and higher vomiting was on its second day.

In general, this section on habituation is concerned with identifying the references of most interest for developing methods to quantify habituation; however, it is useful to note some instances where habituation does not behave as expected. Thomas, Guignard and Willems, 1983 [165], discuss experiments on simulated SES motions (see [35, 105, 166]), and notes "a somewhat anomalous finding in these studies was the lack of habituation". A few possible explanations for this observation are advanced, including [165, 166]; "extremely severe and unusual motion, when continuous and prolonged, may however preclude habituation"; but the lack of a clear cause indicates further study may be warranted. Also, Newman, 1976 [124], describes the somewhat rare but existing phenomenon of "reverse habituation" (e.g. one becomes habituated to the practice of vomiting in response to motion).

The papers cited later in this section cover a wide variety of experimental and observational conditions, some of which may appear not relevant to habituation in the marine environment; however, it seems generally accepted that rates of gaining and losing habituation are relatively constant in very different circumstances [57]. Note that, since habituation is specific to the stimuli involved [32, 52, 58, 59], it is important to distinguish between rates of acquiring and losing habituation, which are of interest here, and the ability to transfer habituation between environments.

Two exceptions to the general applicability of literature on habituation are: (1) experiments where habituation is quantified by measuring optical responses (e.g. [28, 38, 101, 141, 144, 145]); and, (2) habituation in space flight [118, 130]. In the first case, optical responses are generated by induced coriolis forces (tilting the head while rotating at high angular velocity) and by the "caloric" test (irrigating the ear with relatively warm or cool water). Two measures of optical response are; the oculogyral illusion (OGI) and nystagmus; both have a duration measured in tens of seconds. The OGI response quantifies the duration of illusory movement of fixed objects (i.e. time from when the provocative stimulus stops to when fixed objects appear fixed). Nystagmus responses are quantified by measuring decay rates of eye rotations after exposure to provocative stimuli. These optical responses are used to examine the physiological basis of vestibular habituation, and have direct application to the aerospace environment; however, the current author cannot identify any methodology to apply optical response experiments in the naval (marine) environment. In the second case, work on habituation in space flight and in terrestrial situations with long-term exposure to reduced gravity (e.g. underwater simulation of space), introduces a new physiological phenomenon; shifting body fluids becomes a major cause of (or contributor to) motion sickness. Most, if not all, of the work on space sickness incidence and habituation in space is not applicable to the naval environment.

Some of the references cited below are from the literature on drug therapy. The results for "drugged" participants are not for application here; however, all cited drug studies include "placebo" control groups, which are of direct interest (see Section 8.3 for general citations on drug therapy).

6.1 Summary of Experiments and Observations

Habituation quantified: [52, 69, 72, 83, 109, 113, 170, 179]

Relative habituation: [3, 5, 24, 28, 39, 57 58, 124, 134, 137, 173]

7 Symptoms and Severity of Sickness

Methods described earlier for estimating the incidence of motion sickness and the references cited on habituation suggest that an improved model for predicting motion sickness in the naval environment may be possible; however, as noted by a number of authors (e.g. [124, 165, 174]), significant motion sickness symptoms can be present with no or low incidence of vomiting. Thus, it is useful to examine motion sickness symptoms and methods used to evaluate their effects on performance.

Money, 1970 [120]; Reason, 1978 [139]; and, Muir, 1983 [122] identify the symptoms associated with motion sickness and describe their progression. Graybiel et al., 1968 [63], and Graybiel and Lackner, 1983 [57], describe a widely-used "malaise" scale for rating the severity of motion sickness by observing its symptoms. A variety of self-rated, opinion-based questionnaires have been used, and one of particular interest to the naval community is described by Applebee, McNamara and Baitis, 1980 [6]. Results of this subjective approach provide valuable guidance; however, a general lack of objective data makes it very difficult to quantify the degradation of performance. For example, subjective data from questionnaire surveys of two RN frigates [134], shows:

> "About 5% of both crews indicated that they could not work during bouts of sea-sickness, whilst a further 50% had some difficulty in working on these occassions."

The remainder of this section describes the motion sickness symptomatology severity (MSSS) scale of Wiker et al., 1979 [171], and the illness rating (IR) scale of Lawther and Griffin, 1986 and 1988 [96, 98]. Also, the possibility of a proportional relationship between the incidence of motion sickness (i.e. percent vomiting), symptom severity and performance is discussed by examining the relationship between self-rated IR values and observed vomiting incidence.

7.1 Motion Sickness Symptomatology Severity (MSSS)

A series of reports (Wiker et al., 1979 [171]; Wiker, Pepper and McCauley, 1979 and 1980 [172, 174]; Woolaver and Peters, 1980 [180]; and, Wiker and Pepper, 1981 [173]) describe joint USCG/USN side-by-side seakeeping trials with a 95 foot (29 m) Coast Guard Patrol Boat, a 378 foot (115 m) Coast Guard High Endurance Cutter, and a 87 foot (27 m) experimental Navy SWATH vessel. The ships were instrumented to record motions, and a variety of shipboard events were monitored, including a fairly comprehensive battery of tests, questionnaires and observations to assess the incidence and effects of motion sickness symptoms.

The Motion Sickness Symptomatology Severity scale (MSSS) [172], is based on a questionnaire [173, 174] which identifies the presence and severity of motion sickness symptoms. Comparison of MSSS scores with coincident, objective observations [171], indicates that this is a reliable diagnostic tool for assessing the objective and subjective severity of motion sickness symptoms. Also, the MSSS scale provides a better indication of the effects of motion sickness than considering only the time to first emesis (and/or cumulative vomiting incidence)

Wiker, Pepper and McCauley, 1980 [174]; and, Wiker and Pepper, 1981 [173], describe extensive correlation studies which relate the MSSS scale to ship motions and task performance. In summary, "subjects who were exposed to the motion environment of the Patrol Boat as it steamed through sea state 3 conditions suffered severe motion sickness which was associated with physiological stress, slight deterioration in mood and small to moderate decrements in psychomotor task performance". Unfortunately (for the purposes of the current author), motions on the larger High Endurance Cutter and on the experimental SWATH ship were not sufficient to induce significant motion sickness symptoms. Thus, these trials verify the expected relationship between increasing severity of motion sickness symptoms and decreasing performance, but insufficient data are available to establish quantitative links. Note that problems with task performance in large amplitude, low frequency motions (as experienced by the small Patrol Boat) may indicate the presence of biodynamic problems, rather than, or in addition to, motion sickness symptoms.

Wiker, Pepper and McCauley, 1980 [174], present an empirical equation for estimating values of MSSS from vessel motions defined by spectral amplitude, frequency and magnitude of accelerations, but this method suffers from the same major problems as noted earlier for the MSI and VI methods (i.e. habituation not modeled and link to performance not established), and the additional problem that exposure duration is not considered. One recommendation of this paper [174] is to continue using the MSI method (see Section 4.1) for assessing motion sickness.

Note, reference [174] observes that decrements in task performance were attributed primarily to reductions in the quantity of work; not quality. Further, reference [174] suggests that those tasks which require sustained periods of performance (e.g. complex counting, navigational plotting), suffered the most performance degradation, and those tasks which require short periods of effort and which were less complex suffered least.

7.2 Drowsiness, Lethargy and Fatigue

Most papers describing motion sickness symptoms [e.g. 16, 70, 120, 122, 127, 172] are careful to identify drowsiness and lethargy (or appropriate synonyms) as separate and different symptoms and either explicitly, or by omission, indicate that fatigue is not a symptom. This is consistent with the definition of fatigue as "weariness after exertion[3]", and the distinction is more than simply pedantic, as discussed in Section 10.2 of this review; however, regardless of how fatigue is produced, the combined effects of fatigue and motion sickness are worse than either alone [39, 40]. This may be especially important to naval operations in relatively harsh conditions, especially if further compounded by cold weather [14] (e.g. winter in the northern North Atlantic).

7.3 Illness Rating (IR)

Lawther and Griffin, 1986, 1987 and 1988 [96, 97, 99, 98], define a subjective "illness rating" (IR) derived from their survey questionnaire and correlated with the VI method dose and vertical accelerations in [97] and [99]. IR is defined as the following weighted-sum of subjective observations, solicited from ferry passengers at the end of passage.

[3] The Concise Oxford Dictionary, 1978

$$\mathrm{IR} = \frac{N_1 + 2N_2 + 3N_3}{N}$$

where N_1 is for the number of people who felt "slightly unwell", N_2 is for "quite ill", N_3 is for "absolutely dreadful", and N is the total number of responses (N_0 is for those who felt "all right"). The validity of this rating scale is discussed in Lawther and Griffin, 1986 [96].

The next section discusses the possible existence of useful relationships between IR, vomiting incidence and performance.

7.4 Symptom Severity vs. Sickness Incidence vs. Performance

The current author examines the relationship between Lawther and Griffin's [96] IR and observed vomiting incidence in Figure 8, on which the following relationship between IR and vomiting incidence is plotted (straight-line).

$$\mathrm{IR} = 0.030\,\mathrm{VI}_{obs} + 0.20$$

where IR is the subjective illness rating and VI_{obs} is the observed incidence of motion sickness (not the VI method's estimate).

The positive value for IR with $\mathrm{VI}_{obs} = 0$ is consistent with observations cited earlier that motion sickness effects are observed with little, or no, actual emesis; however, the relationship between particular values of IR and performance cannot be quantified.

Note that the current author's relationship between IR and VI differs from curves suggested by Lawther and Griffin, 1987 [97], and by Benson, 1988 [16]. In the first case, Lawther and Griffin [97] propose the curve $\mathrm{IR} = 0.05\ \mathrm{VI}_{obs}$ as a rough estimate only, and so any differences are not especially important; however, the $\mathrm{IR} = 0.045\mathrm{VI}_{obs} + 0.1$ curve-fit proposed by Benson, 1988 [16], shows the same trends as the current author's, but has significantly different slope and offset. The differences between the current author's curve-fit and that of Benson [16] cannot be explained, but both are good fits of the data on which they are based. The current author's data are those published in Table 2 of Lawther and Griffin, 1986 [96], and represent exposure durations of 3 and 4 hours. The data used by Benson [16] are shown graphically in Figures 4 and 16 of Lawther and Griffin, 1987 [97], and represent durations from 2 through 6 hours. Unfortunately, these data are not published in tabular form.

Regardless of which straight-line curve-fit is the "best", the fact that this simple relationship exists provides some useful information. If one can assume that a predictable relationship exists between illness rating and performance degradation, then it is reasonable to suggest that the incidence of motion sickness (i.e. percent sick) is similarly related to performance. Since IR is a measure of severity of motion sickness symptoms, it may be useful to consider the more concise MSSS scale described earlier as a potential method for future work on examining the relationship between severity of symptoms and performance. More detailed analysis of the MSSS/performance correlation studies described in Section 7.1 may provide insight on the relationship between subjective ratings of well-being and performance, and may suggest areas of primary concern for future experimentation.

Note that the presence of a threshold value of IR below which vomiting incidence does not occur (see Figure 8), and the observation that a high proportion of the naval community "never get sick" (see Section 8.4), suggest the possibility that some proportion of the habituated naval population may spend significant time in conditions which do not produce major symptoms of motion sickness, but which do degrade performance. This indicates that it is important to determine whether habituation quantified as a reduction in the incidence of vomiting implies a proportional reduction in the severity of motion sickness symptoms, especially drowsiness (also, see Section 10.2 on motion-induced fatigue).

8 Other Topics

8.1 Subjective Motion (SM)

Lloyd and Andrew, 1977 [102], define a method for calculating the subjective magnitude (SM) of vertical motions on warships, and its use is demonstrated in Andrew and Lloyd, 1981 [5]. This SM method for warships is adapted from experimental work by Shoenberger, 1975 [156], on subjective response to low frequency vibration.

Experiments on subjective response to motion were important in the development of ISO 2631/1 for evaluating WBV effects at frequencies above 1.0 Hz, and they are an important aspect of ride quality, discussed below. Shoenberger, 1975 [156], provides the means to extend these vibration criteria to the low frequency regime; however, it is important to note that SM is not a measure of motion sickness and its associated symptoms, nor of performance [135]. Part II of this document cites a large number of documents concerned with subjective motion and subjective magnitude.

8.2 Ride Quality

As discussed above for subjective motion, most work on "ride quality" and "ride comfort" is concerned with relatively high frequency motions, considered in Part II of this paper; however, some methods consider low frequencies as well.

Payne, 1976 [132], Stark, 1980 and 1982 [162, 163], Allen and Farris, 1986 [43], consider a "composite" approach to assessing ride quality for low frequencies (i.e. motion sickness) and high frequencies (i.e. biodynamic problems). These papers provide an interesting method of blending the ISO 2631/3 and ISO 2631/1 standards; however, the current author urges caution when applying this composite method to the "long-term exposure" naval environment. The time dependence of motion sickness is very different from that for biodynamic problems (i.e. for sickness, long-term exposure is beneficial; for biodynamic problems, long-term exposure is detrimental). Since the general operating procedures for most advanced naval vehicles (ANV) involve relatively short duration of exposure to motions (i.e. near-shore operations from a harbour facility), it may be appropriate to use these methods for ANV (e.g. [43])[4], but this does not imply that this method is suitable for open-ocean operations with frigates and destroyers.

[4] Also, note that habituation can be gained from relatively brief exposures repeated on a daily basis.

8.3 Drug Therapy

Drug therapy for motion sickness is used for a variety of reasons, including: to reduce the incidence of motion sickness; to increase the rate of acquiring habituation; and, to mitigate the effects of motion sickness symptoms. The primarily concern here regarding drug therapy is to locate papers useful for modeling habituation (see Section 6), and to cite the following introductory and review papers [51, 121, 122, 131]; otherwise, this subject is only considered as follows.

In general, most aspects of modeling motion sickness considered in this paper assume (if only by omission) that drugs are not used, or that the population being observed includes an appropriate (but unquantified) proportion of "drugged" participants. A cursory overview of the literature shows that about 12 % of the typical naval community takes medication to prevent or treat motion sickness (8 and 14 % on two RN frigates [134], 12% on a USCG cutter [6]). As long as the proportion of "drugged" participants and the efficacy of anti-motion sickness drugs remain relatively constant, the effects of drug-use are not important; however, if either of these two aspects of drug use in the naval community should change significantly, then many (if not most) of the methods and data cited in Part I of this paper may become completely irrelevant.

8.4 Susceptibility

The variation of susceptibility to motion sickness between individuals is used to "screen" potential candidates for work in sickness-inducing environments, especially space flight. This aspect of susceptibility is not considered here, except to cite the following references related to this topic: [40, 84, 100, 155]. Note that if current trends of reducing crew sizes are continued in the future, the susceptibility of individuals may assume greater importance for the naval community.

The variation of susceptibility of different populations to motion sickness is important. Thomas, Guignard and Willems, 1983 [165], speculate that "there may be two populations of susceptible people who develop motion sickness at different rates, or there may be two underlying rate processes within people". Similarly, the statistical modeling work cited in Section 5 assumes that part of the total population is susceptible to being sick after a relatively short exposure to motion, and the remaining persons are not (the time-dependence of their susceptibility is not quantified).

ISO 2631/3 states, "for the normal travelling public, however, it appears that a small percentage of probably about 5% never adapt to motion below 0.63 Hz". The distribution of high susceptibility to motion sickness in the naval community is not clear. Questionnaire responses indicate from 4 to 13% percent of the naval community "always get sick" in "rough" conditions [24, 134]. This is surprisingly high; however, the current author suspects that more than 5% of the normal travelling public would be sick in conditions described as "rough" by naval standards. The percent of naval personnel who "never get sick" is significantly large, at approximately 32 % (arithmetic mean of figures cited in [5, 24, and 134]). Thus, when methods for modeling either the incidence or effects of motion sickness on naval personnel are devised, the empirical aspects of the models must be assessed using data representative of the naval community.

Very high incidences of vomiting (i.e. up to 100%) are experienced in extreme conditions such as totally enclosed lifeboats (see Landolt and Monaco, 1989 [92]); however, these conditions are not representative of the naval environment, and so are not considered further in this review.

8.5 Simulator Sickness

Simulator sickness is not considered in this review, except to cite the following references: [1, 45, 75, 104].

8.6 Space Sickness

Space sickness is not considered in this review, except to cite Jeffrey et al., 1988 [88], as an overview of the observed incidence of space sickness, and Oman et al., 1986 [130], and Megighan, 1980 [118] for overviews of space sickness etiology and prediction methods. Also, as noted earlier in Section 6, most (if not all) data on motion sickness in space is not applicable to the marine environment.

PART II: BIODYNAMIC PROBLEMS

9 Overview

The bulk of literature on biodynamic problems is associated with "whole-body vibration" (WBV) at frequencies higher than 1 Hz. This is the traditional division between biodynamic and motion sickness problems; however, significant biodynamic problems are encountered in the naval environment at frequencies below 1 Hz. The current author uses the phrase "whole-body motion" (WBM) to describe two categories of biodynamic problems; motion-induced interruptions (MII) and long-term, motion-induced fatigue (MIF). After discussing these WBM problems, the review describes conditions in which WBV problems are encountered at relatively low frequency and discusses using the ISO WBV standard for evaluating performance. The remainder of the review provides brief descriptions and cites relevant literature on the following WBV topics: standards and papers of direct relevance; manual control problems; vision problems; subjective motion; ride comfort and ride quality; low frequency motions; and, complex motions. Where appropriate, papers of special interest to the naval community are cited separately.

This literature review does not consider noise, although some of the standards cited later consider both noise and vibrations. Similarly, this review does not consider local vibrations due to rotating machinery, but many of the references cited below are of direct relevance.

10 Whole-Body Motion (WBM)

10.1 Motion-Induced Interruptions (MII)

A motion-induced interruption (MII) occurs when local motions cause a person to lose balance or slide, and so interrupt any task being performed. The MII concept was introduced by Applebee, McNamara and Baitis, 1980 [185], and is more fully described by Baitis, Woolaver and Beck, 1983 [188], and Baitis, Applebee and McNamara, 1984 [186]. A frequency-domain method for estimating the incidence of MII's, called the lateral force estimator (LFE) [186, 188] is of interest, since it greatly reduces the amount of computation compared with the time-domain approach. The LFE combines earth-referenced lateral acceleration with ship-referenced lateral acceleration to provide an estimate of lateral forces at any particular location in or on the ship. Since the value of the LFE can be related to the incidence of MII's caused by lateral forces [188, 186], the LFE provides a good estimate of MII's in conditions where vertical accelerations are small.

Recent work by Graham, 1989 [211], defines a generalized lateral force estimator (GLFE) which includes vertical forces, and so greatly expands the conditions under which the incidence of MII's can be assessed using frequency-domain techniques.

These methods for estimating the incidence of MII's [186, 188, 211] are derived to model the forces acting on a standing human. Thus, they provide a means to determine when motions will interfere with appropriate actions (e.g. transiting a helicopter landing deck, or performing system maintenance with light, hand-tools). Human activities requiring interaction between humans and heavy, mobile equipment (e.g. UNREP, rearming) can probably be modeled by extensions to the current MII theory, but such methods are not yet developed. Also, wind effects are not considered, and so MII incidence will be underestimated in the presence of high winds. Lloyd and Hanson, 1985 [239], discuss the effects of wind on human activities in helicopter operations, and provide empirical data on wind limits for human operations on the flight deck (in the absence of motion).

10.2 Motion-Induced Fatigue (MIF)

As mentioned in the discussion on motion sickness, fatigue is best considered as a biodynamic problem, and should not be confused with the motion sickness symptoms of drowsiness and lethargy.

Warhurst and Cerasani, 1969 [282], observe "sleep disturbance was often reported as an important negative result of heavy roll", and that "in general, 'one hand for the ship and one hand for self' was the rule". These observations suggest a link exists between low-frequency, large-amplitude motions and both drowsiness (need for sleep) and fatigue (weariness after exertion). Wiker, Pepper and McCauley, 1980 [284], describe at-sea observations by Sapov and Kulesov, 1975 [267], which show roll motions are the predominant contributor to fatigue (i.e. from holding on and bracing against whole-body displacement).

Baitis, Woolaver and Beck, 1983 [188], evaluate the potential for rudder roll stabilizers to improve human performance by examining motion-induced fatigue (MIF), motion sickness incidence (MSI), and MII's for shipboard helicopter maintenance tasks, as follows.

"In seas forward of the beam, maintenance task performance is degraded primarily by MSI and MIF. Thus, roll stabilization in bow seas reduces one of the two factors degrading maintenance - fatigue. In seas aft of the beam, task performance is degraded primarily by fatigue and in the operational sector extending roughly from 15 degrees aft of the beam to 35 degrees aft of the beam by the occurrence of hazardoius MII's."

The current author notes that the preceeding observations on the roll-dependence of fatigue and the variation in relative importance of MSI, MIF and MII's with changing direction between the ship and seas are likely platform-dependent; however, it is clear that motion-induced fatigue is an important biodynamic problem.

Baitis, Woolaver and Beck, 1983 [188], discuss the possibility of assessing trends in MIF from the incidence of MII's, as estimated by the LFE method described earlier. Similarly, Graham has suggested[5] that it should be possible to correlate long-term fatigue with the GLFE [211]. The current author notes that the constraints on LFE as an indicator of MII's should also constrain its use as an indicator of MIF (i.e. LFE is valid where vertical and longitudinal forces are not significant). Also, the current author notes it may be possible to estimate MIF by combining MII theory with a more explicit model of human physiological response (e.g. Oman, 1986 [258], for horizontal displacement), and so estimate fatigue by calculating work-done by the muscles to preserve relative position (i.e. holding-on, bracing against motion, and "moving-with" the ship).

Further discussion in [174] on observations by Sapov and Kuleshov, 1975 [267], notes that the primary effect of motion-induced fatigue on mental and "professional" performance is a reduction in the quality of work, not quantity or rate of completion. This is important to the naval community as it implies a higher incidence of mistakes, and that these mistakes may not be noticed. It is likely that reduced quality of work due to fatigue and reduced quantity of output due to motion sickness symptoms (and/or WBV problems, see Section 7.1) will combine in some circumstances to significantly degrade performance.

11 Whole-Body Vibration, WBV

WBV problems associated with manual control and vision are traditionally considered for frequencies above 1 Hz, but significant WBV problems are experienced at frequencies considerably lower than this in the naval environment, especially for advanced naval vehicles (ANV). For example, Wiker, Pepper and McCauley, 1980 [284] describe work on simulated SES motions [35, 257, 229], which shows significant manual control problems for frequencies from 0.2 to 2.0 Hz and with RMS vertical accelerations from 0.5 to 1.0 g (also, see [241]). This zone of WBV problems is shown in Figure 9, labelled as MOTOR TASKS (SES), along with a similar zone from Griffin, 1975 [213], in which vision problems are encountered at higher frequencies in aircraft, labelled VISION (A/C). Also shown in this figure is the ISO 2631/1 "fatigue-decreased proficiency" boundary, FDPB, for a 2 hour exposure (described in the next section). Note that the dashed portion of the ISO 2631/1 boundary below 1 Hz is an extrapolation by the current author. The validity of extrapolating the ISO boundary

[5]Graham, R.: Private Communication

to lower frequencies is not assessed by the current author; however, much of the literature cited in the following section on ISO 2631/1 and later in Section 11.7 considers this question.

Figure 9 illustrates two points which should be considered when reading the following review of WBV literature:

1. significant WBV problems are encountered at frequencies below 1 Hz;
2. the ISO boundary is conservative for the SES motor task problems (and adequate but unsubstantiated below 1 Hz), but the same boundary is optimistic for the aircraft vision problems.

The first point suggests that the ship designer or operational analyst should investigate the possibility of WBV manual control problems for all vessels which may encounter high accelerations at even relatively low frequencies. The second point suggests that it might not be possible to select a single ISO 2631/1 boundary as a criterion for evaluating different aspects of human performance, especially for high frequency motions (e.g. ANV sprint).

11.1 Standards

The accepted international standard on biodynamic problems associated with whole-body vibration (WBV) is the ISO standard 2631/1 entitled "Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements" [225]. The ISO 2631/1 defines limits of exposure to vertical and horizontal vibrations as functions of the frequency and amplitude of accelerations, for three conditions: "reduced comfort", "fatigue-decreased proficiency", and "exposure limit (health or safely)". The exposure limits are expressed in tabular and graphical form as boundaries, following the same methodology as for the ISO 2631/3 motion sickness standard, discussed earlier (ISO 2631/1 forms the basis for ISO 2631/3).

In addition to defining limits for human exposure to WBV, ISO 2631/1 describes methods for reducing broad-band and complex motions to equivalent narrow-band, single-direction motions. These ISO methods are discussed and used in most of the literature cited in later sections on manual control, vision, subjective motion, and ride quality.

Note that "fatigue" as used in ISO 2631/1 is not the same as described previously for low-frequency, large-amplitude motions. ISO 2631/1 describes the FDPB as follows.

> "The boundary specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks, particularly those in which time-dependent effects ("fatigue") are known to worsen performance as, for example, in vehicle driving."

Thus, the ISO definition of fatigue is different from "weariness after exertion", as used in this review to describe motion-induced fatigue. The apparent ISO usage of "fatigue" represents the combined effects of a variety of symptoms including; motion-induced fatigue (probably not much), mental-fatigue, drowsiness and reduced concentration. In the sense of this review, fatigue associated with "vehicle driving" would be a consequence of effort expended on steering, more than from exposure to vibration.

Other standards and guidelines include: the ISO 6897 standard [227] for evaluating human response to low frequency horizontal motion; the British Standards Institution BS 6841 for evaluating human exposure to whole-body vibration [191]; the American National Standards Institute ANSI S3.18-1979 [184]; the Society of Naval Architects and Marine Engineers, SNAME [276];, and, military standards and specifications [279, 280].

ANSI S3.18-1979 [184] is essentially the same as ISO 2631/1, except it provides explicit frequency-weighting curves.

A number of papers with direct linkage to the ISO 2631/1 standard are cited below. Some substantiate existing ISO practice and others observe differences between observed behaviour and ISO 2631/1 recommendations.

References: [181, 272, 281, 247, 193, 199, 272, 255, 201, 264, 198, 217, 215]

British Standards Institute, BS 6841

The British Standards Institute BS 6841 [191] describes an approach for evaluating exposure to whole-body vibration which is different from ISO 2631/1 and related standards. Indeed, BS 6841 incorporates many of the criticisms of ISO 2631/1 described in documents cited above. The ISO concept of "fatigue-decreased proficiency" is not used in BS 6841, nor is the ISO assumption of direct proportionality between limits for comfort, proficiency and health (i.e. safety). BS 6841 explicitly considers health, hand control, vision, discomfort, motion perception, and motion sickness as separate problems. BS 6841 suggests quantitative limits for each type of problem, and describes different procedures for estimating these quantities. The BS 6841 limits and methods are not evaluated here (except as discussed in Section 3.2 for motion sickness); however, the current author suggests that this approach seems reasonable.

Habituation

The presence or absence of habituation due to long durations of exposure to WBV is not clear. Seidel et al., 1980 [268], note that some habituation is observed in repeated exposures to conditions near the ISO 2631/1 fatigue decreased-proficiency boundaries, FDPB, but prolonged exposure (i.e. more typical of naval environment) demonstrates greater performance decrements with increasing dose. Clarke, 1979 [193], observes that the time-dependency exhibited in the ISO boundaries (i.e. the longer the worse) does not hold for exposures up to 2.5 hrs. Clevenson, 1978 [194], indicates that habituation does occur, especially when considering ride comfort (ISO considers comfort is directly proportional to FDPB).

11.2 Manual Control

Manual control describes a variety of hand-eye and fine motor skill tasks, and, since it directly affects performance, it is of particular interest to the current review; however, most of the work is for frequencies above those experienced in the typical naval environment. Traditionally, WBV manual control problems are associated with frequencies above 1 Hz; however, significant manual control problems have been observed in the ANV naval environment at relatively low frequencies [230, 241, 284].

ISO 2631/3 on motion sickness ($0.1 < f < 0.63$ Hz) [226] comments on low-frequency manual control problems as follows.

> "In the almost complete lack of data on this topic, a RMS value of 1.75 m/s^2, that is a peak value of 0.25 g[6], largely independent of frequency, is suggested as the approximate level at which disturbance may occur to such tasks as writing and fine manual control."

British Standards Institution BS 6841 [191] defines frequency-weighting curves and procedures for evaluating manual control problems, for frequencies from approximately 0.1 to over 100 Hz. BS 6841 comments on quantitative limits (based on frequency-weighted accelerations) as follows.

> "For precise information, detailed investigation will be necessary. However, it may often be found that where hand (or finger) control is required to an accuracy of within 5 mm r.m.s. or 2.5 N r.m.s. the weighted acceleration magnitude in any axis should not exceed 0.5 m·s^{-2}r.m.s. If less accuracy is required the weighted values could be increased in linear proportion."

Irwin and Goto, 1984 [224], describe experiments on the effects of low-frequency horizontal motions (i.e. surge, sway and yaw) on manual dexterity tasks. The results are compared with the ISO 6897 standard [227] for evaluating human response to low-frequency, horizontal motions (0.063 to 1 Hz) in "fixed" structures (i.e. buildings and off-shore rigs.) In summary: "*the results of the manual dexterity tasks ... indicate that the curve shape* and magnitudes in ISO 6897 are in good agreement with the laboratory investigation". This work by Irwin and Goto, and the ISO 6897 standard are not evaluated in any more detail in this review; however, it is important to observe that they illustrate that significant manual control problems can be encountered in the absence of vertical motions.

Lewis and Griffin, 1978 [234], provides a review on continuous manual control, especially hand-eye tracking tasks.

References: [190, 191, 193, 195, 196, 208, 209, 219, 221, 224, 230, 233, 234, 235, 236, 241, 244, 245, 246, 268, 269, 282, 284]

Naval Applications: [190, 195, 196, 230, 241, 246, 282, 284]

11.3 Vision

Problems with reading printed and displayed information are considered separately from the hand-eye manual control problems noted above. Reviews on this subject are provided by Collins, 1973 [197]; and, Griffin and Lewis, 1978 [216].

British Standards Institution BS 6841 [191] provides a frequency-weighting curve for assessing the effects of vibration on vision, and comments on quantitative limits as follows.

[6]Note that this applies only for sinusoidal motion. In the naval environment, the relationship between RMS and peak can be derived using the Rayleigh distribution.

"Precise guidance will require detailed investigation. However, it may often be found that where it is necessary to resolve detail which subtends less than 2 minutes of arc at the eye, the weighted acceleration magnitude should not exceed 0.5 $m \cdot s^{-2}$r.m.s. For every increase by a factor of $\sqrt{2}$ in the size of the detail which is to be resolved the vibration magnitude could be doubled."

References: [191, 197, 213, 216, 230, 237, 243, 248, 249, 250, 257]

11.4 Repeated Shock

Exposure to repeated (mechanical) shock is not truly a vibration problem, but it is related, and it is encountered in some naval environments, especially fast patrol boats. Allen, 1982 [182], and the British Standards Institution BS 6841, 1987 [191], provide quantitative guidance for evaluating the effects of exposure to repeated shock on health and comfort. Also, many of the references cited later for ride quality consider exposure to repeated shock.

11.5 Subjective Magnitude

Two experimental procedures are commonly used in this work: subjective magnitude estimation and intensity matching. In the first procedure, subjects attempt to estimate the proportional magnitude of a given motion with respect to a reference acceleration and frequency. In the second procedure, subjects attempt to determine the level of acceleration at a particular frequency which matches a reference acceleration and frequency. These experiment results provide an empirical basis for much of the ISO 2631/1 standard, and they are used extensively in work on ride quality, discussed later; however, subjective magnitude is not related to task performance.

References: [183, 191, 192, 201, 205, 207, 214, 222, 238, 239, 253, 255, 264, 270, 271, 272, 285, 286]

Naval Applications: [183, 192, 238, 239]

11.6 Ride Quality and Ride Comfort

The terms ride quality and ride comfort describe both a concept for expressing passenger satisfaction and a methodology for modeling that satisfaction, generally based closely on ISO 2631/1. As for subjective magnitude, ride quality is not related to performance. Oborne, 1976 and 1977 [251, 252], provides a review of early work on ride quality, and Stark, 1982 [278], and Farris, 1986 [204], provide useful overviews of more recent applications in the marine environment, especially for ANV. Note that these and many other papers on ride quality use the same time-basis for evaluating both motion sickness and passenger comfort. As discussed earlier in Section 8.2 of this review, this approach is not appropriate for the typical naval environment.

Military specification MIL-F-9490 [279] defines limits on vertical and lateral accelerations using a ride discomfort index, which is calculated using frequency-dependent weighting factors.

British Standards Institution BS 6841 [191] defines relative comfort in terms of (approximate) ranges for frequency-weighted RMS acceleration, calculated from frequency-weighting curves which are defined for variations in body orientation and different axes of vibration.

References: [182, 191, 193, 194, 198, 199, 204, 206, 210, 215, 217, 218, 220, 223, 228, 231, 232, 240, 252, 259, 260, 261, 262, 263, 266, 274, 275, 277, 278, 279]

Naval Applications: [182, 192, 204, 223, 240, 263, 277, 278]

11.7 Low Frequency Considerations

British Standards Institution BS 6841 [191] defines explicit frequency-weighting curves for evaluating WBV problems (health, hand control, vision, and discomfort) for frequencies from approximately 0.1 to 100 Hz.

As mentioned earlier, ISO 2631/3 [226] on motion sickness ($0.1 < f < 0.63$ Hz) suggests that disturbances in manual control tasks will occur for RMS vertical accelerations above approximately 1.75 m/s^2, largely independent of frequency; however, very little data are available on this matter. Irwin and Goto, 1984 [224] compare laboratory experiments on manual control with the ISO 6897 standard [227] for low-frequency, horizontal motions. The results tend to verify the ISO 6897 low-frequency guidelines ($0.063 < f < 1.0$ Hz), which are, essentially, a low-frequency extension of the horizontal motion guidelines in ISO 2631/1 ($1.0 < f < 80$ Hz).

The documents cited below are of interest for extending existing WBV methods and criteria to low-frequency, vertical motions. Most of these works are concerned with subjective magnitude, ride quality and ISO 2631/1 in the frequency range from 0.5 to 1.0 Hz, and all have been cited in previous sections.

References: [183, 191, 192, 198, 203, 204, 215, 223, 224, 239, 238, 240, 245, 246, 255, 263, 270, 277, 278, 279, 282, 284, 285, 286]

Naval Applications: [183, 192, 198, 204, 215, 223, 238, 239, 241, 245, 246, 263, 277, 278, 279, 282, 284]

11.8 Complex Motions

In general, the documents cited here describe experimental results on manual control, vision, subjective magnitude and/or ride quality for exposure to motions which are not narrow-banded or single-frequency. These documents are of particular interest when examining the ISO 2631/1 procedures for reducing broad-band and complex motions to equivalent, narrow-band motion. All documents shown below have been cited in previous sections.

References: [189, 191, 194, 198, 199, 206, 214, 218, 222, 235, 241, 247, 262, 264, 271, 272, 273, 285]

PART III: DISCUSSION AND RECOMMENDATIONS

12 Discussion: Evaluating Human Performance

In order to evaluate human performance in the naval environment, two things are required: the first is a concise description of the environment itself, in terms of the motions experienced, and the second is a methodology, including criteria, for evaluating the effects of these motions on human performance. For any particular type of vessel, the motions experienced are the product of ocean environment, vessel characteristics and operating procedures. The methods for defining the ocean environment (e.g. [12]) and for predicting motions from vessel characteristics and operating procedures (e.g. [53, 54, 55, 154]) are available today and provide sufficient accuracy for the present purposes. The general concepts of performance degradation and operability assessment are well established (e.g. [11, 29, 30, 71, 103, 128, 150, 239]); however, the methodology for quantitative assessment of human performance is not yet available.

12.1 Methodology

From the preceeding review, it is apparent that a methodology for assessing motion effects on human performance in the naval environment should consider at least four different phenomena.

1. motion sickness: low-frequency, short- and long-term exposure (habituation)

2. motion-induced interruption, MII: low-frequency, large-amplitude, short-term event;

3. motion-induced fatigue, MIF: low-frequency, large-amplitude, long-term exposure; and,

4. whole-body vibration, WBV: medium/high-frequency, tolerable exposure determined by severity of motion.

It is important to note that three of these phenomena are "low-frequency", which all naval vessels can expect to experience much, if not most, of the time. Also, the differing natures of these four phenomena with respect to the effects of exposure duration are important. Only motion sickness exhibits beneficial effects with increasing exposure duration (i.e. habituation); all others exhibit increasing degradation of performance with increasing exposure duration.

The human participation in any activity should be assessed in terms of the appropriate time scale. For example, evaluating a long-term activity such as ocean-transit sonar surveillance should include assessing motion sickness and motion-induced fatigue. Alternately, evaluating human participation in a short-term event, such as crossing a flight deck to grasp a helicopter haul-down cable and then inserting it into the haul-down mechanism, may be confined to an assessment of MII's only [9, 186]. Tasks with intermediate-term durations should be evalauted as appropriate. For example, an analysis of helicopter maintenance requiring 10 to 12 hours should consider motion sickness, fatigue and MII's [9].

In many naval scenarios, WBV problems will not occur, or may be of relatively low significance; however, it is important to explicitly consider the possibility of WBV problems. For example, simultaneous MII and manual control problems may occur, but their relative importance will depend on the activity being evaluated.

It is also important to note how the time scale of operating procedures can affect human performance. For example, consider sonar surveillance with sprint and drift tactics [124] (i.e. move at high speed between locations at which the vessel drifts and listens). The changing motion environment may have a significant effect on the incidence of motion sickness (i.e. is it possible to habituate to alternating motion environments ?), and the high-speed sprint may produce significant, short-duration WBV problems.

12.2 Criteria

Since many aspects of human performance cannot be quantified in terms directly related to operability, two kinds of quantitative seakeeping criteria must be considered:

1. absolute performance criteria; and,
2. relative performance criteria.

It is necessary to provide absolute performance criteria when the weak-link in an activity involving human participation is not obvious, or when human and non-human system components are competing (i.e. which is more cost-effective, or which is safer?).

It is sufficient to provide relative performance criteria when the human participation in an activity is necessary. For example, consider sonar operations. It is not possible now, or in the forseeable future, to remove the human from the loop, and so criteria which provide an accurate, relative measure of human performance are sufficient. The major purposes for such criteria are to evaluate the best, worst and/or variation of relative performance with changing location, platform type and/or operating practice. Thus, the relative performance criteria must be platform-independent (i.e. based on the correct motion and response events) and must be related to performance, but operability does not have to be quantified.

An example of the case where human participation is not necessary and absolute performance criteria are required is the human participation in a haul-down assisted helicopter landing. An evaluation of this activity should consider a variety of events, including:

- motion of the flight deck (i.e. MII assessment, can the human walk across the flight deck?);
- relative wind (i.e. can the helicopter approach the flight deck and hold position, will the human be blown off the flight deck?);
- relative motion between the helicopter and flight deck (i.e. can any system, human or not, grasp the haul-down cable? Once attached, can the haul-down winch and cable withstand the forces generated by relative motion?);

For any particular platform type, onboard location and operating procedure, some of these events may be relatively insignificant and other events not mentioned may be very significant; however, since all systems (humans included) involved in this activity experience the same motions, absolute performance criteria must be used. Fortunately, the MII evaluation which is appropriate for the human participation in this activity is relatively easy to express as an absolute performance criterion, at least in the same statistical time- or event-based sense as for the other systems involved. For example, a predicted value of 'n' human MII's per hour compares quantitatively with 'm' exceedences per hour of some vertical velocity or wind criterion. A finite value of 'n' MII's per hour when no other systems exhibit degradation indicates the human should be replaced, or the task modified. A small value of 'n' MII's per hour together with a finite value of 'm' exceedences of cable yield strength indicates the human is not the weak link.

13 Recommendations

1. When evaluating human performance:
    - consider motion sickness, motion-induced interruptions (MII), motion-induced fatigue (MIF), and whole-body vibration (WBV) as separate problems; do not arbitrarily discount the possibility of encountering all four problems on any platform; and,
    - classify activities involving human participation as follows,
        - identify all systems involved and describe how they interact,
        - quantify the duration of activities and determine which events should be modeled to assess performance,
        - determine if human participation is essential (with respect to reasonable alternatives).
2. Develop a method to quantify the process of habituation and its effects on the incidence of motion sickness.
3. Integrate the motion sickness habituation model with the MSI method (McCauley et al., 1976 [109]).
4. Develop a methodology for "tracking" the incidence of motion sickness in a changing environment (see Newman, 1976 [124]).
5. Investigate frequency-domain methods for predicting motion sickness incidence in broad-band motions (following [37, 80, 105]).
6. Modify MII frequency-domain methods to model activities involving interaction between humans and heavy, mobile equipment.
7. Investigate the possibility of quantifying MIF by estimating the work done to remain in position.
8. Compare existing data on naval biodynamic problems with ISO 2631/1 [225] and BS 6841 [191] to determine if relative trends are consistent.

9. Devise experiments and conduct at-sea observations to:

   (a) further test the assumption that motion sickness incidence can be predicted from vertical motions alone (for all reasonable naval environments);

   (b) expand existing data bases on motion sickness incidence and habituation in controlled and random broad-band motions;

   (c) assess the relationship between vomiting incidence, subjective illness and performance;

   (d) assess whether habituation as quantified by a reduction in incidence of vomiting implies a similar reduction in the severity of other symptoms;

   (e) validate the GLFE method [211] for estimating the incidence of MII's in the presence of significant vertical acceleration;

   (f) investigate the relationship between low-frequency, large-amplitude motions and MIF; and,

   (g) assess possible correlation between the GLFE method [211] and motion-induced fatigue.

Acknowledgements

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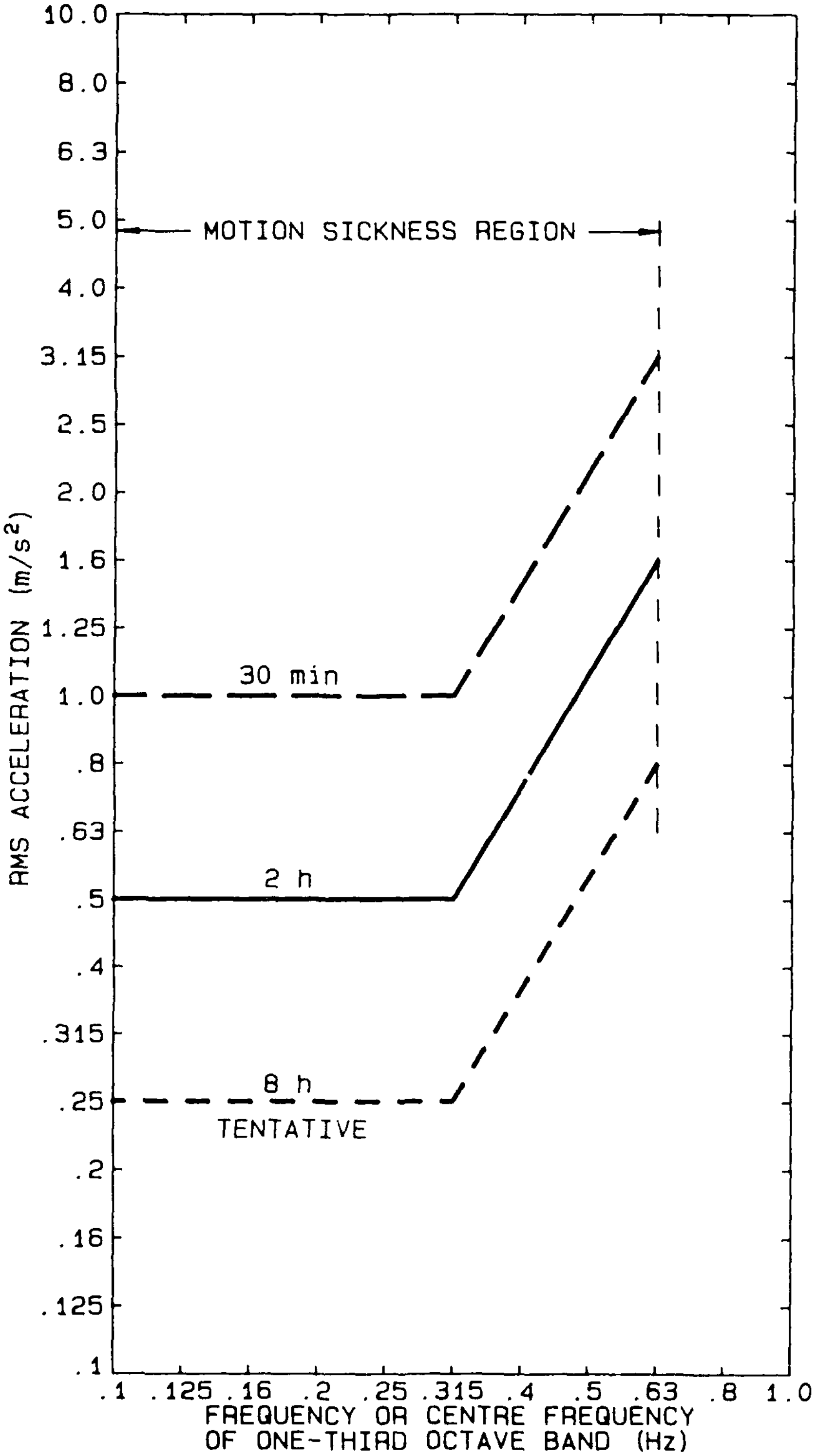

Figure 1: ISO 2631/3 "Severe discomfort boundaries", vertical vibration.

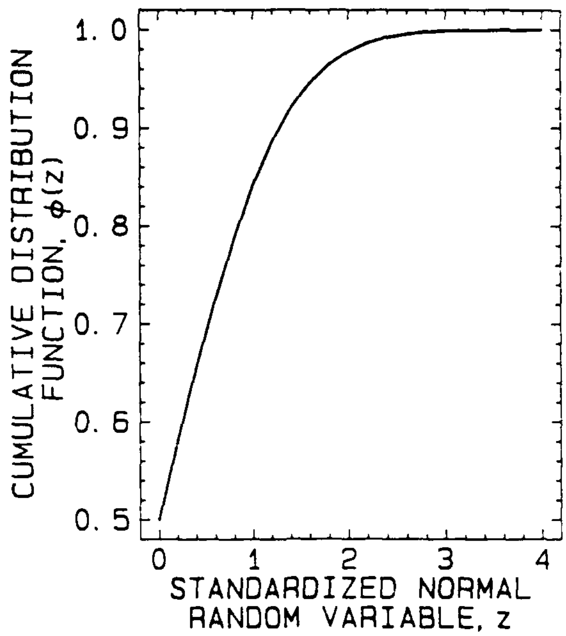

Figure 2: Cumulative Distribution Function, $\Phi(z)$, of the Standardized Normal Random Variable z

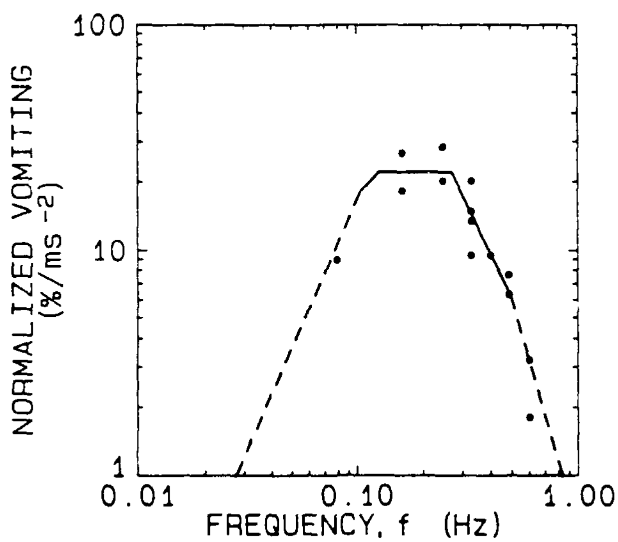

Figure 3: Lawther and Griffin, 1987, Frequency-Weighting Defined by Line-Segment Approximation of Normalized Vomiting vs Frequency Using Experimental Data of McCauley et al., 1976.

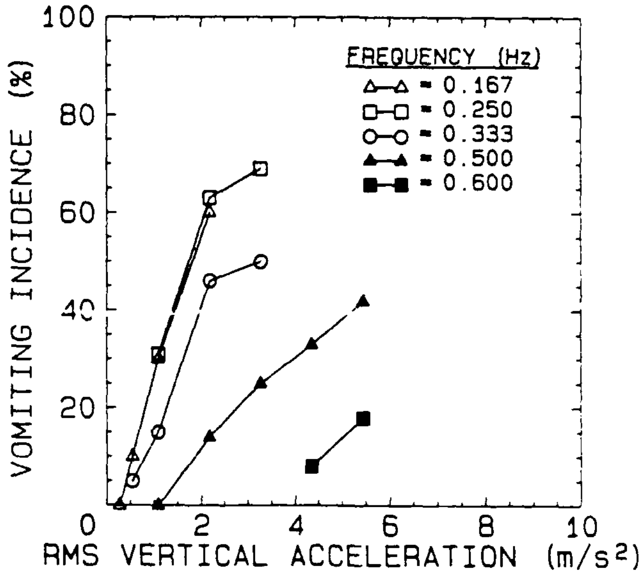

Figure 4: Observed Vomiting Incidence vs Magnitude of Vertical Acceleration at Five Constant Frequencies, from McCauley et al., 1976.

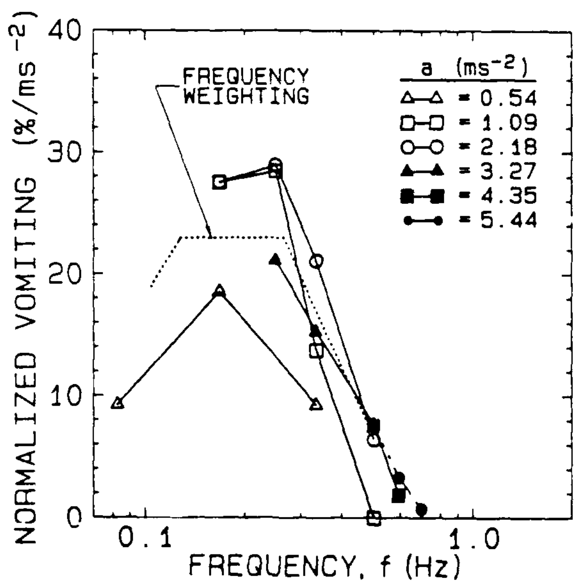

Figure 5: VI Method Frequency Weighting Curve (Dashed Line) and VI Normalized Vomiting vs Frequency, at Six Constant Magnitudes of Acceleration

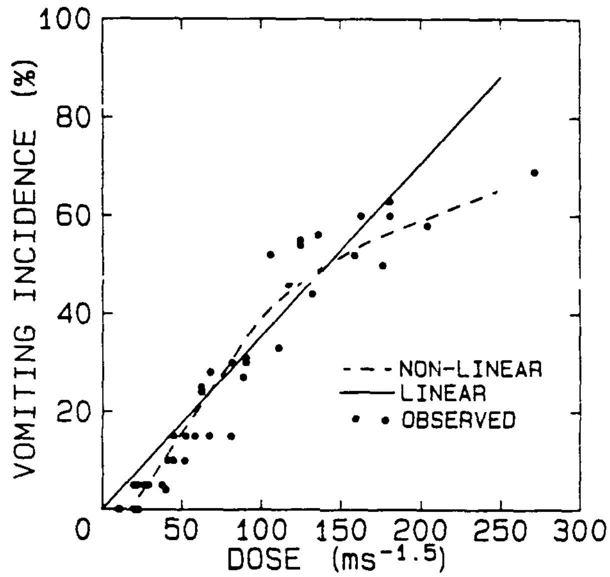

Figure 6: Linear (K Factor) and Non-Linear Curve-Fits to Observed Vomiting Incidence vs VI Method Dose

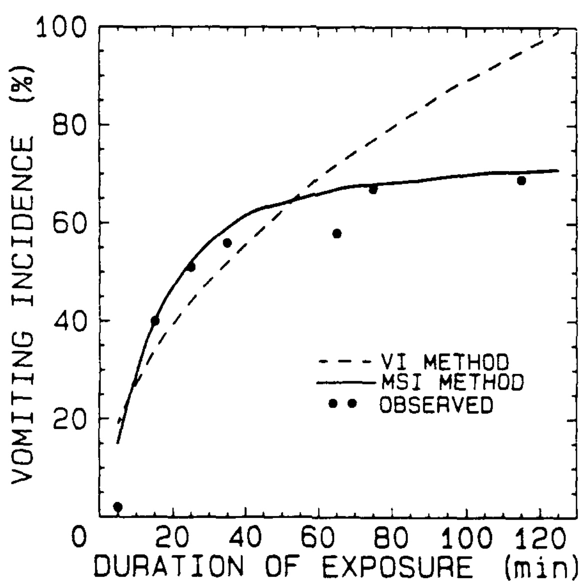

Figure 7: Vomiting Incidence vs Duration of Exposure, Comparison of MSI and VI Methods with Experiments of McCauley et al., 1976, for RMS vertical acceleration of 0.333 (m/s^2)

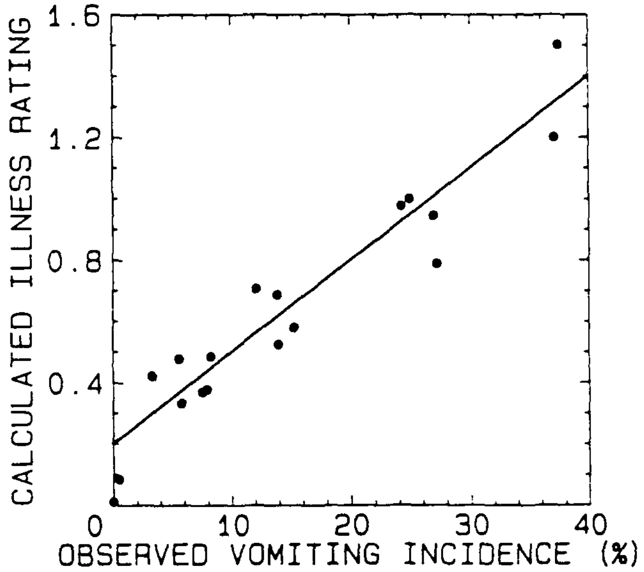

Figure 8: Illness Rating vs Observed Vomiting Incidence, Using Data from Lawther and Griffin, 1986

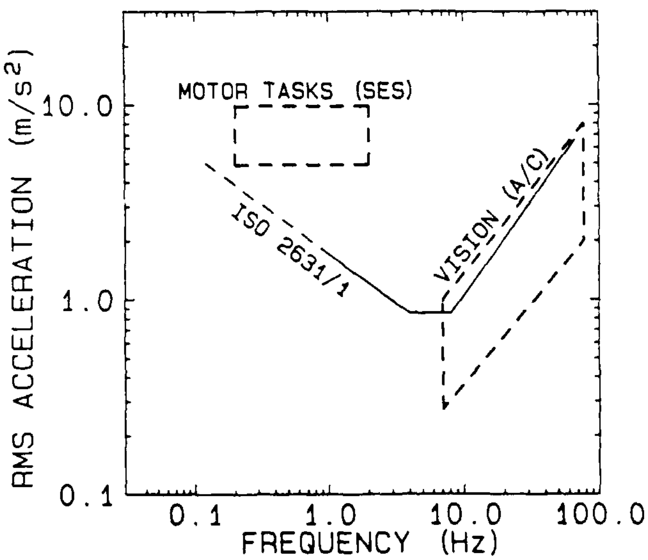

Figure 9: Zones of Significant WBV Problems with Motor Skills in Surface Effect Ship (SES) Motions and with Vision in Aircraft (A/C)

APPENDIX: Comparison of MSI and VI Methods

The MSI and VI methods, as described in Section 4, were implemented in a computer program and used to model the following experiments and observations (upon which the methods are based),

1. O'Hanlon and McCauley, 1974 [126], and McCauley et al., 1976 [109], laboratory experiments with single-frequency vertical, sinusoidal motion, for exposures of approximately 1 and 2 hours (50 experimental conditions), and

2. Lawther and Griffin, 1986 [96]: observations of at-sea behaviour of ferry passengers based on response to questionnaires, for exposures of approximately 3 and 6 hours (22 observations).

The results of this exercise are presented in the following three tables; one table for each reference noted above. Each table defines the input, observed incidence of vomiting, and predicted incidence of vomiting from the two methods. Also, the last three columns define additional information from the VI method.

The following notation is used in this appendix:

f	frequency (Hz)
a	RMS acceleration (g)
t	duration of exposure (min)
MS	observed incidence of motion sickness
MSI'76	MSI method motion sickness incidence (McCauley et al., 1976)
VI'87	VI method vomiting incidence (Lawther and Griffin, 1987)
a(rms)	acceleration (ms^{-2})
$a^\star$	VI method frequency-weighted RMS acceleration (ms^{-2})
dose	VI cumulative dose ($ms^{-1.5}$)

Note that the frequency used in Table A.3 for the data of Lawther and Griffin, 1986 [96], is assumed constant at 0.17 (Hz), based on the "dominant" frequency of a typical acceleration power spectrum for this vessel presented in [96]. As discussed in the text, selecting a single frequency to represent the vessel's broad-band motion is not justified; however, since the same input is used for both MSI and VI methods, the results should be valid for comparative purposes.

Each table sumarizes the average difference and standard deviation between the observed and estimated incidence of motion sickness. The overall results are shown below.

	MSI'76	VI'87
Average Difference (%):	0.9	-3.7
Standard Deviation (%):	6.1	8.0

Table A.1: Comparison of MSI and VI Methods with Experimental Data of O'Hanlon and McCauley, 1974

f (Hz)	a (g)	t (min)	MS (%)	MSI'76 (%)	VI'87 VI (%)	VI'87 a(rms) (ms2)	VI'87 a* (ms-2)	VI'87 dose (ms-1.5)
0.083	0.028	115	0.0	0.5	3.9	0.275	0.134	11.1
0.083	0.055	115	5.0	3.9	7.7	0.539	0.264	21.9
0.167	0.028	115	0.0	2.4	8.1	0.275	0.275	22.8
0.167	0.055	115	10.0	12.2	15.8	0.539	0.540	44.8
0.167	0.111	115	30.0	35.9	31.9	1.089	1.089	90.5
0.167	0.222	115	60.0	64.7	63.9	2.177	2.179	181.0
0.333	0.055	115	5.0	2.6	10.3	0.539	0.351	29.1
0.333	0.111	115	15.0	13.7	20.8	1.089	0.708	58.8
0.333	0.222	115	52.0	37.9	41.5	2.177	1.416	117.6
0.333	0.333	115	52.0	55.1	62.3	3.266	2.123	176.4
0.500	0.111	115	0.0	1.4	8.8	1.089	0.302	25.1
0.500	0.222	115	15.0	8.8	17.7	2.177	0.604	50.1
0.500	0.333	115	25.0	19.1	26.5	3.266	0.905	75.2
0.500	0.444	115	30.0	29.2	35.4	4.354	1.207	100.3
Average Difference (%):				0.9	-4.0			
Standard Deviation (%):				5.5	6.6			

Table A.2: Comparison of MSI and VI Methods with Experimental Data of McCauley et al, 1976

					VI'87			
f (Hz)	a (g)	t (min)	MS (%)	MSI'76 (%)	VI (%)	a(rms) (ms2)	a* (ms-2)	dose (ms-1.5)
0.167	0.111	55	15.0	27.3	22.1	1.089	1.089	62.6
0.167	0.222	55	55.0	58.1	44.2	2.177	2.179	125.1
0.200	0.234	55	69.0	57.8	46.6	2.295	2.296	131.9
0.250	0.111	55	24.0	18.6	22.1	1.089	1.089	62.6
0.250	0.111	65	28.0	20.5	24.0	1.089	1.089	68.0
0.250	0.222	55	54.0	47.2	44.2	2.177	2.179	125.1
0.250	0.222	65	56.0	49.5	48.0	2.177	2.179	136.0
0.250	0.333	65	58.0	67.0	72.0	3.266	3.268	204.1
0.333	0.222	55	15.0	29.3	28.7	2.177	1.416	81.3
0.333	0.222	65	27.0	31.6	31.2	2.177	1.416	88.4
0.333	0.333	65	44.0	49.5	46.8	3.266	2.123	132.6
0.417	0.444	65	33.0	42.0	39.3	4.354	1.781	111.2
0.500	0.222	65	5.0	5.7	13.3	2.177	0.604	37.7
0.500	0.333	55	10.0	12.4	18.4	3.266	0.905	52.0
0.600	0.444	65	4.0	8.3	14.1	4.354	0.639	39.9
0.083	0.027	115	0.0	0.4	3.8	0.265	0.129	10.7
0.083	0.055	115	5.0	3.9	7.7	0.539	0.264	21.9
0.167	0.027	115	0.0	2.2	7.8	0.265	0.265	22.0
0.167	0.055	115	10.0	12.2	15.8	0.539	0.540	44.8
0.167	0.111	115	30.0	35.9	31.9	1.089	1.089	90.5
0.167	0.222	115	60.0	64.7	63.9	2.177	2.179	181.0
0.250	0.111	115	31.0	26.4	31.9	1.089	1.089	90.5
0.250	0.222	115	63.0	55.1	63.9	2.177	2.179	181.0
0.250	0.333	115	69.0	70.8	95.8	3.266	3.268	271.4
0.333	0.055	115	5.0	2.6	10.3	0.539	0.351	29.1
0.333	0.111	115	15.0	13.7	20.8	1.089	0.708	58.8
0.333	0.222	115	46.0	37.9	41.5	2.177	1.416	117.6
0.333	0.333	115	50.0	55.1	62.3	3.266	2.123	176.4
0.500	0.111	115	0.0	1.4	8.8	1.089	0.302	25.1
0.500	0.222	115	14.0	8.8	17.7	2.177	0.604	50.1
0.500	0.333	115	25.0	19.1	26.5	3.266	0.905	75.2
0.500	0.444	115	33.0	29.2	35.4	4.354	1.207	100.3
0.500	0.555	115	42.0	38.2	44.2	5.443	1.509	125.3
0.600	0.444	115	8.0	12.3	18.7	4.354	0.639	53.1
0.600	0.555	115	18.0	18.4	23.4	5.443	0.799	66.3
0.700	0.555	115	4.0	6.6	13.7	5.443	0.466	38.7
Average Difference (%):				-0.3	-3.9			
Standard Deviation (%):				5.8	9.4			

Table A.3: Comparison of MSI and VI Methods with Observations of Lawther and Griffin, 1986.

f (Hz)	a (g)	t (min)	MS (%)	MSI'76 (%)	VI'87 VI (%)	VI'87 a(rms) (ms2)	VI'87 a* (ms-2)	VI'87 dose (ms-1.5)
0.170	0.006	180	0.0	0.0	2.2	0.061	0.061	6.3
0.170	0.049	180	14.0	12.0	17.5	0.477	0.477	49.6
0.170	0.009	180	1.0	0.1	3.4	0.092	0.092	9.6
0.170	0.050	180	14.0	12.8	18.1	0.493	0.494	51.3
0.170	0.031	180	8.0	4.6	11.3	0.308	0.308	32.0
0.170	0.046	180	6.0	10.7	16.5	0.450	0.450	46.8
0.170	0.070	180	27.0	22.2	25.3	0.689	0.690	71.7
0.170	0.042	180	3.0	8.8	15.0	0.408	0.408	42.4
0.170	0.077	180	38.0	25.1	27.6	0.751	0.752	78.1
0.170	0.057	180	24.0	15.9	20.5	0.559	0.559	58.1
0.170	0.034	180	7.0	5.6	12.2	0.331	0.332	34.5
0.170	0.058	180	7.0	16.3	20.8	0.567	0.567	58.9
0.170	0.051	180	13.0	13.3	18.5	0.503	0.503	52.3
0.170	0.040	180	8.0	8.1	14.4	0.391	0.392	40.7
0.170	0.023	180	6.0	1.9	8.2	0.223	0.223	23.1
0.170	0.057	360	37.0	19.0	28.9	0.557	0.557	81.9
0.170	0.031	360	8.0	6.3	15.7	0.302	0.302	44.4
0.170	0.046	360	20.0	13.5	23.3	0.449	0.449	66.1
0.170	0.052	360	25.0	16.9	26.7	0.515	0.515	75.7
0.170	0.034	360	15.0	8.0	17.5	0.337	0.338	49.6
0.170	0.037	360	12.0	9.3	19.0	0.366	0.366	53.8
0.170	0.026	360	8.0	4.4	13.3	0.257	0.257	37.8
Average Difference (%):				3.1	-3.5			
Standard Deviation (%):				6.9	6.8			

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Two types of motion-induced problems affecting human performance in the naval environment are reviewed; motion sickness and biodynamic problems. Methods for predicting the incidence of motion sickness are described and evaluated, and problems associated with modeling complex motions are discussed. References for quantifying habituation are cited and methods for defining the severity of motion sickness symptoms are described. Biodynamic problems are briefly discussed, including the low-frequency, large-amplitude problems of motion-induced interruptions (MII) and fatigue; and the higher-frequency problems of manual control and vision. Methodologies and criteria for evaluating human performance within the systems approach to seakeeping assessment are discussed and topics for future work are recommended.

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