Perceptual Distortion and Its Consequences in Vehicular Simulation: Basic Theory and Incidence of Simulator Sickness

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ABSTRACT

Simulator-induced sickness is a serious problem that can afflict the users of vehicular simulators including aircraft and driving devices. Operators and passengers in training and research simulators have experienced symptoms akin to those of motion sickness both during and following a simulator experience. In some cases, even several hours postexposure, aftereffects or flashbacks to the simulation environment may surface creating sudden disorientation in the individual. The simulator-sickness syndrome appears to be severe and frequent enough that it affects the utility of simulation and may create safety hazards for users. It has, therefore, recently received considerable attention by the human engineering community. This paper provides background information on the sickness problem; its theoretical underpinnings; and a brief, tabularized literature review specific to simulator sickness. All available articles, reports, technical memoranda, and papers directly dealing with the problem of operator discomfort in vehicular simulators were obtained and selectively reviewed.

In the past two decades there has been considerable effort aimed at the improvement of the technology of vehicular simulators used for training and research. However, the utilization of a number of aircraft and driving simulators has been hindered by a recurring syndrome usually termed "simulator sickness." Simulator sickness may be manifested as acute symptomatology during the simulator experience, including such problems as disorientation, dizziness, headache, pallor, burping, nausea, emesis, and degraded vehicular control and task performance, or as residual effects including prolonged nausea, fatigue, motor dyskinesia, visual dysfunctioning, and ataxia lasting for up to several hours after exposure (1,2). Furthermore, delayed flight-simulator aftereffects and flashbacks to simulated flight situations have been experienced by aircrews as long as 10 hr after simulated flight (3).

Simulator sickness has been recognized as a problem since the late 1950s when it first was observed in flight trainees in a helicopter simulator (4). However, it has since received only a limited amount of research attention, perhaps largely because it is a difficult problem to study. A majority of the associated literature presents anecdotal and incidental evidence attesting to the magnitude of the simulator sickness problem. Relatively few research studies resulting in data and design recommendations have been conducted. It is largely agreed that the sickness problem is frequent and severe enough to warrant serious concern and must be reckoned with both in the design of future simulators and in the operation of existing devices to minimize its occurrence. This is perhaps best and most recently evidenced by the collective request from the Naval Training Equipment Center, the Army Research Institute, and the Air Force School of Aerospace Medicine to assemble vision and vestibular research scientists, simulator designers, and simulation practitioners at a recent 1983 National Research Council Workshop on Simulator Sickness--the first known formal gathering aimed at the simulator sickness problem (5). From the results discussed in the Proceedings of this workshop, combined with other recent efforts aimed at the controlled study of simulator design influences on simulator sickness (6,7), it appears that significant interest in the simulator sickness problem has been rekindled and that simulator sickness has become an important topic for scientific research.

THEORETICAL PERSPECTIVE

Terminology: Motion Sickness Versus Simulator Sickness

Motion sickness is a malady generally attributed to exposure to motion or to certain aspects of a moving environment. It is also generally accepted that stimulation of the vestibular apparatus of the inner ear is necessary for the inducement of motion sickness in humans (8). As Tyler and Bard (9) have stated, "the primary cause of motion sickness is motion and the occasional failure to appreciate this factor has led to confusion."

If these definitions are strictly adhered to, the term "motion sickness" should not be used to refer to sickness induced by simulators. This is best supported by the evidence that some fixed-base simulators, which provide no direct vestibular stimulation, produce sickness in their operators. Even though the symptomatology of the simulator-induced syndrome may be similar to that of motion sickness, although typically less severe, the causes may be quite different. In a moving-base simulator, some aspect of the motion cues may influence sickness but it can be questioned whether motion alone is a sufficient

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stimulus. After consideration of the number and extent of visual, auditory, somesthetic, and proprioceptive cues that a simulator subject may experience, it becomes quite apparent that simulator sickness is polygenic and not restricted to a motion-based etiology (10).

A somewhat relaxed posture may be adopted: simulator sickness is a special subset of motion sickness if it is assumed that motion sickness can be used to describe physiological and psychological symptoms that result from the illusion of a moving environment as well as from actual motion. In this conceptualization, direct vestibular stimulation may not be requisite. By the very nature of the vehicles they replicate, simulators attempt to recreate the dynamics of the vehicular control task through combinations of changing cues via some or all of the following avenues: visual out-the-window scene, instrumentation, vestibular cueing, kinesthetic cueing, somesthetic stimulation, control feedback, and auditory cueing. Motion is a consequence of vehicular control actuation and many of these simulator feedback avenues reflect some aspect or conjunctive effect of the motion inherent in the control situation. Therefore, the simulation, whether fixed base or moving, attempts to create the illusion of a moving, dynamic environment, and the sickness that results from the simulator experience most likely emanates from some aspect of the illusory stimulus array. It has been well demonstrated that visual vection alone (i.e., scene movement without concomitant physical body movement) is sufficient to induce symptoms of motion sickness including emesis (11). Parker (12), for example, presented a film of a fast drive down a winding mountain road (as viewed from the driver's position) to stationary, seated subjects, 30 percent of whom became quite ill.

Because a simulator presents an incomplete replication of stimuli inherent in the dynamic vehicular environment, the genesis of its sickness is often attributed to either the total lack of motion cues or incomplete motion cueing. However, as has been seen, the operator dysfunction that occurs is not necessarily a result of physical body motion or lack thereof. Furthermore, sickness occurrences in the simulator do not typically match motion sickness-provocative situations in the actual aircraft or automobile. Therefore, it is the position of these authors, in agreement with others (2,13), that the term simulator sickness, not motion sickness, should be applied to those infirmity symptoms and aftereffects associated with exposure to a simulator. It is

TABLE 1 Driving Simulator Characteristics[a]

	Simulator Designation						
	Goodyear Aerospace 1	Goodyear Aerospace 2	UCLA 1	General Motors Technical Center	General Precision Sim-L-Car	North American Rockwell	VPI&SU
Actual vehicle	Automobile	Automobile	Automobile	Automobile	Automobile	Automobile	Automobile
Type vehicle	Full-sized sedan	Full-sized sedan	Full-sized sedan	General	General	General	Adjustable car
Application	Research	Research	Research and driver rehabilitation	Research	Research	Research	Research
Visual system							
Type	CCTV projection	CCTV monitor	Motion picture	Motion picture	Point-light projector	CCTV projection	CGI
Image source	Model board	Model board	Film	Film	Transparency	Model board	Hybrid CGI
Medium	Spherical screen	CRT	Spherical screen	Spherical screen	Flat, rear-projected screen	Screen	Monochrome CRT
Infinity (∞) cueing	Viewing distance	Reflective ∞ optics	Viewing distance	Reflective optics	Refraction, 6-ft viewing distance	Unknown	Refractive ∞ optics
Lighting condition	Daylight	Daylight	Adjusted by film	Adjusted by film	Sunset	Unknown	Dusk, night
H/V FOV (deg)[b]	50/39	54/unknown	150/unknown	77-90/unknown	45/unknown	~39/52	~48/30
Scene content	Road and periphery	Road and periphery	Film of actual road	Film of actual road	Road and objects	Road and signs	Road and periphery, other vehicles
Motion System							
Type	Fixed-base	Fixed-base	Fixed-base	Cascade	Fixed-base	Cascade	Cascade
Degree of freedom				Tilt simulation of LN, LT acceleration		V; tilt simulation of LN, LT acceleration	R, Y, LN, LT
g-seat/g-suit							
g-display dim							
Vibration			Yes	Yes		Yes	Yes
Cockpit environment							
Cab type	Car body	Car body	Car body	Enclosed custom	Car components	Enclosed custom	Open/enclosed custom
No. crew	Driver	Driver	Driver, passenger	Driver	Driver, passenger	Driver	Driver
Audio	Engine, drive train	Engine, drive train	Engine, drive train	Engine, drive train, tire	Engine, drive train	Engine, road noise	Engine, drive train road noise, tire
Operating procedure							
Part/whole task	Whole	Whole	Whole	Whole	Whole	Whole	Whole
Typical task length	30 min	30 min	Unknown	Unknown	10 min	Unknown	20 min
Freeze capacity							
Slew/reset capacity							
Exterior view allowed	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Not by subjects
Other characteristics							Operation in dark room

[a]According to studies referenced in Table 2. [b]H = horizontal, V = vertical, FOV = field-of-view, P = pitch, R = roll, Y = yaw, LN = longitudinal, LT = lateral, and V = vertical (six total).

suggested that "motion sickness" be reserved for those situations (automobile, air, sea, etc.) in which the eliciting stimulus is actual motion that mobilizes vestibular activity.

Theory of Simulator Sickness

A number of theories that attempt to explain the origin of motion sickness have surfaced in the literature and are reviewed by Kennedy and Frank (10) with respect to their plausibility for simulator sickness. The most widely accepted theory is that of perceptual conflict, also known as neural mismatch, sensory conflict, sensory rearrangement, cue conflict, and perceptual decorrelation. It postulates that motion sickness, a disorder of the central nervous system, is a reaction to discrepancies among motion information perceived by various sensory channels and also may be due to inconsistencies between expected sensory inputs and experi-

TABLE 2 Driving Simulator Study Summary

	Authors					
	Barrett and Nelson (1965) *(31)*	Barrett and Nelson (1966) *(32)*	Barrett and Thornton (1968) *(13)*	Testa (1969) *(33)*	Reason and Diaz (1971) *(22)*	Casali and Wierwille (1980) *(34)*
Simulator designation	Goodyear Aerospace 1	Goodyear Aerospace 2	Goodyear Aerospace 1 and 2	UCLA 1	Sim-L-Car	VPI&SU
Type report	Laboratory	Laboratory	Laboratory	Laboratory	Laboratory	Laboratory
Intent	Simulator evaluation	Virtual image display evaluation	Perceptual style differences[a]	Simulator sickness	Simulator sickness	Simulator sickness
Simulator tasks						
Scenario	Freeway driving with stops	Freeway driving with stops	Freeway driving with stops	Two-lane winding mountain road	Winding perimeter road	Freeway driving
Duration	30-50 min[a]	30-50 min[a]	30-50 min[b]		10 min	20 min
Subjects						
Type	Male engineering department employees	Male engineering department employees	Male engineering department employees	Male college students	Students/technicians	Students
Number	25	25	46	40	15 male/16 female	64
Active/passive	Active	Active	Active	Active	Passive	Active
Independent variables	Emergency stop, speed	Emergency stop, speed	Emergency stop, speed	Perceptual style, instructional set	Restricted vision, sex, driving experience	Lateral acceleration cueing, delayed dynamic feedback, simulator enclosure, perceptual style
Dependent measures[c]	D, S	D, S	D, S, Q	R, Q	Q	Q, R
Incidence sickness (%)	64	72		100	90	
Leaving simulator (%)	44	56	50		1 case	
Signs/symptoms[d]						
Queasiness						
Sweating	x	x		x	29	
Nausea	x	x			42	
Emesis	x					
Eyestrain		x				
Headache		x			45	
Pallor					29	x
Respiration changes				x		x
Skin resistance changes				x		x
Heart rate changes						
Fatigue/drowsiness					3	
Disorientation	x					
Visual dysfunction						
Ataxia						
Dizziness	x	x			71	
Vertigo						
Aftereffects						
Other	Upset stomach, faint feelings		Subject rating of discomfort, sugject estimate of discomfort duration, no. of trials subject able to stay in simulator, rod and frame test	Galvanic skin response, rod and frame test, embedded figures test, instructional set	Bodily warmth, 48%; stomach awareness, 42%; increased salivation, 19% dry mouth, 6%	Pulse rate, arithmetic proficiency, yaw standard deviation, steering reversals
Habituation effects[e]						
Experience effects[f]					x	
Instructor/student effects						
Significant effects			Extremely field independent, more susceptible	Sweating, respiration, perceptual style, instructional set	Females and experienced drivers more susceptible	Pallor, skin resistance, respiration rate, yaw deviation, no. of steering reversals

[a]This was a post hoc analysis of the effects of field independence/dependence on the Barrett and Nelson *(31,32)* data.
[b]Estimated from Barrett and Nelson *(31,32)*.
[c]How obtained: Q = questionnaire, I = interview, R = instrumentation, D = direct observation, S = subject comment.
[d]A number indicates % incidence; x-occurrence reported, but not by %.
[e]Lessens with exposure.
[f]More experienced real-world vehicle operators more susceptible.

TABLE 3 Flight Simulator Characteristics[a]

	Simulator Designation						
	2–FH-2	V/STOL	2F87F 1	2F87F 2	SAAC (2 cockpits)	CP 140 FDS	2E6 ACM (2 cockpits)
Actual vehicle	Bell HTL-4	General V/STOL	P-3C turboprop	P-3C turboprop	F-4 jet	Aurora turboprop (P-3C)	F-14/F-4 jet
Type vehicle	Helicopter	Jet-lift	Patrol	Patrol	Fighter	Patrol	Fighter
Application	Hover training	Research	Training	Training	Air-air combat training	Training, limited research	Air-air combat training
Visual system							
Type	Point-light projector	Point-light projector	CCTV monitor, Redifussion Duoview	CGI MDEC[b] Vital IV	CGI mosaic[c]	CGI	Point-light projector[c] (MDEC)
Image source	Transparency	Transparency	Model board	Digital CGI	Digital CGI	Digital CGI	2 transparency spheres
Medium	Curved screen	Spherical screen	CRTs	Calligraphic CRTs	8 monochrome raster CRTs	2 CRTS	40-ft-diameter dome
Infinity (∞) cueing	Refraction, 6 to 12 ft viewing distance	Reflection, viewing distance	Reflective ∞ optics	Reflective ∞ optics	Reflective ∞ optics	Unknown	20-ft viewing distance
Lighting condition	Dim, daylight	Daylight	Day, dusk, night	Dusk, night	Unknown	Dusk, night	Day, dusk, night
H/V FOV (deg)[f]	260/75	100/30	48/36[g]	48/36[g]	~296/180	Unknown	~350/280
Scene content	Sky, earth	Sky, earth, objects	Sky, earth	Sky, earth	Sky, earth, A/C	Sky, earth, objects	Sky, earth, A/C
Motion system							
Type	Fixed-based	Unknown	Synergistic	Synergistic	Synergistic	Synergistic	Fixed-based
Degree of freedom[f]		P, R, Y	All 6	All 6	All 6	All 6	
g-seat/g-suit					Both		Both
g-display dim					Yes		Yes
Vibration	Yes	Unknown					Control stick vibration
Cockpit environment							
Cab type	Open	Unknown	Enclosed, A/C cab	Enclosed, A/C cab	Actual cockpits with canopies	Enclosed	Actual cockpit with canopies
No. of crew	2	1	3	3	1 each cockpit	3	2 each cockpit
Audio	Engine	Unknown	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple
Operating procedure							
Part/whole task	Whole flight	Unknown	Takeoff and landing	Takeoff and landing	In-air combat	Whole flight	In-air combat
Typical task length	30 min	Unknown	4 hr	4 hr	45-60 min	30 min–2 hr	45 min–1 hr
Freeze capacity	Yes	Yes	Unknown	Unknown	Yes	Yes	Yes
Slew/reset capacity	Yes		Unknown	Unknown	Yes	Yes	Yes
Exterior view allowed	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	No
Other characteristics	Control lag noted	Originally fixed-base, motion added		Flight engineer had off-axis display view that caused sickness	0.2-0.4 Hz motion spectrum component apparent		Gantry handrails in view of cockpit

[a]According to studies referenced in Table 4.
[b]McDonnell-Douglas Electronics Corporation.
[c]CCTV camera model target projectors.
[d]CCTV camera model target projectors and CGI for landing via MDEC Vital IV.
[e]CGI target projection via rediffusion CT5.
[f]H = horizontal, V = vertical, FOV = field-of-view, P = pitch, R = roll, Y = yaw, LN = longitudinal, LT = lateral, V = vertical (six total).
[g]One window FOV; monochrome display added for flight engineer in Brunswick, Me., device (No. 11).
[h]Crew instructed not to view display during reset.

enced sensory inputs. Basically, the theory states that sensed motion information from the vestibular, kinesthetic, and visual systems is input to a referencing framework whereby the inputs are compared with a neural bank of expectancy information based largely on past experiences or on naturally endowed system wiring (10). As noted by Kennedy, Berbaum, and Frank (14), motion sickness may be manifested as an emetic reaction to a stimulus, which results in decorrelation among receptor expectancy inputs that have been ingrained over time. This cue conflict, in the decorrelation sense, can be thought of as a discrepancy between stimuli appearance (perceived) and stimuli reality (15). Under normal conditions, the perception of the stimuli coincides with the known reality of the stimuli, and the stimulus-response expectations are built up in a neural bank over time and become more salient with continuing motion experience. Conflict occurs when stimuli perceptions are not in accord with expectancies in memory store for each sensory channel, either spatially (gain) or temporally (phase), or both.

In its original form, the perceptual conflict theory tended to concentrate on the lack of intermodality correlation, such as between visual and vestibular inputs. However, intramodality decorrelations are also explicable under the perpectual conflict notion. Differing perceptions from the semicircular canals and the utricle and saccule otoliths may constitute a vestibular-vestibular conflict sufficient to elicit space sickness (16). In space, the canals still signal angular acceleration as head turns start and stop, and the otoliths still signal linear acceleration but fail to signal head orientation because of the lack of gravity. Furthermore, Leibowitz and Post (17) report data that point to the possibility that visual-visual intramodality conflict may occur between the focal visual system, which is concerned with object discrimination and identification, and the ambient visual system, which is concerned with orientation. This is alluded to in an early citing of simulator sickness in a helicopter simulator, where ambient visual perception of the display scene gave the impression of forward motion while focal perception cues provided the impression of receding depth (18).

This leads to the utility of perceptual conflict theory in accounting for simulator sickness. Several examples of conflict situations warrant mention. First, in the case of the fixed-base simulator sickness problem (13,19), it has been suggested by a number of authors that a cue conflict arises when the subject visually senses the appearance of incident motion but never receives corresponding ac-

2F112	2F106	2F64C	2F110	2F117	2F121	2E7 ACTT (2 cockpits)	2F132
F-14 jet	SH-2F	SH-3	E-2C turboprop	CH-46E	CH-53D	F-18 jet	F-18 jet
Fighter	Helicopter	Helicopter	AEW/tactical	Helicopter	Helicopter	Fighter	Fighter
Air-air combat and miscellaneous training	Training	Training	Training	Training	Training	Air-air combat and tactics	Training
Point-light projector[d]	CGI (MDEC Vital III)	CGI (MDEC Vital IV)	CGI (Rediffusion Noroview SP1)	CGI (Rediffusion CT5)	CGI (Rediffusion CT5)	CGI[e] (IMI generator)	CGI (MDEC Vital IV)
2 transparency spheres	Digital CGI	Digital CGI	Digital CGI	Digital CGI	Digital CGI	CGI	Digital CGI
40-ft-diameter dome	Calligraphic CRTs	Calligraphic CRTs	Calligraphic CRTs	Raster CRTs	Raster CRTs	Raster TV projected on 35-ft-diameter dome	Raster TV projected onto dome
20-ft viewing distance	Reflective ∞ optics	Reflective ∞ optics	Reflective ∞ optics	Reflective ∞ optics	Reflective ∞ optics	Viewing distance	Viewing distance
Day, dusk, night	Night	Dusk, night	Dusk, night	Day, dusk, night	Day, dusk, night	Day, dusk, night	Dusk, night
~350/280	~144/32	130/30 and chin window	~139/35	200/50 and chin window	200/50 and chin window	~360/150	~48/32
Sky, earth, objects, carrier	Sky, earth, ships, objects	Sky, earth, ships, objects	Sky, earth, carrier, objects	Sky, earth, ships, objects	Sky, earth, ships, objects	Sky, earth, A/C	Sky, earth, carrier objects
Fixed-base	Synergistic	Synergistic	Synergistic	Synergistic	Synergistic	Fixed-base	Fixed-base
	All 6	All 6	All 6	All 6	All 6		
Both						Both	Both
Yes						Yes	Unknown
Control stick vibration	Yes, multiple	Yes	Yes	Yes	Yes	Yes	
Actual cockpit with canopy	Enclosed helicopter cab	Enclosed helicopter cab	Enclosed A/C cab	Enclosed helicopter cab	Enclosed helicopter cab	Actual cockpits with canopies	Actual cockpit with canopy
2	2	2	2	2	2	1	1
Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple	Yes, multiple
Whole flight	Whole flight	Whole flight	Whole flight	Whole flight	Whole flight	In-air combat	Takeoff and landing
1-1.5 hr	1.5 hr	Unknown	2-2.5 hr	1.5-2 hr	1.5-2 hr	Unknown	Unknown
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes		Yes	Yes	Yes[h]	Yes[h]	Unknown	Yes
No	Yes	Unknown	Yes	Yes	Yes	Unknown	
							Dynamic replay seat buffet, carrier takeoff/landing

celeration or positional cues, or both. That is, the visual-motion cues must be interpreted in isolation from physical-motion cues. As Puig (20) reports, the visual perception of displayed acceleration, deceleration, or reversal in the direction of motion, not the visual depiction of motion itself, is the critical stimulus for eliciting discomfort (i.e., the vestibular apparatus is sensitive to acceleration not velocity). The conflict arises when the vestibular and kinesthetic systems indicate no motion or no postural changes in spite of compelling visual cues that indicate otherwise. Thus there is an intermodality conflict between the vestibular and kinesthetic cues that indicate to people that they are not moving and the visual cues that tell them that they are.

The well-documented finding that experienced pilots and drivers are more susceptible to simulator sickness than are novices (4,21,22) may also be accounted for within the perceptual conflict theory framework. For instance, the new trainee, inexperienced in flying the aircraft, has not developed a strong referencing framework of expectancies regarding the aircraft's responses to control inputs. Therefore discrepancies in simulator-motion feedback and aircraft-motion feedback are not as evident to the novice and may not give rise to perceptual conflict leading to discomfort. However, the veteran or instructor pilot, highly tuned to the aircraft's control behavior, may experience cue conflict if feedback systems in the simulator are not in accord (e.g., inappropriate phasing differences between visual and motion updating) or if important cues are missing (e.g., lack of vestibular and kinesthetic sensations that the pilot has learned to interpret and use). Furthermore, cue conflict may arise in the visual system as a result of display distortion that may be more apparent to the experienced pilot than to the novice. If the simulator display is distorted, blurred, or inappropriately collimated or if cues that the display is actually much closer than optical infinity are apparent (e.g., visible edges of a cathode ray tube), then the visual input may be in spatial conflict with expectancies about the dynamic real scene. In this case, the distortion is likely to be more of a problem to the experienced pilot who has learned to scan the complete scene rather than concentrate on a specific portion, as the novice may do (18,23).

A final example of simulator-induced cue disparity, which fits in well with the perceptual conflict notion, is that of differential discomfort levels among simulator crew members. Several reports (18, 20,24,25) indicate that "passengers" in the simulator, such as instructor pilots, may have a higher incidence of sickness than pilots or drivers. This parallels the finding that motion sickness is rare among drivers of actual vehicles but prevalent among passengers (9). Barrett and Thornton (13) offer an explanation within the cue conflict framework. Because the passenger receives no feedback from the vehicle controls and may not be in an optimum position for viewing the visual control part of the task, he or she may not have the necessary referents to anticipate vehicular motions. Therefore response expectancies for the passengers may be more incongruous with actual feedback cues than are those for the operator who is inside the control loop. However, in some simulators, higher incidence of sickness among passengers than operators may be due to other factors. For instance, an aircraft simulator display may be designed for pilot viewing only; instructors, flight engineers, or copilots may view the display from a distorted, off-axis position and receive a poor visual representation. Others may be seated in a position where the center of rotation or translation, or both, of the simulator's motion base may not be optimal for mimicking the expected motions of the actual vehicle.

It should be noted that the perceptual conflict theory has several drawbacks in that it does not clearly predict the incidence of sickness in some well-known sickness-inducing situations (5). Furthermore, it is primarily useful in an ex post facto explanatory sense rather than in a predictive sense. One example of a situation in which the theory may exhibit difficulty is in explaining the case in which copilots are not as susceptible to simulator sickness as are pilots in certain devices (in contrast with the prevalence of passenger over pilot sickness discussed earlier). In the Navy 2F121 moving-base CH-53D helicopter simulator, the primary out-the-window displays are for the pilot and the copilot is largely in an instrument flight conditions (IFC) mode. However, both receive the same inertial cues and the pilot is much more susceptible to simulator sickness, according to a number of reports made to the authors. In keeping with the cue conflict framework, the copilot would appear to have the major conflicts (i.e., lack of visual cues to correspond with physical motion cues, lack of control feedback, etc.), and therefore might be expected to have more of a tendency toward discomfort. However, the absence of these cues may be insufficient to constitute a sensory conflict for the copilot, while the possible discrepancy between compelling visual and physical motion cues or between these cues and their real system analogues, or both, may constitute a salient conflict for the pilot, sufficient to induce sickness.

In conclusion, although the perceptual conflict theory may exhibit certain deficiencies, it does offer plausible explanations of most known phenomena associated with simulator sickness. Most researchers agree that it offers the best working model framework for simulator sickness and therefore warrants further validation effort (5).

INCIDENCE REPORTS AND INVESTIGATIONS OF SIMULATOR SICKNESS

In this final section a brief overview of the literature citing specific instances of simulator sickness is presented. Because of space limitations and for ease of reference, the overview is presented in a tabular format. All available references that have direct mention of simulator sickness occurrences among flight trainees or research subjects were obtained and reviewed. Most of the literature on simulator sickness consists of either formal documentation or anecdotal mention of subject or trainee discomfort arising from the use of a particular simulator. Usually these reports of sickness are mentioned in the context of their hindrance to the objectives of a simulator evaluation, training, or research effort and are not the focus of empirical investigation in the document. Some reports are scant in their documentation of the sickness problem whereas others offer much insight into the potential causes of sickness specific to the simulator and mention potential countermeasures to alleviate the problem. Other reports detail controlled research efforts aimed directly at investigation of the etiology of the simulator-sickness problem. In all cases the reports are reviewed herein to the fullest extent possible with respect to those aspects pertinent to simulator sickness.

The overview tables are organized as follows: Table 1 gives information regarding driving simulators that are known to elicit simulator sickness or that have been used in studies of simulator sickness. Whenever possible, aspects of the simulator visual display, motion system, operator cockpit, auditory system, operating procedures, intended applications, and corresponding actual vehicle are included in Table 1. Table 1 is intended to be paired with Table 2 that represents an attempt to annotate pertinent information from reports of driving simulation sickness in a manner that facilitates comparison across studies. Blanks in the tables indicate that the information was either not evaluated or not reported in the study. Significant effects refer only to statistically significant findings. In like fashion, Tables 3 and 4 give analogous information for flight simulators, for which greater documentation of simulator sickness is available.

In Table 4, it should be noted that the Hartman and Hatsell (26) study on the simulator for air-to-air combat (SAAC) was performed when the motion system was on, whereas the Kellogg, Castore, and Coward (3) study was performed with the motion system off. (The SAAC is now used for training without the motion system.) Hartman and Hatsell conducted a spectral analysis of the heave motion in the SAAC. Their findings indicated that the majority of spectral energy fell between 0.2 and 0.4 Hz, peaking at about 0.25 Hz. It has been well established that the "optimal" frequency for inducing motion sickness symptoms is 0.2 Hz (8,27,28). Consequently, the inherent motion energy spectrum of a simulator could be an important factor in the etiology of simulator sickness [see Frank et al. (2) for a detailed discussion].

Table 5 gives the relative incidence of simulator sickness in 13 additional simulators that were not amenable to the format of Tables 2 and 4. (Engineering details of each of these simulators are provided in Tables 1 and 3.) The incidence rates reported by Kennedy et al. (7) for the flight simulators represent preliminary results of a comprehensive field study by the Naval Training Equipment Center. Several human performance and engineering measures have been and are currently being collected and have yet to be fully analyzed.

As can be determined from Table 5, there are two vastly different incidence rates reported for the SH-3 helicopter simulator, device 2F64C. These differences cannot be explained by the utilization procedures at the two locations where the simulators reside but are believed to be due to differences in throughput delay. The East Coast 2F64C has been found to have a visual system throughput delay from control stick to x, y, z position ranging from 155 to 340 msec (29). Ninety-eight percent of the throughput delays were between 155 and 285 msec. Although the

TABLE 4 Aircraft Simulator Study Summary

	Authors							
	Havron and Butler (1957) *(4)*	Miller and Goodson (1958, 1960) *(18, 19)*	Ryan, Scott, and Browning (1978) *(35)*	Crosby and Kennedy (1982) *(6)*	Kellogg, Castore, and Coward (1980) *(3)*	Hartman and Hatsell (1976) *(26)*	Money (1980) *(36)*	McGuinness, Bouman, and Forbes (1981) *(37)*
Simulator designation	2-FH-2	2-FH-2	2F87F I	2F87F II	SAAC	SAAC	CP 140 FDS	2E6[a]
Type report	Field study	Field study	Field study	Field study	Field observation	Field study	Field study	Field survey
Intent	Training effectiveness evaluation	Simulator sickness	Transfer of training	Simulator sickness	Simulator sickness	Simulator sickness	Simulator sickness	Simulator sickness
Simulator tasks								
Scenario	–[b]	–[b]	Landing	Patrol mission	Air combat maneuvering	Air combat maneuvering[c]		Air combat maneuvering
Duration	30 min	30 min	4 hr	4 hr	About 60 min	About 60 min		30-45 min
Subjects								
Type	Instructor/student pilots	Instructor/student pilots	Instructor/student pilots	Flight engineers	Pilot	Pilot	Pilots	Pilots/navigators
Number	36	10	47	20 plus	48	100-114	14	66
Active/passive	Active	Active	Active	Passive	Active	Active	Active	Active/passive
Independent variables			Motion/no motion	Field-of-view				
Dependent measures[d]	Q	Q, I	Q	D, Q, I	I	Q, I	Q	Q
Incidence sickness (%)	78[e]	60 instructor, 12 student	11	50	88	52	43[f]	27
Leaving simulator (%)								
Signs/symptoms[g]								
Queasiness								
Sweating	x				54			
Nausea	x				79	14	x[h]	9
Emesis						2		
Eyestrain						50		
Headache	x		6					7
Pallor								
Respiration changes								
Skin resistance changes								
Heart rate changes								
Fatigue/drowsiness						38		11
Disorientation						52		
Visual dysfunction								8
Ataxia			11	50	60			
Dizziness								17
Vertigo	x	x						11
Aftereffects	x	x		x				x
Other					Spinning sensations, 54%; maneuvering sensations, 25% headache, leans, dizziness or loss of situational awareness, 23%; vivid involuntary flashbacks, 35%; vivid dreams, daydreams, 35%; inverted visual field, 10%			Leans, 9%; discomfort, 8%; other, 9%
Habituation effects[i]	x	x			x		x	
Experience effects[j]	x	x						x
Instructor/student effects	x	x						
Significant effects								

[a]Both F-4 and F-14 cockpits evaluated.
[b]Two scenairos: low-level (5.5-ft) or high-level (500-ft) maneuvers.
[c]Also had a maximum maneuvering scenario.
[d]How obtained: Q = questionnaire, I = interview, R = instrumentation, D = direct observation, S = subject comment.
[e]In addition, 11 instructors were assigned to the simulator, but 7 had to quit because of sickness.
[f]Three other individuals experienced symptoms while working, observing, or flying the simulator.
[g]A number indicates % incidence; x-occurrence reported, but not by %.
[h]Slight discomfort to mild nausea.
[i]Lessens with exposure.
[j]More experienced real-world vehicle operators more susceptible.

visual throughput of the West Coast simulator has not been measured, it is believed to be 150 msec or less.

Because so few of the studies on simulator sickness have defined the stimulus conditions under which the inducement occurred, it is difficult to draw firm conclusions about the salient variables. In addition, the problem of simulator sickness is one of great complexity. Some 60 independent variables are thought to contribute to its etiology (5). Nevertheless, on the basis of the data cited, two other factors appear to be worth noting. First, Tables 1 and 3, and anecdotal evidence, suggest that field-of-view may play an important role in the occurrence of simulator sickness. In general, wide field-of-view displays appear to be more likely to induce sickness (2). This has theoretical appeal because the ambient visual system is more sensitive to orientation and peripheral display update rates. The role field-of-view plays needs to be investigated, along with the role of scene detail. The second factor of note is that simulators vary considerably in their dynamic characteristics, such as range of motion, onset rates, and temporal delays. In simulator design, it is of paramount importance to ensure that (a) the vestibular and visual subsystems are informed within the dynamic range in which they operate and (b) they are informed spatially and

TABLE 5 Simulator Sickness Incident Reports

Simulator Designation	Vehicle	Active/Passive	Sample Size	Incidence
General Motors Technical Center[a]	Generic automobile	Active	50 plus[b]	2 cases plus[b]
North American Rockwell[c]	Generic automobile	Active	40	3 cases
V/STOL[d]	Jet-lift	Active	1	1 case
2F112[e]	F-14	Active	65	16%
2F106[e]	SH-2F	Active	28	13%
2F64C[e,f]	SH-3	Active	36	13%
2F64C[e,g]	SH-3	Active	153	55%
2F110[e]	E-2C	Active	75	49%
2F117[e]	CH-146E	Active	160	29%
2F87[e]	P-3C	Active	55	44%
2F121[e]	CH-53D	Active	208	36%
2E-7[e]	F/A-18	Active	102	33%
2F132[e]	F/A-18	Active	26	23%

[a]Beinke and Williams (1968) *(38)*.
[b]Precise figures not provided.
[c]Broda, Kirkpatrick, and Shaffer (1972) *(39)*.
[d]Sinacori (1967) *(40)*.
[e]Kennedy, Dutton, Ricard, and Frank (1984) *(7)*.
[f]Simulator located on West Coast.
[g]Simulator located on East Coast.

temporally simultaneously (in terms of perceptual simultaneity). In addition, it should be remembered that the visual and proprioceptive senses attend to different characteristics of the moving environment. Visual receptors detect displacement and velocity of motion, whereas proprioception detects acceleration and rate of change (jerk) of linear motion (30).

For the interested reader, a more complete discussion of potential simulator design characteristic etiological factors, drawing from the available literature on simulator sickness, can be found in the paper by Casali and Wierwille in this Record. Given the vast application potential of vehicular simulators and the large investments they entail, it is incumbent upon simulator users, designers, and researchers to recognize, address, and solve the simulator-sickness problem.

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The thoughts and recommendations offered in this paper (such as the suggestions for proposed countermeasures) were formulated by the authors on the basis of the scientific literature. However, research on simulator sickness is still in a stage of infancy and many of the issues raised in this paper require experimental investigation.

REFERENCES

1. J.G. Casali. Evaluation of Various Design Alternatives Influencing Discomfort in a Driving Simulator. In Manned Systems Design, Methods, Equipment and Applications (J. Moraal and K.F. Kraiss, eds.), Plenum, New York, 1981, pp. 449-463.
2. L.H. Frank, R.S. Kennedy, M.E. McCauley, and R.S. Kellogg. Simulator Aftereffects: Sensorimotor Disturbances Induced in Flight. Proc., Second Symposium on Aviation Psychology, Department of Aviation, The Ohio State University, Columbus, April 1983, pp. 587-596.
3. R.S. Kellogg, C. Castore, and R. Coward. Psychophysiological Effects of Training in a Full Vision Simulator. Preprints of the 1980 Aerospace Medical Association Meeting, 1980, pp. 203-215.
4. M.D. Havron and L.F. Butler. Evaluation of Training Effectiveness of the 2FH2 Helicopter Flight Trainer Research Tool. Technical Report NAVTRADEVCEN 1915-00-1. Naval Training Device Center, Port Washington, New York, April 1957.
5. M.E. McCauley, ed. Research Issues in Simulator Sickness: Proceedings of a Workshop. Committee on Human Factors, National Research Council, Washington, D.C., 1984.
6. T.N. Crosby and R.S. Kennedy. Postural Disequilibrium and Simulator Sickness Following Flights in a P3-C Operational Flight Trainer. Presented at the 53rd Annual Scientific Meeting of the Aerospace Medical Association, Bal Harbor, Fla., May 1982.
7. R.S. Kennedy, B. Dutton, G.L. Ricard, and L.H. Frank. Simulator Sickness: A Survey of Flight Simulators for the Navy. Technical Paper 841597. Society of Automotive Engineers, Warrendale, Pa., 1984.
8. K.E. Money. Motion Sickness. Physiological Review, Vol. 50, 1970, pp. 1-39.
9. D.B. Tyler and P. Bard. Motion Sickness. Physiological Review, Vol. 29, 1949, pp. 311-369.
10. R.S. Kennedy and L.H. Frank. A Review of Motion Sickness with Special Reference to Simulator Sickness. Technical Report NAVTRAEQUIPCEN 81-C-0105-16. Human Factors Division, Naval Training Equipment Center, Orlando, Fla., 1985.
11. J. Dichgans and T. Brandt. Optokinetic Motion Sickness as Pseudo-Coriolis Effects Induced by Visual Moving Stimuli. Acta Otolaryngologica, Vol. 76, 1973, pp. 339-348.
12. D.M. Parker. An Investigation of Autonomic Function in Motion Sickness and Revulsion. Ph.D. dissertation. University of California at Los Angeles, 1964.
13. G.V. Barrett and C.L. Thornton. Relationship Between Perceptual Style and Simulator Sickness.

Journal of Applied Psychology, Vol. 52, No. 4, 1968, pp. 304-308.
14. R.S. Kennedy, K.S. Berbaum, and L.H. Frank. Visual Distortion: The Correlation Model. Technical Paper 841595. Society of Automotive Engineers, Warrendale, Pa., 1984.
15. R.S. Kennedy. Visual Distortion: A Point of View. Monograph 15. Naval Aerospace Medical Institute, Pensacola, Fla., Jan. 1970.
16. F.E. Guedey, Jr. Conflicting Sensory Orientation Cues as a Factor in Motion Sickness. In Fifth Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-314, Naval Aerospace Medical Institute, Pensacola, Fla., Aug. 1970, pp. 45-51.
17. H.W. Leibowitz and R.B. Post. Two Modes of Processing Concept and Some Implications. In Organization and Representation in Perception (J. Beck ed.), Lawrence Erlbaum, Hillsdale, N.J., 1982, pp. 345-363.
18. J.W. Miller and J.E. Goodson. A Note Concerning "Motion Sickness" in the 2FH2 Hover Trainer. Report 1, Project NM 7 01 11, Subtask 3. Bureau of Medicine and Surgery, Naval School of Aviation Medicine, Pensacola, Fla., Feb. 1958.
19. J.W. Miller and J.E. Goodson. Motion Sickness in a Helicopter Simulator. Aerospace Medicine, Vol. 31, 1960, pp. 204-212.
20. J.A. Puig. The Sensory Interaction of Visual and Motion Cues. Commemorative Technical Journal, NTDC 15th Anniversary, Naval Training Device Center, Orlando, Fla., Nov. 1971.
21. J.H. Casto. Simulator Sickness. Weekly Summary of Aircraft Mishaps, U.S. Naval Safety Center, No. 38-82, 1, Sept. 1982.
22. J.T. Reason and E. Diaz. Simulator Sickness in Passive Observers. Report FPRC/1310; AD 753560. Flying Personal Research Committee, Ministry of Defence, London, England, July 1971.
23. J.A. Puig. Motion in Flight Training: A Human Factors View. Technical Report NAVTRADEVCEN IH-177. Naval Training Device Center, Orlando, Fla., 1970.
24. COMPATWINGSLANT. 2F87(F) Serial No. 5 FE and Co-Pilot Display. U.S. Navy Message from COMPATWINGSLANT, Brunswick, Me., to CNO, Washington, D.C., April 1980.
25. J.E. Wenger. Motion Sickness in the P-3C Fleet Readiness Trainer at Naval Air Station, Brunswick, Me. Technical Memorandum NBDL:60:jah;6500. U.S. Navy memorandum from Commanding Officer, Naval Biodynamics Laboratory to Commander, Naval Air Systems Command, Washington, D.C., 1980.
26. B.O. Hartman and C. Hatsell. Field Study: SAAC Simulator. USAF School of Aerospace Medicine, Brooks Air Force Base, Tex., Oct. 1976.
27. M.E. McCauley and R.S. Kennedy. Recommended Human Exposure Limits for Very-Low-Frequency Vibration. TP-76-36. Pacific Missile Test Center, Point Mugu, Calif., 1976.
28. J.F. O'Hanlon and M.E. McCauley. Motion Sickness Incidence as a Function of the Frequency and Acceleration of a Vertical Sinusoidal Motion. Aerospace Medicine, Vol. 45, No. 4, 1974, pp. 366-369.
29. R.M. Evans, P.G. Scott, and M.G. Pfeiffer. SH-3 Helicopter Flight Training: An Evaluation of Visual and Motion Simulation in Device 2F64C. Technical Report 161. Naval Training Equipment Center, Orlando, Fla., 1984.
30. A.J. Benson. Some Notes on Simulator Sickness. Presented at the National Research Council Workshop on Simulator Sickness, Monterey, Calif., 1983.
31. G.V. Barrett and D.D. Nelson. Human Factors Evaluation of a Driving Simulator--Summary of Human Factors Evaluation 15. Goodyear Engineering Report 12400. Goodyear Aerospace Corporation, Akron, Ohio, Dec. 1965.
32. G.V. Barrett and D.D. Nelson. Human Factors Evaluation of a Driving Simulator--Summary of Virtual Image Display Studies, 20. Goodyear Engineering Report 12400. Goodyear Aerospace Corporation, Akron, Ohio, March 1966.
33. C. Testa. The Prediction and Evaluation of Simulator Illness Symptomatology. Ph.D. dissertation. The University of California at Los Angeles, 1969.
34. J.G. Casali and W.W. Wierwille. The Effects of Various Design Alternatives on Moving-Base Driving Simulator Discomfort. Human Factors, Vol. 22, No. 6, 1980, pp. 741-756.
35. L.E. Ryan, P.G. Scott, and R.F. Browning. The Effects of Simulator Landing Practice and the Contribution of Motion Simulation to P-3 Pilot Training. TAEG Report 63. Naval Training Analysis and Evaluation Group, Orlando, Fla., Sept. 1978.
36. K.E. Money. Flight Simulator Motion Sickness in the Aurora CP 140 FDS. DCIEM Technical Communication 80-C-44. Defence and Civil Institute of Environmental Medicine, Downsview, Ontario, Canada, 1980.
37. J. McGuinness, J.H. Bouwman, and J.M. Forbes. Simulator Sickness Occurrences in the 2E6 Air Combat Maneuvering Simulator (ACMS). Technical Report NAVTRAEQUIPCEN 80-C-0135-4500-1. Naval Training Equipment Center, Orlando, Fla, 1981.
38. R.E. Beinke and J.K. Williams. Driving Simulator. Presented at the General Motors Corporation Automotive Safety Seminar, Milford, Mich., July 1968.
39. W.M. Breda, M. Kirkpatrick, and C.L. Shaffer. A Study of Route Guidance Techniques. Report DOT-FH-11-7708. North American Rockwell Corporation, Columbus, Ohio, 1972.
40. J.B. Sinacori. V/STOL Ground-Based Simulation Techniques. USAAVLABS Technical Report 67-55. Northrop Corporation, Norair Division, Hawthorne, Calif.; U.S. Army Aviation Material Laboratories, Fort Eustis, Va., Nov. 1967.

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