VISION MOTION-INDUCED SICKNESS IN NAVY FLIGHT SIMULATORS: GUIDELINES

LCDR Michael G. Lilienthal
Naval Training Systems Center
Orlando, Florida 32813-7100

Robert S. Kennedy, Ph.D.
Kevin Berbaum, Ph.D.
Essex Corporation
Orlando, Florida 32803

LT James Hooper
Naval Air Systems Command
Washington, DC 20361-1205

ABSTRACT

Since 1982 the Naval Training Systems Center, with support from the Office of Naval Technology and the Naval Air Systems Command, has been investigating the occurrence of simulator sickness in Navy flight simulators. Simulator sickness is defined as that group of symptoms experienced by crew members in connection with maneuvers in flight simulators which would not be experienced by those same crew members in aircraft. Symptoms include nausea, dizziness, general discomfort, eyestrain, headache, disequilibrium, and pallor. In rare cases there have been aftereffects (e.g., visual flashbacks and disorientation) that have occurred up to 12 hours after exposure to the simulators. This paper reviews results of the Navy's research and subsequent recommendations that have been provided to Navy trainer acquisition managers who formulate specifications for future flight simulators. The rationale for these suggestions is derived from literature reviews, field observations, laboratory experimentation, and the results of a biomedical panel convened to address the simulator sickness problem.

Background

Training, the military's primary mission during peacetime, has large and continuing demands on the financial resources allocated to the Department of Defense. For example, it costs about $3.6 billion per year for fuel and supplies needed to operate military aircraft in the United States. Many of these operations are conducted for training purposes. Flight simulators, however, can be operated at costs that vary from 5%-20% of the cost to operate comparable aircraft [20]. Generally, pilots trained in simulators can acquire necessary mission skills with fewer flight hours than those pilots who are not trained in simulators.

Advancing engineering technologies permit a range of capabilities to simulate the real world through very compelling kinematics and computer generated visual scenes. This synthetic vestibular and visual environment can, on occasion, be so successful that conflict is established among the different forms of sensory input. This discrepancy adheres most closely to the cue conflict theory of motion sickness which has been accepted as the working model for a phenomenon labeled as simulator sickness [10]. In brief, the model postulates the referencing of motion information signaled by the retina, vestibular apparatus or proprioception to "expected" values based on a neural store which reflects past experience. A conflict between expected and experienced flight dynamics of sufficient magnitude can exceed a pilot's ability to adapt, inducing in some cases simulator sickness [10].

Simulator sickness is considered to be a form of motion sickness. Motion sickness is a general term for the constellation of symptoms which result from exposure to changing accelerations, but occasionally changing visual motions may also induce the malady. Motion sickness is characterized by vomiting and retching, and has overt signs of pallor, sweating, salivation, drowsiness, and nausea [12].

The symptoms of simulator sickness found in Table 1 parallel those of motion sickness [12, 19] and can produce serious residual aftereffects in pilots [6, 17]. Differences between the symptoms of simulator sickness and more common forms of motion sickness are that in simulator sickness, visual symptoms tend to predominate and vomiting is rare. The aftereffects already pose a threat to operational readiness because, in some simulators, pilots are restricted in their activities after simulator hops.

Navy Programmed Study of Simulator Sickness

For the past five years, the Navy has conducted a program of research on simulator sickness. This program was initiated to (1) provide problem definition using field survey data [6, 11, 13, 14], (2) conduct a review of the literature [3, 4, 5, 12], and (3) convene a workshop [15].

Results from the 10 Navy flight simulators that have been surveyed show a variation in their incidence from 10%-60% [11]. Table 2 provides the results by simulator. Table 3 shows the self-reported incidence of four characteristic symptoms of motion sickness (which are also characteristic of simulator sickness) -- dizziness with eyes open, vertigo, stomach awareness, and nausea for each of the 10 simulators. The samples for each symptom exclude instances in which symptoms occurred prior to simulator exposure.

Table 4 presents for each simulator the self-reported incidence and frequency of eyestrain symptoms -- headache, eyestrain, and difficulty focusing. These symptoms are less likely than motion sickness symptoms to habituate during training. Again, pilots employed were those who were free of symptoms upon entering the simulator. From these tables it is clear that some simulators elicit symptoms in few individuals, whereas other simulators elicit symptoms in many.

TABLE 1. DIAGNOSTIC CATEGORIZATION OF SIMULATOR SICKNESS

PATHOGENIC SYMPTOM
- Vomit

MAJOR SYMPTOMS
- Increased salivation
- Nausea
- Sweating
- Pallor
- Retch
- Drowsiness

MINOR SYMPTOMS
- Increased salivation
- Nausea
- Pallor
- Sweating
- Drowsiness

MENTAL SYMPTOMS ("minor" and "other" symptoms)
- Difficulty concentrating (minor symptom)
- Confusion (minor symptom)
- Fullness of head (other symptom)
- Depression (other symptom)
- Apathy (other symptom)

VISUAL SYMPTOMS ("minor" and "other" symptoms)
- Difficulty focusing (minor symptom)
- Visual flashbacks (minor symptom)
- Blurred vision (other symptom)
- Eye strain (other symptom)

"OTHER SYMPTOMS"
- Character facies
- Increased yawning
- Stomach awareness
- Anorexia
- Burping
- BM desire
- Headache
- Dizziness
- Aerophagia
- Vertigo
- General fatigue
- Experimenter's report of emesis

TABLE 2. INCIDENCE OF SIMULATOR SICKNESS SYMPTOMATOLOGY

SIM-ULATOR	N	AIRCRAFT	SIM-TYPE	LOCATION	INCIDENCE*
2E7	94	F/A-18	WTT	Lemoore	31%
2F132	26	F/A-18	OFT	Lemoore	27%
2F112	52	F-14	WST	Miramar	10%
2F110	55	E-2C	OFT	Miramar	47%
2F64C	223	SH-3	WST	Jacksonville	60%
2F87F	66	P-3C	WST	Jax/Brunswick	39%
2F117	281	CH-46	WST	New River	26%
2F121	159	CH-53D	OFT	New River	36%
2F120	230	CH-53E	OFT	New River	33%

Total N = 1186

*NOTE: (CRITERION: At least one minor symptom checked off on the POSTHOP Symptom Checklist)

Using data from these tables, the simulators may be classified into categories of high, medium, and low symptom frequencies. (The data for the 2F120NR will be excluded since only 14 cases were available from that simulator). Tables 5 and 6 present these classifications for motion sickness and eyestrain symptoms, respectively. There is some, but not complete, agreement between the classifications of simulators according to the two symptom categories. Two simulators (i.e., 2F120T and 2F64C) produced a high incidence of both motion sickness and eyestrain, two other simulators (i.e., 2F112 and 2F132) produced low incidence of both symptom categories, and one simulator (i.e., 2F121) produced medium incidence of both categories. The other four simulators (i.e., 2F110, 2F117, 2F87F, and 2E7) had a one-level difference (high/medium or medium/low) between production of the two symptoms.

Studies of Motion Systems

A recent study examined the effects on sickness rates of differing energy spectra in moving-base simulators [1]. The 2F64C (SH-3) and 2F87F (P-3C) simulators were selected because, while both were moving-base simulators, the 2F64C previously had revealed a high incidence of simulator sickness, but the 2F87F did not. During data collection, the simulators were in constant use (15 to 16 hours/day) for military aviation training by fleet replacement pilots, operational squadron pilots, and midshipmen.

Figure 1 shows a comparison of the nominal mean run of the 2F87F simulator with the nominal run for the 2F64C simulator, overlaid on Military Standard 1472C (MIL-STD-1472C) [18] for exposure to Very Low Frequency (VLF) vibration. It is obvious that the force environment of the two devices is markedly different, and that the 2F64C presents motion profiles largely in regions which MIL-STD-1472C counsel against if one is to avoid the nauseogenic features of the VLF vibration. Furthermore, differences in the pilots' reports of sickness were statistically increased by exposures in the 2F64C but were virtually absent in the 2F87F.

These findings reveal that the incidence of sickness was greater in a simulator with energy spectra in the region described as nauseogenic by MIL-STD-1472C and high sickness rates were experienced as a function of time exceeding these VLF limits. Therefore, for any moving-base simulator reported to have high incidences of sickness, frequency x acceleration recordings of pilot/simulator interactions should be made and compared with VLF guidelines from MIL-STD-1472C. However, in those cases where illness occurs in a fixed-base simulator, other explanations must be sought. These results are dealt with more completely elsewhere [22].

RECOMMENDATIONS

Motion System Specifications

If a moving base is specified, we recommend that *the accelerations at or near 0.2 Hz be* avoided or at least limited to 1/4 to 1/2 of the MIL-STD-1472C VLF vibration 10% nausea limits for motion sickness. Research by McCauley and Kennedy [16] have determined that exposure to sufficient acceleration energy at or near 0.2 Hz will induce motion sickness in 10% of those exposed to that energy (see Figure 1). Most simulator sickness is self-limiting in that few pilots remain in the simulator until they vomit since milder symptoms appear (such as headache and nausea) which cause the pilot to discontinue the simulator flight long before vomiting. The previously cited comparison of two simulators (i.e., 2F87F and 2F64C) with different energy spectra (Van Hoy et al., 1987) and different reported incidence rates of simulator sickness indicate that sickness, in this case, is a function of the time the pilot spent exceeding the VLF limits found in MIL-STD-1472C. However, this finding does not mean that exceeding the limits is the only causal factor of simulator sickness. The occurrence of sickness in fixed-based systems [21] is of particular interest because of the absence of inertial displacements. This strongly indicates that unknown characteristics of optical information which normally accompany and visually specify inertial displacements may lead to illness in some simulators.

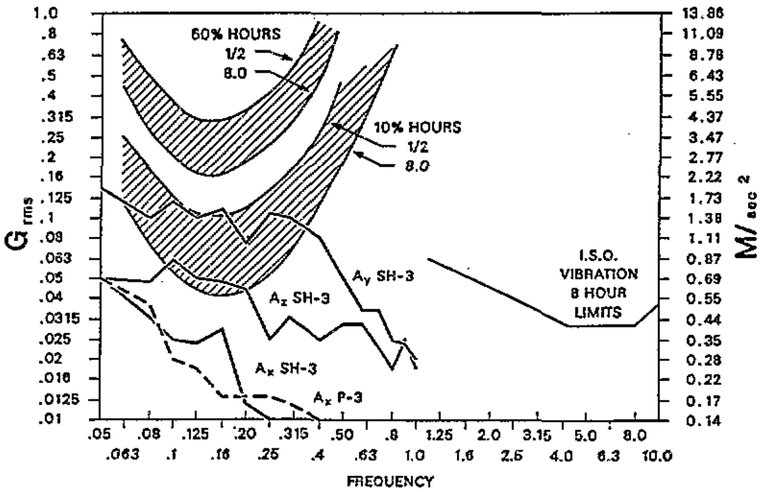

Figure 1. SH-3 (2F64C) Sea King nominal energy spectra frequency analysis versus P-3C (2F87F) Ax (x AXIS MOTION)

TABLE 3. PRIMARY MOTION SICKNESS SYMPTOMS

(a) Percentages of those not reporting a symptom before exposure that report the symptom after exposure)

Simulator	Dizziness	Vertigo	Stomach Awareness	Nausea
2E7	4.2%	10.5%	12.2%	5.4%
2F132	0.0%	0.0%	0.0%	0.0%
2F112	0.0%	2.9%	6.1%	0.0%
2F110	7.6%	5.7%	3.8%	5.7%
2F64C	6.3%	4.2%	14.1%	13.3%
2F87F	4.8%	0.0%	0.0%	0.0%
2F117	2.0%	2.7%	10.2%	8.9%
2F121	0.6%	2.6%	4.0%	6.5%
2F120NR*	0.0%	7.1%	0.0%	7.7%
2F120T*	6.7%	8.3%	6.7%	13.6%

(b) Ratio of Frequencies (Frequency of postexposure symptoms report with preexposure negative report/Frequency of preexposure negative report of symptoms)

Simulator	N	Dizziness	Vertigo	Stomach Awareness	Nausea
2E7	95	4/95	10/95	11/90	5/92
2F132	22	0/22	0/22	0/22	0/22
2F112	34	0/34	1/34	2/33	0/34
2F110	53	4/53	3/53	2/53	3/53
2F64C	144	9/144	6/144	20/142	19/143
2F87F	21	1/21	0/21	0/21	0/20
2F117	148	3/147	4/148	15/147	13/146
2F121	156	1/156	4/156	6/156	10/153
2F120NR*	14	0/14	1/14	0/13	1/13
2F120T*	60	4/60	5/60	4/60	8/59

*A 2F120 simulator is available at MCAS New River (NR), NC and MCAS Tustin (T), CA. They are similar, but not identical.

TABLE 4. EYESTRAIN RELATED SYMPTOMS

(a) Percentages of those not reporting a symptom before exposure that reported a symptom after exposure

Simulator	Headache	Eyestrain	Difficulty Focusing
2E7	7.5%	12.6%	6.3%
2F132	0.0%	18.2%	4.8%
2F112	0.0%	0.0%	0.0%
2F110	20.0%	22.9%	9.4%
2F64C	26.9%	38.4%	23.6%
2F87F	10.5%	25.0%	9.5%
2F117	8.6%	11.7%	2.1%
2F121	9.8%	16.8%	4.6%
2F120NR*	7.1%	7.1%	0.0%
2F120T*	25.5%	29.4%	15.0%

(b) Ratio of Frequencies (Frequency of postexposure symptoms report with preexposure negative report/Frequency of preexposure negative report of symptoms)

Simulator	N	Headache	Eyestrain	Difficulty Focusing
2E7	95	7/94	11/87	6/95
2F132	22	0/20	4/22	1/21
2F112	34	0/33	0/33	0/33
2F110	53	10/50	11/48	5/53
2F64C	140	36/134	51/133	33/140
2F87F	21	2/19	5/20	2/21
2F117	148	12/140	17/145	3/145
2F121	156	15/153	25/149	7/153
2F120NR*	14	1/14	1/14	0/14
2F120T*	60	14/55	15/51	9/60

*A 2F120 simulator is available at MCAS New River, NC and MCAS Tustin, CA. They are similar but not identical.

TABLE 5. CHARACTERISTICS OF SIMULATORS THAT ELICIT MOTION SICKNESS-LIKE SYMPTOMS

Simulator	Nausea	6 DOF Motion Base	FOV H/V (Degrees)	CRT/Dome	Helo/ Fixed Wing	Image Generation
High Incidence						
2F120T	13.6%	yes	200/50 & chin window	CRT	Helo	Digital CGI/ raster CRT
2F64C	13.3%	yes	130/30 & chin window	CRT	Helo	Dusk/Night CGI/calli-graphic CRT
2F117	8.9%	yes	175/50 & chin window	CRT	Helo	Day/Night/ Dusk CGI/ raster CRT
Moderate Incidence						
2F121	6.5%	yes	200/50	CRT	Helo	Digital CGI/ raster CRT
2F110	5.7%	yes	139/35	CRT	Fixed	Dusk/Night CGI/Hybrid virtual image CRT
2E7	5.4%	no	360/145	Dome	Fixed	Day/Night/ Dusk CGI/ TV camera A/C models
Low Incidence						
2F112	0.0%	No	350/150	Dome	Fixed	TV camera A/C model point light source Background
2F132	0.0%	no	48/32	CRT	Fixed	Day/Night/Dusk CGI/CRT Raster
2F87F	0.0%	Yes	48/36	CRT	Fixed	Day/Night/Dusk CIG/off axis reflective

TABLE 6. CHARACTERISTICS OF SIMULATORS THAT ELICIT EYESTRAIN-RELATED SYMPTOMS

Simulator	Headache	6 DOF Motion Base	FOV H/V (Degrees)	CRT/ Dome	Helo/ Fixed Wing	Image Generation
High Incidence						
2F120T	25.5%	yes	200/50 & chin window	CRT	Helo	Digital CGI/ Raster CRT
2F64C	26.9%	yes	130/30 & chin window	CRT	Helo	Dusk/Night CGI/ Calligraphic CRT
2F110	20.0%	yes	139/35	CRT	Fixed	Dusk/Night CGI/ Hybrid virtual image CRT
Moderate Incidence						
2F121	9.8%	yes	200/50	CRT	Helo	Digital CGI/ raster CRT
2F87F	10.5%	yes	48/36	CRT	Fixed	Day/Night/Dusk CGI/ off axis reflective
2F117	8.6%	yes	175/50 & chin window	CRT	Helo	Day/Night/Dusk CGI/Raster CRT
Low Incidence						
2F112	0.0%	no	350/150	Dome	Fixed	TV camera A/C model point light Background source
2F132	0.0%	no	48/32	CRT	Fixed	Day/Night/Dusk CIG/CRT raster projection
2E7	7.5%	no	360/145	Dome	Fixed	Day/Night/Dusk CGI/ TV camera A/C models

Visual System Specifications

It is recognized that simulator sickness is a by-product of our high technology capability that allows a rich and compelling visual imagery that aviators find realistic and satisfying as substitutes for the real aircraft. These features and simulator sickness may need to be traded off, keeping in mind that training effectiveness is the primary criterion. Our recommendations to reduce simulator sickness must be understood in this context of cost, maintenance, and training trade offs. It is recommended that a dome projection display be used rather than multiple infinity optics CRT displays. Table 6 indicates that eyestrain symptoms such as headache are reported and observed in CRT/infinity optics simulators much more often than in domed, projection simulators. Eyestrain-related symptoms may in some cases exacerbate conditions of simulator sickness.

The optometric and ophthalmological communities' recommendations concerning the causes and remedies to reduce asthenopia (i.e., eyestrain) are found in McCauley [15]. It appears that eyestrain may be caused by the conflict among the simultaneous disparate vergence, version, and accommodation demands for the different distance cues in the visual simulator system. Accommodative-convergence would signal excessive vergence relaxation while convergence-accommodation would call for excessive (positive) accommodation. Each system would be under tension and require error correction under negative feedback control. Experts in the optometric and ophthalmological communities [8] frequent, even small, shifts in accommodation and/or convergence which satisfy the need for error correction, are sufficient conditions for the generation of eyestrain.

If a dome projection system is not possible, the design eye points should be a constant radius from the operator for all CRTs. A change in the distances of the CRTs collimating mirrors forces a constant shift in the accommodation/convergence of the pilot's visual system as he views the visual scenes across CRTs. The collimating mirror distances from the design eye point range, for example, from 47 to 92 inches for the 2F120 helicopter simulator, and from 42 to 75 inches for the 2F64C helicopter simulator (see Table 7). These two simulators have a much higher incidence of eyestrain-induced problems than domed simulators. Besides the benefit of reduced stress on the visual system of the pilot, a projected visual system allows both crew members of a simulator access to the visual scene and thus allows for crew coordination training.

Future Research

No single factor will account for sickness in all simulators. The study of this malady is complicated by the fact that the symptoms are different in different people, in the same person on successive occasions, and in different simulators. Motion-base systems, computer-generated imagery, long hops and helicopter simulators appear to produce greater than average eyestrain, changes in ataxia, and other adverse symptoms. Since many of these conditions appear in the same simulators, therefore, it is generally agreed that no single simulator attribute has been found to be clear-cut in giving rise to more problems than any other. Future technological work must conduct converging operations on a variety of elements to determine the extent that each contribute to the incidence of simulator sickness.

TABLE 7. PILOT DESIGN EYE POINTS FOR THE 2F120 AND 2F64C SIMULATORS

CH-53E (2F120)	----------PILOT DESIGN EYE POINT-------------					
	LEFT SIDE	LEFT QTR	FRONT	RIGHT QTR	RIGHT SIDE	CHIN
MIRRORS RADIUS OF CURVATURE (INCHES)	60	60	50	60	50	60
DISTANCE TO EYEPOINT	92	76	47	70	50	89
DIFFERENCE	+32	+16	-03	+10	0	+29
SH-3(2F64C)	--COPILOT------BOTH-----------PILOT------------ ----------DESIGN EYE POINTS------------------					
MIRROR RADIUS OF CURVATURE	49.5	49.5	49.5	49.5	49.5	66
DISTANCE TO EYEPOINT	40*	44*	49.5	42*	46	75
DIFFERENCE	-9.5	-5.5	0	-7.5	-3.5	+9

*IBERIA OPTICS: NOMINAL EYEPOINT NORMALLY LIES APPROXIMATELY 3 INCHES FROM LINE FROM CENTER OF SPHERICAL MIRROR TO CENTER OF CURVATURE OF SPHERICAL MIRROR

A common factor shared by fixed-base simulators with high levels of reported sickness is the presence of a visual display capable of presenting the dynamic visual transformations that specify aerial self motion. Many sickness reports occur in newer simulators that possess superior visual imagery capabilities. Patterns of motion of visual elements (optical flow) ecologically valid for self movement can be displayed over a wider area with greater spatial and temporal resolution, brightness, and contrast. The problem is to identify the properties of the visual stimulus which contribute to the impression of illusory self motion (vection) and to determine whether these properties result in simulator sickness.

The term "vection", refers to a stationary observer's illusory experience of self motion induced by perceived transformations in the optic array similar to those which normally accompany physical movement through the environment. This phenomenon, which is the percept likely to be at the crux of the compelling impressions of motion which occur in simulator and cinerama, has become the topic of considerable study [7, 9]. A panel of experts provided consensus, although not unanimous, that vection seems to be a necessary though insufficient cause for the occurrence of simulator sickness [7, 2] -- sickness generally does not occur in the absence of vection, but the experience of vection does not necessarily lead to sickness.

The trend towards enhanced realism in simulation contributes to more powerful experiences of vection on the part of observers. However, the relationship between display characteristics which give rise to vection and those which tend to promote simulator sickness need to be clarified in order to provide acceptable design criteria for training devices. Moreover, the development of simulator visual systems must insure that the pilot's impression of self-movement in the simulator will not be at odds with the experiences in the actual aircraft.

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ABOUT THE AUTHORS

LCDR MICHAEL G. LILIENTHAL received his Ph.D. in experimental psychology from the University of Notre Dame in 1978. He is a Navy Lieutenant Commander with nine years of professional experience in human factors engineering. He has a designated subspecialty of Weapon Systems Acquisition Management (WSAM) and is an Associate Fellow of the Aerospace Medical Association. He presently is the Branch Manager of the Training Technologies Development Branch, Human Factors Division, of the Naval Training Systems Center.

DR. ROBERT S. KENNEDY is Vice President of Essex Corporation and Facility Director of Essex' Orlando office. He has more than 25 years' experience in applied experimental psychology and development, and has worked extensively in the areas of vestibular and visual perception, motion and simulator sickness, and individual differences in human performance.

DR. KEVIN S. BERBAUM is a consulting scientist with Essex Corporation. He has been involved in many forms of applied vision research and is currently involved in the evaluation of area-of-interest displays and the investigation of simulator sickness.

LT JAMES HOOPER is a designated aerospace experimental psychologist stationed at the Naval Air Systems Command, APC 205. He has several years of professional experience in human factors engineering and training systems design. He currently holds a Master's degree in experimental psychology. Lt. Hooper has a vast amount of "hands-on" experience with aircraft and weapons systems from his tour of duty as a helicopter pilot during the Vietnam war.