
Increasing Accuracy in the Assessment of Motion Sickness: A Construct Methodology

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Increasing Accuracy in the Assessment of Motion Sickness: A Construct Methodology

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Summary

The purpose of this paper is to introduce a new methodology that should improve the accuracy of the assessment of motion sickness. This construct methodology utilizes both subjective reports of motion sickness and objective measures of physiological correlates to assess motion sickness. Current techniques and methods used in the framework of a construct methodology are inadequate. This paper reviews current assessment techniques for diagnosing motion sickness and space motion sickness and calls attention to the problems with the current methods. Further, we describe in detail principles of psychophysiology that when applied will probably resolve some of these problems.

I. Introduction

The purpose of this paper is to review current techniques for assessing motion sickness malaise in human subjects and to introduce a new "construct" methodology which should improve the accuracy of this assessment. A construct methodology is one in which two or more existing techniques are combined to produce a new method which is appreciably more effective than either of the two original techniques alone. The method proposed in the present paper makes use of two converging indicators of this disorder: subjective reports of motion sickness symptoms and observed physiological correlates.

Subjective assessments of motion sickness symptom severity are derived from verbal reports of internal experiences, similar to reports of pain and fear. Researchers have attempted for decades to quantify the subjective experience of motion sickness by developing diagnostic scales. Clearly, these scales are necessary if one is to assess precisely the effectiveness of therapies for motion sickness. However, in this paper we will make the case that the diagnostic scales currently used to report symptoms both on Earth and in space are insufficient for accurately quantifying motion sickness severity. Further, we will develop the hypothesis that the various scaling techniques utilized make valid comparisons among studies, motion environments, and subject populations virtually impossible.

Objective assessments of symptom severity are derived from recordings of physiological responses, such as peripheral blood flow, electrodermal activity, gastric motility, and heart rate. This paper reviews a number of investigations where such measures were recorded under a variety of stimulus conditions, and describes problems encountered in interpretation of these data due to large individual variability in the way that people respond physiologically. Research which overcomes this difficulty makes use of psychophysiological principles (i.e., rules for interpreting individual differences in human autonomic responding), and are described in detail. We will advance the hypothesis that valid interpretations of physiological correlates of motion sickness without recourse to these psychophysiological principles is virtually impossible.

Lastly, a construct methodology is proposed, with procedures for psychophysiological measurement and analyses which incorporate a sensitive and practical use of diagnostic reporting. A primary goal of research in the field of motion sickness is to control the debilitating effects of this disorder. Only when we can accurately assess motion sickness can we evaluate the effectiveness of countermeasures and improve current therapies. The methodological tool proposed here should contribute significantly to the attainment of this goal.

II. Subjective Assessment of Motion Sickness Symptoms on Earth and in Space

Ground-Based Tests

Motion sickness as experienced on Earth is characterized by a constellation of symptoms, including cold sweating, dizziness, drowsiness, pallor, epigastric awareness, epigastric distress, nausea, and vomiting. It is a widely held theory that these symptoms are a product of sensory conflict involving the vestibular system (refs. 1 and 2). Indeed, individuals without a functioning vestibular system do not develop motion sickness (ref. 3). There are basically three ways of inducing motion sickness on Earth: linear acceleration, angular or rotating acceleration, and visual stimulation. All Earth-based conditions in

which symptoms develop, whether by cars, aircraft, trains, or boats, involve some combination of these three forms of stimulation (ref. 2). Linear accelerations are produced with horizontal or vertical “sleds” and simulators, angular accelerations by rotating chairs or rotating rooms, and visual or optokinetic stimulation by a variety of methods involving a visual surround that provides subjects with visual information that conflicts with vestibular inputs (e.g., visual information indicates motion when there is none) (ref. 2).

On Earth, the evaluation of motion sickness typically involves subjecting test participants to a gradual increase in stimulus intensity (e.g., an increase in rotational velocity in a rotating chair) which enables investigators to observe the time course of the development of symptoms (ref. 4). As the stimulus intensity increases, subjects assess the specificity and intensity of their symptoms, usually with verbal reports. Traditionally, the development of an assessment scale for any perceptual system has been based on methods from sensory psychophysics. Development of a diagnostic scale to assess motion sickness begins with the evaluation of the correspondence between stimulus intensity and sensation and the formation of a psychophysical relationship. Stevens proposed that the perceived magnitude of various sensory dimensions increases in proportion to stimulus intensity, raised to a power (ref. 5). According to Stevens, the correspondence between stimulus intensity and sensation must be established for a diagnostic scale to be valid.

Only Reason and Graybiel have developed a motion sickness scale described in terms of a psychophysical function (ref. 6). These investigators calculated a psychophysical function derived from the magnitude estimations of sensations and the stimulus intensity (angular velocity) of a rotating platform during exposure in the “Slow Rotation Room” (SRR). Subjects estimated the strength of the sensation based on a standard stimulus intensity set at 10 rpm and assigned this standard intensity an arbitrary number of 10. Stimulus intensity at 6, 8, 10, 12, 14, and 16 rpm was presented at random following each of four presentations of the standard. Magnitude estimation and angular velocity were fitted by the method of least squares. The exponent (regression coefficient, or “b” value) derived from this relationship was approximately 2.0, which represents the power that stimulus intensity is raised. Thus, motion sickness sensations increase at a higher rate than the intensity of the stimulus which produced it.

To validate a diagnostic scale with the derivation of a psychophysical relationship, according to Stevens, the diagnostic scale must possess the psychometric characteristics of a ratio scale (ref. 5). Ratio scaling methods are

designed to measure directly sensation magnitude experienced by humans and require the subject to assign numbers to a series of stimuli under instruction to make the numbers proportional to the apparent magnitude of the sensations produced. Subjects also are instructed that a doubling of the numerical estimate corresponds to a doubling of the intensity of the stimulus and there is no limit to either the range or type of numbers used to estimate sensation attributes of the stimulus. The ratios permit subjects to make quantitative estimates of the dimensions in question: either fractionation estimates or absolute numerical estimates. A ratio scale — a scale that possesses a true zero, is the only scale in which the concept of “twice as strong” has meaning. The method of ratio scaling has empirical face validity because subjects are instructed that a doubling of the rating of sensation intensity should correspond to a doubling of stimulus intensity.

Many investigators, including Reason and Graybiel in the study described above, have used a ratio scaling technique for evaluating motion sickness symptoms (refs. 5, 7, and 8). For example, Bock and Oman (ref. 9) instructed subjects to report discomfort levels based on a ratio scale while performing sequences of head movements and wearing left-right vision reversing goggles. The experiment was implemented in three stages. During the initial training period, subjects executed head movements in order to experience a wide range of symptom intensities. The investigators asked subjects to rate a moderate discomfort level as “10” and to rate all other levels that followed with respect to this standard level. They were asked to rate levels half as severe as a “5” and levels twice as severe as “20.” Subjects were also instructed to focus on an overall estimate of sensation discomfort, rather than on discomfort produced by specific symptoms. During the second training period, subjects familiarized themselves and practiced consistently rating discomfort levels. During the third measurement period, subjects performed specific head movements while reporting levels of subjective discomfort at approximately one minute intervals, and occasionally more frequently.

Another scaling method which possesses different psychometric properties than a ratio scale and is frequently used by researchers to assess motion sickness symptoms, is the categorical scale. Similar to ratio scaling techniques, subjects use numbers that are equally spaced to describe stimulus attributes and are instructed to construct equal sensation intervals. Unlike ratio scaling techniques, fractions are not allowed and extreme values of the scale are anchored by numbers supplied by the experimenter. In addition, the subject is not instructed that

a sensation magnitude can be “twice as strong” or “half as strong.”

Several researchers have used categorical scales in their assessment of motion sickness symptoms (refs. 10–12). For example, Dobie and his co-workers (ref. 11) frequently use categorical scales to assess an overall level of motion sickness (from 0 to 10 or 0 to 20) when evaluating the effectiveness of cognitive-behavioral therapy on motion sickness symptoms. In addition to assessing general malaise, a number of investigators have employed categorical scales to assess specific symptoms. In a recent investigation of transfer of adaptation from one motion sickness stimulus to another, Dobie and his co-workers (refs. 11, 13, and 14) employed a categorical scale in which subjects estimated their degree of dizziness (0–20) upon cessation of exposure to active bodily rotation and visually-induced self-vection. Lentz and Guedry (ref. 15) also used a categorical assessment technique that focused on specific symptoms. Subjects rated a number of symptoms, including stomach effects, dizziness, and temperature change, on 7-point scales, with 1 representing favorable or no reaction and 7 indicating extreme reaction.

Two problems with categorical scaling methods are worth noting. First, a psychophysical function derived from a categorical scale does not produce a linear function, but one that varies according to the assignment of the upper and lower limits of the scale (ref. 16). Stevens suggests that this outcome is caused by variation in individuals’ sensitivity. Although subjects are instructed to space the intervals of estimation equidistantly, the typical subject is unable to do so. At the lower end of a scale, discrimination is good; at the upper end of the scale, discrimination

is less easy. The resulting function is described as a slope that is distorted and no longer linear (ref. 5). Second, because categorical scales do not possess the characteristic that a sensation can be “half as strong” or “twice as strong,” critics argue that these scales lack face validity (ref. 5).

By far the most extensively employed scale for assessing motion sickness symptoms is the Pensacola Diagnostic Rating Scale (PDRS). The original scale was based on a symptomology scale developed for research in the SRR (refs. 17 and 18) and was subsequently revised and designated the Pensacola Diagnostic Rating Scale (PDRS) (refs. 19–21). On the basis of data from several investigations, a scale was designed that possessed the psychometric characteristics of an ordinal scale and that included an array of symptomatology that preceded vomiting (ref. 19) (see table 1). Typically, the diagnostic scale is presented to the subject every five minutes of testing and the subject responds verbally. The presence or absence and/or strength of drowsiness, sweating, and salivation are assessed by the subject (mild “I,” moderate “II,” or severe “III”). The subject has the option of rating two levels of increased temperature and dizziness (mild-moderate “I” or moderate-severe “II”). The rating of headache is limited to either present or absent. Nausea is evaluated on five levels; epigastric awareness, epigastric discomfort, and nausea which is reported as either mild (I), moderate (II), or severe (III). Pallor is assessed by an independent observer and reported as either I, II, or III. These symptoms are assigned point values, according to their type and intensity, and a weighted sum is then taken to provide a single numerical score. For example, a subject may report headache (1 point), moderate-severe drowsiness (4 points), and severe sweating (8 points),

Table 1. The Pensacola diagnostic report scale (PDRS)

Malaise level	Points	VMT	TMP	DIZ	HAC	DRZ	SWT	PAL	SAL	NSA	ED	EA
Pathognomic	16	I										
Major	8					III	III	III	III	II,III		
Minor	4					II	II	II	II	I		
Minimal	2					I	I	I	I		I	
AQS ^a	1		I,II	I,II	I							I

VMT = vomiting, TMP = increased warmth, DIZ = dizziness, HAC = headache, DRZ = drowsiness, SWT = sweating, PAL = pallor, NSA = nausea, ED = epigastric discomfort, EA = epigastric awareness.

^aAQS = Also qualifying symptoms

summing to 13 points. Motion sickness scores between 1 and 4 points represent mild malaise (M I); scores between 5 and 7 represent moderate malaise (M IIA and M IIB); scores between 8 and 15 represent severe malaise (MII); and scores greater than or equal to 16 points represent frank sickness.

Microgravity or Spaceflight

The symptoms of space motion sickness (SMS), to a great extent parallel motion sickness symptoms that occur on Earth (ref. 22). In contrast to ground-based motion sickness, SMS is believed to be caused by a lack of stimulation to the gravity-sensing organs in the vestibular system. The type of stimulation to the inner ear experienced in space is unique to that environment and cannot be duplicated (except for brief microgravity exposure during parabolic flight) in Earth-based tests.

Prior to Shuttle flights (STS-1; 1981), no systematic method to assess quantitatively motion sickness symptoms occurring under operational conditions during spaceflight was pursued. During early space flights, e.g., Apollo (1968–1972), monitoring of space motion sickness was limited to verbal reports by the astronauts during post-flight medical debriefing (refs. 23 and 24). Although astronauts may have reported detailed descriptions during debriefing, relatively few details have been documented in the scientific literature. The descriptions given in the literature are anecdotal, primarily describing symptoms such as stomach awareness, nausea, and vomiting (ref. 23). During the Skylab flights (1973), SMS was investigated in a slightly more systematic manner (refs. 25 and 26). Astronauts were subjected to a rotating chair test preflight, inflight, and post-flight. During all testing, symptoms were evaluated with the PDRS. Under inflight testing conditions astronauts were virtually symptom free, reporting only slight sweating and dizziness. Under inflight operational conditions, identification of symptoms was not structured according to the PDRS and was limited to verbal descriptions, for example, “decreased appetite” or “epigastric awareness.” During debriefing, with more extensive detailing of the events that occurred during spaceflight, it became evident to investigators that the crew had experienced difficulty in diagnosing the symptoms of motion sickness under inflight operational conditions and were often in error.

During STS-9 (1983), investigators designed a detailed method to collect data on symptoms (ref. 27). For this purpose, crew members were provided with a pocket recorder and a symptom checklist; they were instructed to report symptoms as they occurred. This checklist assessed signs of 20 specific symptoms based on a 4-point scale: absent/slight/moderate/intense. Unfortunately, operational

considerations limited the amount of time allowed for the completion of the checklist throughout the mission. When time was limited, astronauts evaluated their symptoms based on a single score by means of a ratio scaling technique (ref. 9). They were asked to choose a sensation magnitude halfway to vomiting, a sensation corresponding to the number “10.” Thus, a score of “0” represented the absence of symptoms and a score of “20” represented vomiting. To date, these reports provide the most detailed description and time course of inflight symptoms (refs. 8 and 27).

In an effort to predict susceptibility to space motion sickness from ground-based studies, a team of investigators collaborated on the development of an extensive protocol for assessing space motion sickness during Shuttle flights (ref. 28). This protocol was designed to familiarize astronauts in observing and reporting motion sickness symptoms during flight. Crew members participated in motion sickness tests preflight and their symptoms were evaluated with the PDRS. During Shuttle flights STS-1 through STS-4 (1981–1982), crew members were asked to record symptoms they experienced during the day on a micro cassette tape recorder and symptom checklist that was similar to the PDRS (refs. 29 and 30). This report was to be made at a designated time (pre-sleep) on each day.

Cowings et al. (refs. 31 and 32) used a similar approach during the Spacelab-3 (1985) and Spacelab-J (1992) missions. During preflight motion sickness tests in the laboratory and in aircraft, crewmembers were taught how to use the PDRS to self-assess their symptom levels. During the mission, crewmembers were provided with a diagnostic log book, a pocket-sized notebook with the PDRS printed on each page. The log book was used as an 11-item checklist on which the crewmembers could self-report symptoms by checking the appropriate box of the PDRS scale. Timeline diagnostic reports were performed during pre- and post-sleep periods and symptom-contingent reports were made whenever symptoms arose during the mission. This approach worked well, as it had a number of advantages over previous approaches. Crew privacy was better assured with a written log book as entries were coded (i.e., each crewmember was assigned an identification number known only to himself and the investigators, and therefore no names or mission positions were entered in the log book). Also, other crewmembers in the subject’s immediate vicinity could not “overhear” verbal reports of symptoms as they could with the micro cassette. Providing crew privacy tends to elicit greater cooperation, but the value of any diagnostic scoring technique depends on the subject’s willingness to perform it as specified by the investigators. In this investigation, like previous approaches, symptom-contingent

reports were rarely done at the time of symptom onset (due to inflight operational time constraints) but were written later in the day, usually during the presleep activity period.

Because the methods of evaluating motion sickness varied across 24 Shuttle missions, it was difficult to ascertain the exact frequency of symptoms. In 1984 a standardized questionnaire was developed at Johnson Space Center (ref. 28) which graded motion sickness according to the following levels:

- | | |
|----------|---|
| None | No signs or symptoms reported with exception of mild transient headache or mild decreased appetite. |
| Mild | One to several symptoms of a mild nature; may be transient and only brought on as the result of head movements; no operational impact; may include a single episode of retching or vomiting; all symptoms resolved in 36 to 48 hours. |
| Moderate | Several symptoms of a relatively persistent nature which wax and wane; loss of appetite; general malaise, lethargy and epigastric discomfort may be the most dominant symptoms; includes no more than two vomiting episodes; minimal operational impact, all symptoms resolved within 72 hours. |
| Severe | Several symptoms of a relatively persistent nature that may wax and wane; in addition to loss of appetite and stomach discomfort, malaise and/or lethargy are pronounced; strong desire not to move head; includes more than two episodes of vomiting; significant performance decrement may be apparent; symptoms may persist beyond 72 hours. |

Transcripts of medical debriefings were analyzed retrospectively from 24 shuttle flights for 85 crewmembers representing 125 individual exposures to weightlessness. Fifty-seven cases of motion sickness were reported; 26 were classified as mildly sick, 20 as moderately sick, and 11 as severely sick (ref. 33). As we can see, the use of subjective reports on the severity of SMS symptoms experienced cover a wide range (where a single vomiting episode may be described as "mild"), and there has been very little consistency between measures taken in space and those observed during ground-based motion sickness tests.

III. Objective Assessment of Motion Sickness: Physiological Correlates

There are few consistencies in the methods which investigators have chosen to assess physiological responses and symptoms in the framework of a construct methodology. Some investigators have approached the problem of relating physiological and self-reported symptoms by differentiating groups based on their symptoms and examining the differences in physiological responses among these groups. Crampton, for example, reported differences in physiological responses between subjects who experienced different symptoms, according to these three groups: (1) not-sick – subjects who experienced symptoms other than nausea, (2) nausea-only – subjects who experienced nausea only, and (3) vomiters – subjects who experienced emesis (ref. 3). Although a high degree of variability was present among subjects, vasoconstriction, increased pulse rate, increased gastric motility, sweating, and pallor distinguished the vomiters from the not-sick subjects.

Hu and co-workers classified subjects based on a constellation of symptoms derived from the PDRS (ref. 34). Subjects reported symptoms every two minutes during a 16-minute exposure to a rotating optokinetic drum. Individuals were categorized into four groups based on their reported symptoms: Group A subjects reported nausea; Group B subjects reported no nausea, but cold sweating; Group C reported no nausea, no cold sweating, but other less severe symptoms, such as stomach awareness, dizziness, headache, warmth, and salivation; Group D reported no symptoms. Compared to individuals in the other groups, individuals in group A had increased activity in electrogastrogram (4–9 cpm), skin conductance, and decreased heart rate variability. In addition, significant correlations were found between a mean symptom score for the 16-minute rotation period and electrogastrogram 4–9 cpm, skin conductance, and decreased heart rate variability.

In a recent study, Uijtdehaage (ref. 35) categorized subjects into two groups. One group consisted of subjects who reported motion sickness symptoms, including stomach discomfort or nausea, and the other group reported motion sickness symptoms excluding stomach discomfort or nausea. Motion sickness symptoms were assessed with the PDRS every 2 minutes during a 16-minute exposure to a rotating optokinetic drum. Distinct physiological differences in heart rate, electrogastrograms, and respiratory sinus arrhythmia emerged between the two groups during rotation.

Stern and his co-workers extended their earlier findings, examining the relationship between visually induced motion sickness and gastric myoelectric activity (ref. 36). The authors reported a significant positive relationship between the number of subjects who experienced symptoms, (using the PDRS) and electrogastrogram (EGG) 4–9 cpm activity during drum rotation, but they did not report a correlation coefficient (ref. 36).

The degree of correspondence between symptoms and physiological responses was further analyzed in two experiments examining conditions under which subjects adapted to repeated exposures to an optokinetic stimulus (ref. 37). These experiments varied in the time between exposures to motion stimuli. In the first, 10 subjects were given 3 motion sickness tests, separated by 4 to 24 days. During these 15-minute tests, subjects were instructed to indicate the severity of their symptoms on a scale from 0 (no symptoms) to 7 (near vomiting). Although the authors did not report how often subjects rated these symptoms, group mean scores were reported at 3.5, 3.7, and 3.3, for tests 1, 2, and 3, respectively. Because the average symptom levels reported and degree of tachy-gastria observed were similar across these tests, the authors concluded that subjects had not habituated to repeated test exposures. There is no description in this paper of the time-course of the development of symptoms or whether or not the degree (i.e., frequency) of tachy-gastria was related to different symptom levels. In the second experiment, 14 subjects were instructed to indicate the intensity of their symptoms using the PDRS during three motion sickness tests, separated by 48 hours. The investigators reported that subjects did show habituation, with both symptom scores and tachy-gastria decreasing across tests. Although the authors reported a significant correlation between tachy-gastria and symptom levels, no correlation coefficients were presented.

Cowings et al. also attempted to determine the relationship between several different physiological responses and diagnostic reports (PDRS) in large samples of subjects (ref. 38). They reported significant correlations between initial symptom scores and changes from the first to the fifth minute of rotation for both heart rate and basal skin resistance.

The research described in this section establishes a link between physiological responses and motion sickness symptoms and indicate that physiological responses vary according to the level of symptom intensity. However, these methodologies do not trace the course of symptom progression and physiological changes simultaneously. In the studies presented below, the time course of symptoms

and their relationship to physiological responses are more closely examined.

At Wright-Patterson Air Force Base, a collaborative effort between five investigators focused on development of a mathematical model integrating reported discomfort and several physiological parameters (refs. 39–43). Based on subjective reports of discomfort obtained by rating sensation on a scale of 1 (asymptomatic) to 10 (emesis was imminent), these equations predicted a level of motion sickness from respiration rate and volume, finger pulse volume, galvanic skin response, heart rate, and temperature.

The correspondence between skin conductance levels and symptoms was investigated by Golding (ref. 44). Golding employed both cross-coupled accelerations and linear accelerations to provoke motion sickness symptoms. During cross-coupled accelerations, subjects reported their well-being on a scale from 1 to 4, (1 = OK; 2 = very mild symptoms; 3 = mild nausea; 4 = moderate nausea). During linear accelerations, subjects indicated their discomfort on a scale from 1 to 7 every minute (1 = no symptoms; 2 = any slight symptoms; 3 = more symptoms but no nausea; 4 = mild nausea; 5 = mild to moderate nausea; 6 = moderate nausea but can continue; 7 = moderate nausea wish to stop). Skin conductance results from each motion sickness level (1–4; 1–7) were compared in two separate analyses. Results from analyses of both stimuli indicated that sweat activity increased as symptom levels increased.

Similar analyses were conducted by Cowings et al. (ref. 45). However, in addition to skin conductance, they used heart rate, blood volume pulse, and respiration rate. The investigators made comparisons of two separate motion sickness tests on each of 58 subjects. Using an analysis of covariance (ANCOVA), she showed that the magnitude of responses varied according to severity of reported symptom. For each of the physiological variables, there was a significant difference in response levels observed between baseline (PDRS = 0), mild symptoms (PDRS = 1 to 4), and severe malaise (PDRS \geq 8).

Recently, we examined the relationship between three physiological responses and malaise across the entire motion sickness test for 33 subjects (ref. 46). Our results indicated that malaise is positively related to change in heart rate and respiration rate, and negatively related to changes in blood volume pulse across the time course of the motion sickness test. As heart rate and respiration rate increase and blood volume decreases, malaise levels increase.

IV. The Use of Psychophysiological Techniques to Assess Motion Sickness

As described above, a variety of physiological parameters such as heart rate, blood pressure, blood volume pulse, respiratory rate, gastrointestinal, and electrodermal responses have been measured during motion sickness testing (refs. 25, 34, 36, 40, 44, and 47). As psychophysiologicalists have discovered while measuring these parameters, there are certain characteristics and problems unique to these responses that must be addressed and considered when designing methodologies to study these parameters. Without recognizing and addressing these characteristics and problems it is difficult to establish a valid construct methodology. Within the field of psychophysiology a number of principles have emerged that are designed to facilitate interpretation of human physiological data. Below, we describe these principles, characteristics, and problems inherent in measuring physiological responses that occur during motion sickness testing. We also describe the research that has spawned much of this information and the methods that researchers have used to overcome some of these problems.

Early studies of motion sickness invariably revealed a large degree of individual variability of physiological responses and differences in responses across different tests. Because physiological reactions to motion stimuli were not consistent across and even within participating in different types of tests, Money concluded that physiological information could not be used to represent motion sickness (ref. 48). Crampton also concluded that, despite significant group differences, there remained so much individual variability that he questioned the value of using autonomic nervous system (ANS) measures to characterize motion sickness (ref. 3). Instead of ignoring individual differences in autonomic reactivity, we and others (refs. 43 and 47) suggest that it would be useful to address the sources of this variability in the study of physiological responses.

A large part of individual variability is related to individual differences in response stereotypy. The phenomenon of "individual response stereotypy," the propensity of individuals to respond maximally in the same ANS variable to a variety of different stimuli, is well known in the psychophysiological literature (refs. 4, 49, 50–52). For example, in the presence of any stimulus (for example, a loud noise), all subjects may show a rise in heart rate, but some individuals will make a much larger response than others. And for any given individual, the heart rate response may be of greater

magnitude than his or her skin resistance level or other measured response. To examine this principle, Cowings and her colleagues made comparisons of two separate motion sickness tests on each of 58 subjects (ref. 45). The goal of this study was to identify individual response patterns and to determine if they were stable from test to test. The ANS variables of heart rate, respiration rate, finger pulse volume, and skin resistance were monitored because they are easily measured, represent different aspects of the ANS, and had been used in previous studies on motion sickness.

In their examination of the stability of individual response patterns, Cowings et al. considered the psychophysiological phenomenon, known as "the law of initial values" (LIV) (ref. 53), according to which an autonomic response to stimulation is a function of the pre-stimulus level. Thus, as Wilder has described it, "The higher the prestimulus level of functioning, the smaller the response to function-increasing stimuli. And, at more extreme prestimulus levels there is more tendency for no response to stimulation and even for a paradoxical response, those which reverse the typical direction of the response" (ref. 53). Hence, it can be seen that both the extent to which a subject will react to a stressor (e.g., motion sickness stimulus) and the extent to which his or her response is different from another subjects' response is largely dependent on his or her prestimulus activity level.

To correct for individual differences in pre-stimulus levels in the Cowings et al. study, an analysis of covariance (ANCOVA) was performed, using the pre-test baseline data as the covariate and motion sickness tests 1 and 2 as the repeated measures. Using the results of this ANCOVA, the physiological data were transformed to standard scores which enabled comparisons across different physiological responses by providing a common unit of measurement. The results revealed 11 separate patterns of physiological responding in which all or some combination of the four physiological measures clearly reflected severe motion sickness malaise (MIII, where PDRS \geq 8) during the final minute of the tests of each of the 58 subjects. Individual response patterns produced on the first tests were not significantly different from those of the second test. Analyses showed that of the 58 subjects, 27 showed the stable response patterns on both rotating chair tests for all four physiological measures, 14 were stable for three variables, 6 were stable for two and 11 were stable responders for at least one variable (see fig. 1).

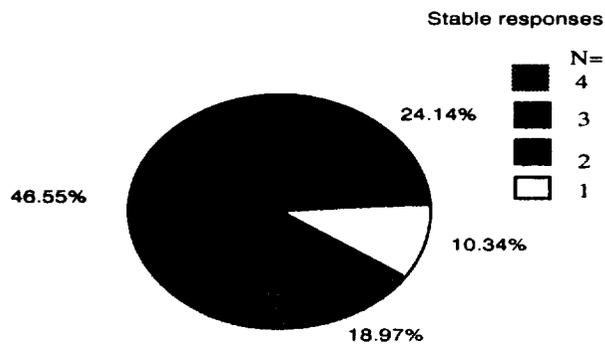


Figure 1. Proportion of subjects showing stability in ANS responses across two tests. (N = 58).

In addition to addressing the issue of response stereotypy and the law of initial values in individual variability, Cowings and her colleagues attempted to describe general ANS changes before, during, and after motion sickness stimulation in a large sample of people and determine whether high-, moderate-, and low- susceptible individuals differ in their ANS response to motion sickness stimulation and could also be a source of individual variability (ref. 38). One hundred and twenty-seven people were given a rotating chair motion sickness test in order to describe the general trend of their ANS responses. Earlier work by Cowings et al. suggested that differences in initial susceptibility may account for at

least one major source of variability in ANS responding (ref. 54). The study therefore investigated differences in high-, moderate-, and low-susceptible groups in terms of ANS responding to motion stimulation. Susceptibility was defined on the basis of duration of time the subject could withstand rotation before reaching severe malaise (MIII, see table 1): 15 minutes or less = high susceptible group; 16–30 minutes = moderate susceptible group and >30 minutes = low susceptible group. In this way, they also could determine if specific autonomic responses could serve as *predictors* of motion sickness susceptibility. The ANS variables of heart rate, respiration rate, finger pulse volume, and skin resistance were monitored. The results revealed sympathetic activation of all four ANS responses during motion sickness stimulation. Physiological response levels changed rapidly and dramatically at the onset of stimulation and at the conclusion of the test. Differences in ANS responding among motion sickness susceptibility groups were observed, with highly susceptible subjects producing, in general, changes of greater magnitude than the moderate or low susceptible subjects. Table 2 shows the distribution of different symptoms reported by susceptibility groups (high = 15 minutes of rotation or less; moderate = 16–30 minutes of rotation; low = greater than 30 minutes of rotation) after five minutes of motion stimulation, and at the end of the test when subjects had reached severe malaise level (MIII).

Table 2. Frequency of each symptom reported by groups after 5 minutes of rotation and at the end of the test (Malaise Level III)

Groups	N	VMT	TMP	DIZ	HAC	DRZ	SWT	PAL	SAL	NSA	ED	EA
After 5 minutes of the rotating chair test												
High	46	0	34	33	12	10	22	1	19	6	6	20
Moderate	43	0	20	19	4	5	8	1	7	0	2	14
Low	38	0	8	15	1	0	3	0	5	0	0	4
At the end of the test												
High	46	1	42	40	14	12	38	21	26	38	7	0
Moderate	43	1	34	34	6	14	36	20	20	36	4	1
Low	38	4	26	24	4	10	22	25	18	25	4	1

VMT = vomiting, TMP = increased warmth, DIZ = dizziness, HAC = headache, DRZ = drowsiness, SWT = sweating, PAL = pallor, NSA = nausea, ED = epigastric discomfort, EA = epigastric awareness.

A more sensitive means of determining the reproducibility of autonomic changes entails assessing the reliability of responses across five motion sickness tests (ref. 46). This investigator determined the reliability across multiple days of testing for four autonomic responses and concluded that heart rate, blood volume pulse, and respiration rate were reliable after five test occasions. These findings, despite the disparity in statistical approaches, not only replicate the Cowings study (ref. 45), but extend these findings from two to five days of motion sickness testing. Establishing the reproducibility of autonomic responding to a specific stimulus is important when evaluating the impact of an intervention or countermeasure on autonomic responding. Clearly, if responses to a specific stimulus are variable from test to test, the impact of an intervention cannot be accurately assessed.

As mentioned, individual response stereotypy is one psychophysiological principle that has greatly influenced Cowings et al. in their determination of individual autonomic response profiles. A second important principle is "stimulus specificity," which refers to the fact that a single stimulus evokes a consistent hierarchy of responses within a group of subjects. A study performed in the Cowings laboratory (ref. 55) examined physiological responses to three types of motion sickness tests: rotating chair, vertical acceleration, and optokinetic stimulation. Results showed that individual subjects differed in the length of time they could tolerate these tests (i.e., some had greater tolerance for vertical acceleration than for rotation). However, virtually all subjects succumbed to optokinetic stimulation in a comparatively short period of time. Despite differences in tolerance, when subjects reached MIII (severe malaise) as defined by the PDRS, there was no significant difference in their autonomic stress profiles across the three stimulus conditions. Change scores from pretest baseline to the end of tests showed no significant differences for heart rate, respiration rate, skin conductance, or blood volume pulse. These investigators concluded that individuals tend to respond maximally with specific idiosyncratic response patterns, regardless of the motion sickness stimulus.

V. A Proposed Construct Methodology

Investigators can improve current construct methodology by addressing several methodological issues in assessing subjective symptoms and objective physiological responses. To provide a precise determination of the time course of symptoms both in space and on Earth, the evaluation of symptoms and responses must meet certain criteria. These criteria are presented below.

First, the diagnostic scales should be based on psychometric properties characteristic of ratio scales and these scales must be validated by comparing sensations to stimulus intensity. The diagnostic scale developed by Bock and Oman (ref. 9) and subsequently employed in Spacelab-1 (ref. 27) fulfills this criterion. However, it might be more practical when attempting to assess symptom levels in the field or in spaceflight, to use a scale with a narrower range of symptoms reports (e.g., mild, moderate, severe) such as used in the PDRS or a scale similar to that used by Golding (1 to 4) (ref. 44). Second, our diagnostic scales must be consistent so that comparisons can be made between the symptoms that occur on Earth and those that occur in space. Unfortunately, the types of scales used to describe the severity of symptoms cover a wide range. To facilitate agreement in the interpretation of symptom report levels, it is good practice for the diagnostic report method to be one that is generally used in the field.

Third, symptoms must be reported as they occur, both in flight and during ground-based testing. Typically during a ground-based test, symptoms are reported every 5 minutes, although in more recent research this method is changing and symptoms are being reported more frequently (refs. 35 and 44). During space missions, the frequency of symptom reporting varied from reporting as the symptoms occurred (Spacelab-1) (ref. 27) to post-flight debriefings. When reviewing current literature in this field, it is apparent that even when physiological responses are recorded continuously, subjects report their symptoms at discrete time intervals which tends to conceal the temporal pattern and progression of symptom development. The PDRS, which is the most commonly used symptom measure, was designed for symptom recording only at 5-minute intervals (refs. 38 and 54). More frequent reports, (i.e., one a minute), using diagnostic scales like the PDRS, would improve the power of analyses on the correspondence between physiology and malaise.

It would be optimal if a method could be devised for continuous, or near-continuous, recording of symptoms that parallels the recording of physiological responses. Such a method would enable greater precision in characterizing the progression and decline of symptoms and their relationship to physiological responses. Use of a key-pad designed to allow the subject to report specific symptoms and their intensities at his own discretion might be an even better technique for establishing this relationship. The PDRS might be applied in this way, with a single thumb-press indicating "epigastric awareness," two thumb-presses indicating "epigastric discomfort," a single index finger press indicating "mild nausea," and so on, using different fingers and specific numbers of button

presses to describe the perceived intensity of specific symptoms as they are experienced. Laboratory experiments could easily be conducted to test such an approach.

Fourth, in the current literature, most investigators use an overall indicator of symptom well-being and compare this index to specific physiological responses, ignoring the assessment of specific symptoms. This index is either based on a composite score, as with the PDRS, or an indicator of overall malaise, such as "I feel discomfort." A composite score provides a relevant indication of motion sickness because it encompasses the entire spectrum of symptoms and signs of motion sickness. However, information on specific symptoms is lost in the calculation of a single composite score and the information provided is incomplete. In refining the assessment of motion sickness, it would, perhaps, be more valuable to examine individual types of symptoms (pallor, sweating, etc.), as well as their perceived intensity as they are related to changes in physiology.

For the optimal use of objective physiological indicators, four factors must be present. First, physiological recordings must be made continuously, not at discrete intervals, since the time course of symptom onset differs widely among subjects. Graybiel and Lackner investigated the relationship between motion sickness reports and blood pressure, pulse rate, and body temperature (ref. 56). The physiological measures were taken at discrete intervals throughout the test. These investigators saw no change in physiological response levels and therefore concluded that there was no relationship between these responses and malaise. However, this measurement approach may have led them to "miss" critical changes in response levels which occur very rapidly at stimulus onset or termination, and can therefore, only be detected reliably with continuous, rather than periodic, response measures (ref. 38).

Second, there must be a sufficient number of different physiological measures taken since some individual variability in responding may be masked if relevant parameters are not measured. Third, establishment of these response profiles requires that data be obtained under multiple baseline conditions, preferably including: (a) resting; (b) ambulatory; and (c) at least two types of motion sickness tests (e.g., rotating chair and vertical accelerator). Finally, psychophysiological principles (e.g., the LIV, individual response stereotypy), must be taken into account when interpreting the data.

VI. Conclusions

Motion sickness is a construct, an abstract idea, that can be represented and therefore measured, in a number of ways. The presence of motion sickness can be identified by subjective reports and by physiological changes. In measuring the construct of motion sickness, it is logical to conclude that the combination of both of these types of measures is preferable to either one alone. Physiological measures combined with symptom reports can increase the accuracy of motion sickness diagnosis, if the following criteria are met:

1. The diagnostic report method possess the characteristics of a ratio scale and is in general use in the field so that agreement in the interpretation of symptom report levels can be facilitated.
2. Symptom reporting is done continuously to establish the relationship between the time-course of symptom development and physiological changes. Where this is not feasible, reporting frequently (e.g., once a minute), would serve this purpose.
3. Reports are obtained on individual types of symptoms (pallor, sweating, etc.) as well as their perceived intensity.
4. Physiological responses are recorded continuously, not just at discrete intervals, since the time course of symptom onset differs widely among subjects.
5. A sufficient number of different physiological measures are taken, since some individual variability in responding can be masked if relevant parameters are not measured.
6. Individual response profiles are obtained using multiple baseline conditions, preferably including: (a) resting; (b) ambulatory; and (c) at least two types of motion sickness tests (e.g., rotating chair and vertical accelerator).
7. Psychophysiological principles such as law of initial values and individual response stereotypy are taken into account when interpreting the data obtained.

The critical importance of assessing the correspondence between physiological responses and symptoms cannot be over-emphasized. The selection of optimal strategies to counteract motion sickness symptoms is guided by our accurate assessment of motion sickness. Clearly, the use of both continuous symptom reporting and physiological recording during ground-based testing and in spaceflight

would add greatly to our accuracy to assess both motion sickness and countermeasures. The value of continuous symptom recording cannot be underestimated. On the basis of symptom data collected from ground-based studies and space missions, we cannot predict

susceptibility to symptoms. Potentially, our understanding of these dynamics can add to our predictive potential and provide useful avenues to supplement current countermeasures and develop new countermeasures to combat motion sickness.

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