EFFECTS OF VISUAL DISPLAY AND MOTION SYSTEM DELAYS ON OPERATOR PERFORMANCE AND UNEASINESS IN A DRIVING SIMULATOR

by

Lawrence H. Frank

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APPROVED:

Dr. W. W. Wierwille, Co-chairman

Dr. J. G. Casali, Co-chairman

Dr. H. L. Snyder

Dr. A. M. Prestrude

Professor P. T. Kemmerling

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Blacksburg, Virginia

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(ABSTRACT)

The role of visual-motion coupling delays and cueing order on operator performance and uneasiness were assessed in a driving simulator by means of a response surface methodology (RSM) central-composite design. Three levels of visual delay and three levels of motion delay were completely crossed in the two-factor, between-subjects, central-composite design. The driving simulator which was used had no history of inducing simulator sickness and therefore was modified so that delays could be introduced and controlled. Six subjects were assigned to each of the nine treatment conditions based upon pretest scores on the rod-and-frame test and under the constraint that an equal number of males and females were assigned to each treatment.

The most salient finding of the study was that visual delay appears to be more disruptive to an individual's control performance and well-being than is motion delay. Empirical multiple regression models were derived to predict 10 reliable measures of simulator operator driving performance and comfort. Principal components analysis on these 10 models decomposed the dependent measures into two significant models which were labeled vestibular disruption and degraded performance. Examination of the empirical models revealed

that, for asynchronous delay conditions, better performance and well-being were achieved when the visual system led the motion system. This finding is in direct opposition to current design recommendations and philosophy.

Caution is advised that the predicted values obtained from the models herein are specific to the simulator used in this study. It is recommended that the models derived in this study be used only as a means of determining relative trade-offs among competing design alternatives. Tradeoffs could be accomplished by simply rank ordering each alternative based on the models herein and selecting the design that produces the best outcome.

A secondary analysis of the role of subject gender and perceptual style on susceptibility to simulator sickness revealed that neither of these independent variables was a significant source of variance.

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Science bestowed immense new powers on man, and, at the same time, created conditions which were largely beyond his comprehension and still more beyond his control.

Sir Winston Churchill

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

APPENDICES:

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

LIST OF FIGURES

INTRODUCTION

Vehicle simulators are widely used in research, design, and training of private, commercial, military, and astronaut operators. This usage is understandable considering the economies in equipment and fuel, advantages in maintenance, availability, and safety, and demonstrated training effectiveness (Orlansky and String, 1977). Unfortunately, however, there has also been an increase in the reports of discomfort and distress following the use of vehicle simulators.

The experience of symptoms akin to motion sickness (e.g., nausea, disorientation) that occur either during or following simulator exposure is referred to as "simulator sickness." Incidences of simulator sickness have been reported in both fixed-base and moving-base simulators. Simulator sickness has occurred in automobile, fighter, patrol, transport, and helicopter simulators; to drivers, pilots, other aircrewmen, and instructors. Incidence has ranged from 10% to nearly 90%, depending upon the simulator (Frank, Kennedy, McCauley, and Kellogg, 1983).

Although the precise etiology of simulator sickness is not known, it is believed to result from a conflict or mismatch among sensory cues (Money, 1980). This premise, known as the perceptual conflict theory, postulates a referencing function in which motion information, signaled by the eyes, vestibular apparatus, or the proprioceptors, is at variance with these inputs' expected values (Reason and Brand, 1975). To complicate matters even further, the mismatch can occur not only between sensory modalities (e.g., visual and vestibular), but can arise within a single modality as well (e.g., the focal and ambient subsystems of the eye; Leibowitz and Post, 1982a).

It is apparent that if a real vehicle produces sickness, a simulator which mimics that vehicle is likely to produce the same response. However, when the simulator produces effects which are dissimilar from those which ordinarily occur, the consequences of such a situation must be carefully examined (Kennedy, Dutton, Ricard, and Frank, 1984). The question of concern for the human factors practitioner is not just one of why sickness arises, but of the consequences of such a disruption. The implications of simulator sickness can be grouped into six interrelated categories (Frank and Casali, in press; Frank et al., 1983):

(1) Artificial behaviors. Because simulators simulate, the cues presented in a simulator are different from those experienced in the actual vehicle. Consequently, some conscious and unconscious behaviors acquired in the successful operation of the simulator may be inappropriate or undesirable in the real vehicle, thereby compromising performance.

(2) Compromised training. Symptomatology may interfere with and retard learning in the simulator through distraction and, since humans are flexible, trainees may adapt to unpleasant perceptual experiences. If newly learned responses are not similar to responses required in the real vehicle, the new responses comprise negative transfer or habit interference to real-world conditions. Although not documented,

there is the possibility that novice operators, who originally learn to operate a vehicle through simulation, would be more likely to experience sickness or disorientation in the real vehicle because of a perceptual decorrelation between what is expected and what actually occurs.

(3) Decreased simulator use. Because of the unpleasant side effects, simulators may not be used and persons may lack confidence in the training that they receive. Frank (1981), for example, has reported that in one instance, the utilization rate of a simulator decreased by 50% when experienced fighter pilots became disoriented when performing air combat maneuvers in the simulator.

(4) Simulator aftereffects. Operators may be at risk following simulator exposure. For example, postural disequilibrium has been reported following the use of the P-3 aircraft simulator (Crosby and Kennedy, 1982). The possible negative consequences of unstable gait are numerous. There have also been reports of individuals who, while driving their automobile after a flight simulator exposure, had to pull off to the side of the road because they became too disoriented to continue (Kennedy, Frank, McCauley, Bittner, Root, and Binks, 1984; Miller and Goodson, 1958). Kellogg, Coward, and Castore (1980) have reported the onset of visual flashbacks and "bedspins" as late as 10 hours following simulated flight in the U.S. Air Force Simulator for Air-to-Air Combat (SAAC).

(5) Ethics. There are ethical issues which must be addressed when using a simulator that has the potential for eliciting simulator

sickness. In training simulators, such as those used in the military, the benefits of simulator use often far outweigh the possible occurrence of simulator sickness. However, it is incumbent to advise simulator users of the possible consequences. The U.S. Navy, for example, has an instruction (OPNAVINST 3710.7L) which recommends that aircrew exhibiting symptomatology of simulator sickness abstain from same-day flight in an actual aircraft.

In simulator-based studies, the use of human participants in experimentation demands compliance with the principles of informed consent.

(6) Threats to validity. Because artificial and/or degraded operator behaviors are likely in the presence of simulator sickness, the generalization of the resultant simulator data is suspect and validity is threatened.

Part of the problem in identifying the causal factors contributing to simulator sickness is that it is polygenic (Frank, Kennedy, McCauley, and Kellogg, 1983) and, in many cases, is believed to be simulator specific. For instance, at the recent National Academy of Sciences/National Research Council workshop on simulator sickness, a select group of scientists listed nearly 60 possible contributory variables (McCauley, 1984).

These variables encompass simulator design characteristics, either hardware or software, and procedural operating characteristics which are adopted in simulator use. Design characteristics may involve visual display variables, motion cuing variables, simulator dynamics (such as delays and computational lags), interface control/display configurations, and operating environment qualities. Critical procedural characteristics include the lèvel of operating kinematics, use of freeze (stop-action) and reset progression of trainee exposure over the course of a training syllabus, and duration of exposure, among others. For the interested reader, a detailed discussion of design and procedural variables with potential for inducing sickness appears in Casali and Wierwille, 1986.

Many of these variables may interact in their stimulation effect on the human sensory systems to convey the illusion of flying or driving. As such, their tendency to influence the incidence of operator uneasiness may also result from an <u>interaction</u> of antecedent sensory events. Furthermore, the influence of one variable may compound that of another. For instance, high peripheral scene detail may provide a much more pronounced vection cue when coupled with a wide field of view display.

The U.S. Navy has an extensive research and development program underway, attempting to identify simulator design and usage factors that contribute toward simulator sickness and the effects these factors have on user psychomotor, cognitive, and subcortical performance. Preliminary data from their early efforts suggest that visual-motion system coupling delays may be an important, <u>controllable</u> factor (Frank, 1984). For example, it was found that there were delays approaching nearly 400 ms between the onset of the motion subsystem and the movement of the visual subsystem in a helicopter simulator (Evans, Scott, and Pfeiffer, 1984). The incidence rate of simulator sickness in this simulator was over four times greater than that experienced in an "identical" simulator at another naval air station where it was later determined that the delay between the onset of the motion and visual systems was 47 to 77 ms, depending upon the axis measured (Lilienthal and Merkle, 1986). In addition, the final report of the aforementioned workshop on simulator sickness stated that (McCauley, 1984, p. 11):

> Experienced pilots have learned a set of temporal and spatial patterns in the aircraft related to control stick inputs and the resultant visual, vestibular, and proprioceptive feedback of acceleration information. In the simulator, they are confronted with a new set of temporal and spatial patterns, i.e., lags, rise times, washout, etc. This discrepancy is probably the main source of simulator sickness.

The role motion-visual coupling delays play in simulator sickness and degraded operator performance is the focus of this dissertation. As will be seen, simulator motion-visual coupling delays are of particular interest for at least the following reasons:

(1) The literature on human sensory capabilities and motion sickness predicts motion-visual delays to be provocative.

(2) The literature on the effects of visual lag indicate that delays are detrimental to operator performance and that transfer of training is decreased.

(3) Current simulator design philosophy is that the onset of the motion subsystem should lead the onset of the visual subsystem. In some cases the reverse may be true.

(4) Both the delay length and the sequencing between the visual and motion subsystems are modifiable and controllable.

These factors will be addressed in greater detail in the next section, along with a brief discussion of the types and causes of delay.

LITERATURE REVIEW

Delay

Types of delay. Although second-order (sigmoid) lags occur in vehicle simulators, transport (also known as zero-order, transmission, dead-time, or pure) delays and exponential (first-order) lags are the most common (Puig, 1984). In transport delay, an input is exactly reproduced at the end of the delay period. Consequently, transport delay affects phase but not gain. Unlike transport delay, exponential lag does not precisely reproduce the input, but displays an exponential response to a step input. Exponential lags are frequency dependent and function much like low-pass filters. They do not affect low frequency inputs, but attenuate the high frequency ones (Ricard and Puig, 1977).

An exponential lag can either enhance or degrade operator performance in a simulator depending upon its interaction with the system dynamics (Ricard and Puig, 1977). However, as will be discussed in detail in a later section, even very small transport delays (50 ms) can degrade compensatory tracking performance. For example, if delay length is one quarter of a cycle, the vehicle's track is correcting at this frequency before a corresponding control movement can take effect (Puig, 1984). If the delay length is one half of a cycle (i.e., 180 deg phase lag), a control movement intended to correct a vehicle's track will produce track displacement opposite to that desired.

Perhaps because transport delay is inherent in vehicle simulators and contributes towards degraded operator control performance, it is the only type of delay that the Federal Aviation Administration has set tolerances on for certification of aircraft simulators (Draft FAA Advisory Circular 120-40A, 1985). In addition, transport delay is also thought to be a causal factor of simulator sickness (McCauley, 1984). For these reasons, this dissertation is concerned with the effects of transport delay.

Causes of delay. Modern vehicle simulators are controlled by digital control systems which are needed to perform a massive array of control calculations. In part, these calculations are used to mimic the aerodynamic and dynamic responses of a specific vehicle, monitor and respond to the operator's control activities and instructor or experimenter inputs, provide feedback data to an instructor-operator station, and provide computer-image generation (CIG) for a visual simulation of the external-vehicle environment.

As the number of calculations increases, there is a concomitant increase in the transport delay, i.e., "the delay between an input to a system and the appearance of its output, where that output waveform is delayed a fixed time interval" (Ricard and Puig, 1977, p. 37). The greater the number of faces, edges, and/or points required in a CIG display, the greater the calculation time and the greater the transport delay. Since the computer typically calculates the simulated vehicle's current position before it calculates (usually serially) the CIG visual scene, delays occur. This problem can be exacerbated even further by the current practice of using separate computers of differing update frequencies for the motion and visual subsystems. In several flight simulators, for example, the motion subsystem updates at 30 Hz, whereas the visual subsystem has a 15 Hz update. Using a faster visual subsystem update rate will reduce the time delay.

Delay provocativeness. The perceptual conflict theory predicts that when sensory stimuli in the simulator differ from those experienced in the actual vehicle, simulator sickness will arise and that, the more experienced the individual is in the real-world vehicle, the more likely he/she is to be disrupted. In other words, when ingrained real vehicle sensory experiences are not in accord with current (simulator) experiences, simulator sickness occurs.

In actual aircraft flight, for example, when a person banks the aircraft, his/her visual system, vestibular system, and non-vestibular proprioceptive system all provide change-of-position information (assuming movement is above threshold), and they do so at perceptually the same time. In a simulator, when the motion subsystem starts its movement 100, 200, or even 300 ms before the visual subsystem starts its corresponding journey, conflict and its concomitant sickness can be expected. Leibowitz and Post (1982a) have pointed out the importance that expectations can play as a source of error in perception and its resultant performance. Expectations of certain relationships (based on real-world experience) are anticipated to occur in a simulator. When they do not, sickness will arise and performance will suffer.

Perusal of the studies on tracking performance in visual-motion delay experiments reveals that simulator sickness has occurred. These disclosures are usually thrown out as an aside in the reports, since experimenters are focused on their independent and dependent variables and may have failed to appreciate the significance of the symptoms exhibited by their subjects. For example, Miller and Riley (1977) reported nausea in their subjects (experienced aviators) when the visual subsystem followed the motion subsystem by as little as 125 ms.

Performance as a function of visual-motion delay. In an excellent review of the literature on the delay of visual feedback, Ricard and Puig (1977) reported a consistent finding that visual delay is detrimental to skilled-control performance. Miller and Riley (1977, 1978) found that, as the task difficulty increased, the amount of delay that could be tolerated between the onset of the motion and visual subsystems decreased. Similarly, Queijo and Riley (1975) found that, as the handling characteristics of the simulator became less desirable (i.e., more unstable), delay had a more powerful (detrimental) effect. In fact, under some conditions, a delay as little as 47 ms adversely affected pilot performance.

This interaction between task difficulty and delay time is interesting when compared to the work of Gundry. Gundry (1976), in assessing the detection threshold for roll motion in a flight simulator, concluded that threshold varies as a function of workload. The higher the workload, the higher the limen.

The data on visual delay clearly demonstrate that the greater the time delay, the poorer the operator performance and the greater the task difficulty, the smaller the acceptable time delay.

Motion cueing order. Current philosophy in simulator design dictates that the onset of the motion subsystem should lead the visual subsystem. This rationale stems from two factors: First, since the position of the simulated vehicle is calculated prior to the CIG updating the new visual scene, it is functionally convenient to allow a delay between the motion and visual subsystems. Second, many simulator design engineers believe that humans perceive vestibular and proprioceptive cues of motion before they perceive visual cues. This is a tenuous assumption.

Granting for the moment that this assumption is true for <u>supratheshold</u> proprioceptive stimuli, considerable evidence indicates that this is not necessarily true for subthreshold stimuli. Subthreshold vestibular inputs are a classic cause of aircraft disorientation incidents. A pilot may be totally unaware that he or she has slowly rolled inverted while flying without visual reference. Similarly, everyday experience indicates that automobile drivers unknowingly "drift" from their lane because of inadequate proprioceptive cues while concentrating, say, on turning the car radio or visually attending to the adjacent passenger.

It is also arguable that suprathreshold proprioceptive cues are always attended to before visual-motion cues. Reaction time (RT) experiments have shown the dominance of vision over kinesthetic and auditory stimuli. Although simple RT to a tone or to a kinesthetic stimulus is faster than to a visual stimulus, when either auditory or kinesthetic cues are combined with vision, their RT increases and vision dominates (Colavita, 1974; Fleishman and Rich, 1963; Jordon, 1972; Klein and Posner, 1974). Colavita (1974) has reported that several subjects, when presented a light and tone simultaneously, were unaware of the presence of the tone, even though the tone was the same or twice the psychological intensity of the light.

Young (1978) noted that circularvection can influence non-visual acceleration thresholds. When inertial accelerations are applied in a direction opposite to that of the visually-induced motion, it takes longer for them to be detected. On the other hand, complimentary vestibular and visual onset cues give rise to a more rapid onset of visually-induced motion.

According to the Federal Aviation Administration, all Phase II and Phase III simulators must have the motion subsystem lead the visual subsystem, but by not more than 150 ms (Draft FAA Advisory Circular 120-40A, 1985). Whiteside (1983) has commented that this is the reverse of what things ought to be:

> The point is that if one is looking through the window of a vehicle or aircraft at a structured field - earth, stars, etc., and if the cabin then begins to move, the first indication of that movement will be seen as a displacement of the stabilized structured external field with respect to the window frames if the movement is below the threshold of the vestibular stimulation. (p. 10-11)

Similarly, Kennedy, Frank, and McCauley (in press) have emphasized that the philosophy in simulation is different depending upon whether visual or inertial cues are being addressed. In terms of visual fidelity, the goal has been to replicate the real world as closely as possible. In contrast, simulation designers have set about to fool the vestibular system through suprathreshold stimulation and washout.

In simulator design it is of paramount importance to ensure that (a) the vestibular and visual systems are informed within the dynamic range in which they operate and that (b) they are informed spatially and 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 the rate of change (jerk) of acceleration (Benson, 1983).

In a simulator it is possible to provide a suprathreshold proprioceptive cue of motion when, in the real world, the proprioceptive cue would be below threshold and movement perception would be signaled only by the visual system. Thus, rather than augmenting the perception of motion, a conflict has been introduced. There is a mismatch between the linear and angular acceleration signaled by the vestibular system and that perceived visually. The vestibular system is signaling rapid movement while the visual system signals slow movement.

There are occasions then, when motion is signaled either initially or totally by the visual system. Moreover, Dichgans, Held, Young, and Brandt (1972) have provided evidence that a moving visual field can cause a modulation of the true gravity vector. Modulation of the resting potential of the vestibular nerve of the goldfish (Klinke and

Schmidt, 1970) and the vestibular nuclei of the rabbit (Dichgans and Brandt, 1972) have been shown to occur in response to moving visual fields. Furthermore, in a closed-loop system, visual cues appear to dominate sensation at low frequencies, whereas vestibular cues dominate at the high frequencies. To complicate matters even further, the visual and vestibular cues combine in a non-linear fashion, yielding a wideband sensory system (Zacharias and Young, 1981). These data and real-world experience would suggest that there are occasions in which the visual subsystem of a simulator should lead the motion subsystem.

The question of which modality dominates and which responds faster is not just an academic exercise. It is of paramount importance to good simulator design. Because of the mechanical limitations of a simulator, perfect replication of a vehicle's dynamic characteristics is unlikely. An A-4M aircraft, for example, has a roll rate of 720 deg/s at sea level. It is impossible to duplicate these dynamics in a simulator. The level of fidelity required in a simulator is an important and difficult question. However, it is generally agreed that, in designing a simulator, it is imperative to maintain the relationships among the stimuli and responses experienced in actual vehicle operation. For example, if one pushes forward on the throttle in an aircraft and thrust increases, the same relationship should hold in the simulator. If one's kinesthetic, vestibular, and visual systems are all perceived to be stimulated simultaneously in flight, then the simulator should also preserve the simultaneity relationship. The role of perceptual simultaneity in simulation is significant. If the visual and proprioceptive stimuli are perceived simultaneously in the simulator, then it can be conjectured that simulator sickness would be ameliorated and transfer of training would be improved.

It would be expected that if one sensory system responds faster than another, and one wanted to time the onset of these two sytems such that an observer perceives them to occur at the same moment in time, one would lead the faster system by the slower one. A fascinating study by Rutschmann and Link (1964) surprisingly found just the opposite to occur.

In their study, Rutschmann and Link examined perceptual simultaneity between a visual and auditory stimulus using reaction time (RT) as an estimate of uncertainty. Reaction time was measured by the subject removing his right index finger from a plate which resulted in the stopping of an electronic timer. Temporal order judgments, RT to the noise burst alone and RT to the light flash alone, were obtained from two trained subjects. Over 1000 measures of RT to each stimulus for each subject were obtained. Although RT to the auditory stimulus was shorter than to the visual stimulus by about 45 ms for each subject, perceptual simultaneity was found to occur when the auditory stimulus preceded the visual stimulus by approximately 43 ms.

In other words, the faster sensory modality (as measured by RT) had to precede the slower modality for simultaneity to be perceived. It is also of interest to note that 94% of the time subjects reported that the visual stimulus preceded the auditory stimulus when, in fact, there was physical simultaneity.

Hirsh and Sherrick (1961) have performed perhaps the most thorough set of experiments investigating perceived order among different sensory modalities (visual, auditory, and tactile). Their findings indicate that for the perception of temporal order to occur, a minimum temporal delay of 20 ms is required. In addition, it appears that the amount of delay required is constant within and between the visual, auditory, and tactile sensory systems.

What does this mean for simulator design? It means that, if the operator does respond to proprioceptive cues before visual cues for movement detection as simulator engineers believe, then the slower visual system should actually follow the onset of the motion subsystem. If, on the other hand, proprioceptive cues are slower, then the visual subsystem should lead. The simulator can be engineered to do just that. Through faster computer iteration rates and a slight delay in the onset of the motion system, visual can lead.

There are performance data which permit speculation that, in some cases, it may be better for the visual subsystem to lead the motion subsystem. Newell and Smith (1969) reported that the presence or absence of a visual scene had more effect on pilot performance than the presence or absence of motion cues. This finding suggests that one may attend to visual cues for movement/motion perception in a simulator more than inertial cues and that vision may be a more dominant sensory modality than proprioception of movement detection.

Albery, Gum, and Kron (1978) reported that for two U.S. Air Force simulators, the motion system lagged the visual system up to 200 ms.

Their study on the effects of roll tracking as a function of visual lead time indicated that a delay of 200 ms produced performance equivalent to the no motion condition. A delay beyond 200 ms produced performance worse than the no motion condition. They recommended that motion following visual delay should be in the range of 50-200 ms. Best performance was obtained when no delay occurred.

In a study on the effects of visual-motion display mismatch in a single-axis compensatory tracking task, Shirachi and Shirley (1977) have shown that, for a condition in which the simulated aircraft dynamics were of low gain (subjectively satisfactory to the pilots), visual lead produced less tracking error than the converse relationship.

In summary, it is readily apparent from the foregoing that vehicle motion can be detected in many ways by the human sensory system. The perception of velocity and orientation is dominated by vision in the steady state and for low frequencies below 0.1 Hz (Young, 1978). At higher frequencies and rapid acceleration, vestibular cues appear to dominate. Similarly, the temporal sequencing of our perceptual sensors is state dependent. Experiments on simple reaction time have shown that such factors as stimulus intensity, expectancy, and temporal uncertainty all interact and affect simple reaction time. Clearly, neither the proprioceptive modality nor the visual modality is independent of the other. In addition, the review of the literature on visual-motion coupling strongly suggests that visual lead may produce better operator performance and less simulator sickness in many cases.

Based upon the foregoing review of the literature on delay, the following conclusions appear warranted:

(1) Temporal delays between the onset of simulator motion and the visual subsystems appear to contribute toward simulator sickness.

(2) Design guidance regarding the synchronization of visual-motion subsystems is lacking and often arbitrary. The only consistent finding is that, the shorter the delay between the onset of the motion and visual subsystems, the better the operator's performance.

(3) Studies are suggestive that the current design philosophy of a visual lag in visual-motion coupling may be appropriate only for quick-onset, suprathreshold motion cueing.

(4) The literature on perceptual simultaneity and temporal order suggests that the faster sensory system may have to lead the slower for simultaneity to be perceived and that the temporal separation should be less than 20 ms.

(5) A parametric evaluation of the effects of visual-motion coupling delays and delay order on simulator sickness and operator performance is needed.

Motion Sickness

Recently, a comprehensive review of the motion sickness literature, with special reference to simulator sickness, was prepared by Kennedy and Frank (1985). Their paper details the signs and symptoms, stimuli and response characteristics, anatomical structures, susceptibility factors, and prevalent theories of motion and simulator sickness. The interested reader is referred to Kennedy and Frank (1985) for an in-depth discussion.

Motion sickness, in the pure use of the term, is an adversive reaction to actual physical body motion. Linear oscillations, vertically (i.e., parallel to the long z-axis of the body), are generally considered to be the most debilitating, but horizontal motions are also provocative and are frequently used in the laboratory because they are easy to produce. Rotary motions produced by carnival devices and centrifuges are very effective in producing motion sickness (Kennedy and Graybiel, 1965). Complex waveforms, however, are more effective than sinusoids (Graybiel and Miller, 1970; Guignard and McCauley, 1982). Very low frequency vibrations in the range of 0.12 - 0.25 Hz appear to be the most provocative stimulus conditions for inducing sickness (McCauley and Kennedy, 1976).

In its impure usage, motion sickness can be defined as an adverse reaction to perceived body motion. There is considerable evidence that visual motion alone is a sufficient stimulus. Movement of a visual field can induce the perception of self movement and sickness (Crampton and Young, 1953; Dichgans and Brandt, 1973).

Conventionally, both sickness induced by body movement and sickness induced by visual-scene movement have been referred to as motion sickness. This convention is reasonable, since the signs, symptoms, and postulated underlying causal mechanisms are the same for each.

Several reactions can occur in response to motion sickness. The most frequently reported signs (overt manifestations) are pallor, sweating, salivation, and emesis (Money, 1970; Wiker, Kennedy, McCauley, and Pepper, 1979). The primary symptoms are drowsiness, dizziness, and nausea. Other signs and symptoms that have been reported include disorientation, headache, stomach awareness, loss of appetite, lassitude, yawning, burping, confusion, ataxia, dejection, and, in some cases of simulator sickness, visual flashbacks (Kellogg, Coward, and Castore, 1980). Other effects include changes in cardiovascular, respiratory, gastrointestinal, biochemical, and temperature regulation functions.

There are six major theories of motion sickness: overstimulation, fluid-shift, fear/anxiety, balance of autonomic activity, toxic reaction, and perceptual conflict (see Kennedy and Frank, 1985, for a detailed discussion of each). Of these six, the most widely accepted theory among those researchers in the area of motion sickness is the perceptual conflict theory (Homick, Reschke, and Vanderpleug, 1984). The perceptual conflict theory is known by several names: mismatch, neural mismatch, cue conflict, incongruity, and sensory rearrangement being the most common. In brief, the perceptual conflict theory postulates a referencing function in which motion information signaled by the eyes, vestibular apparatus, or the proprioceptors, is at variance with these inputs' expected values (Reason and Brand, 1975).

The correlation model of the perceptual conflict theory has been recently extended by Kennedy, Berbaum, and Frank (1984) and Kennedy and

Frank (1985). Very simply, the correlation model suggests that motion sickness is a result of decorrelated sensory channels. This notion is in total concert with the perceptual conflict theory. It has been suggested before that the perceptual conflict theory is based upon a lack of correlation between appearance and reality (Held, 1965; Kennedy, 1979; Reason, 1970). Through interaction with the environment, correlations between and within sensory modalities build up over time. These correlations can be thought of as a neural store of information. Decorrelation occurs when inputs are not in accord with what is expected from the neural store. When decorrelation occurs, sickness usually follows.

When talking of perceptual decorrelation, it is common to think only in terms of conflict between sensory modalities. This is not necessarily so. Within sensory system conflict can also arise. One hypothesis for space sickness, for example, is that there is a vestibular/vestibular conflict. In space, the otoliths signal linear acceleration, but fail to signal head orientation because of the lack of gravity. Hence, a decorrelation occurs between the canals and the otoliths. A more down-to-earth example is the conflict that can occur between the focal and ambient visual systems of the eye (Leibowitz and Post, 1982b).

Each sensory modality has channels and bandwidths of sensitivity. Conflict occurs when spatial (gain) and temporal (phase) aspects of the stimuli are not in accord (Kennedy, Berbaum, and Frank, 1984). If the lack of accord occurs at ranges where the two channels are both sensitive, there is more disruption than at ranges where one or the other may be insensitive. Thus, a very small absolute difference (conflict) within the bandwidths of sensitivity can be disruptive, whereas a large absolute discrepancy outside the bandwidths of sensitivity may not cause a problem.

Simulator Sickness versus Motion Sickness

Simulator sickness, like motion sickness, can be viewed as a special case of "orientation sickness" (Gillingham, 1983) that manifests itself either during or following exposure to vehicular simulation. It has been reported in both fixed-base (e.g., McGuinness, Bouwman, and Forbes, 1981) and moving-base (e.g., Casali and Wierwille, 1980) simulators designed for aircraft and automobile research and training. Signs and symptoms of simulator sickness include disorientation, dizziness, headache, stomach awareness, loss of appetite, pallor, cold sweats, nausea, emesis, fatigue, lassitude, yawning, burping, confusion, spinning sensations, extreme unsteadiness, flashbacks, and visual dysfunction, among others. These signs and symptoms are not unlike the signs and symptoms reported for other types of orientation sicknesses (e.g., airsickness).

Although motion sickness and simulator sickness are closely related, some investigators have argued (viz., Barrett and Thornton, 1968b) that the primary distinction between the two is that motion is not requisite for the occurrence of simulator sickness, whereas it is for motion sickness. Historically, however, all orientation sicknesses, regardless of the stimulus conditions that initiate their onset, have been generically referred to as motion sickness. For example, studies examining aspects of the sensory rearrangement theory of motion sickness have often used circularvection as the provocative stimulus. During circularvection, the subject remains stationary while a large visual field is rotated around him/her. This situation appears analogous to what occurs in a fixed-base simulator with a moving visual scene. However, the resultant sickness can be appropriately classified as a Type II, visual-inertial conflict motion sickness (Reason and Brand, 1975).

The point is that motion sickness and simulator sickness are not inherently different. Both stem from a decorrelation of sensory-motion information. The reason that the untoward psychophysiological events that arise in the simulator should be labeled simulator sickness is that the term simulator sickness helps to generally define the stimulus conditions under which the sickness arose -- not that it is necessarily etiologically different than motion sickness. Use of the terms airsickness and seasickness, for example, immediately help to define to the reader the general stimulus conditions that were responsible. It is in an analogous fashion that the term simulator sickness is used in this paper.

Simulator Sickness

The phenomenon of simulator sickness was first reported by Havron and Butler (1957) in the fixed-base 2-FH-2 Bell helicopter hover trainer. During the next 23 years, until 1980, only 11 different simulators were reported (in the open literature) to cause sickness. However, since 1980, another 21 simulators have been documented. This dramatic increase in the reported incidence of simulator sickness is the result of several factors. Certainly, a major reason for the increase is that, circa 1982, the U.S. Navy began a systematic study of the incidence of simulator sickness in its simulators. The Navy has attempted to make aircrew aware of the problem of simulator sickness and has emphasized that, like disorientation in flight, simulator sickness is a natural, normal occurrence. Consequently, more aircrews have been willing to report incidents. Another factor contributing to the increased incidence rate over the past few years is, curiously enough, the increased sophistication of simulator technology. In particular, it is felt by the author that the rapid advances made in visual display technology have outdistanced those in motion simulation. This has lead to compelling mismatches between what is seen and what is felt by the simulator operator and therefore more sickness has occurred.

As noted in the introductory section, the precise etiology of simulator sickness is unknown. Part of the problem inherent in attempting to isolate the causal factors of simulator sickness is that it is polygenic (Frank et al., 1983). In the following literature review, it will be seen that simulator sickness has occurred in both fixed-base and moving-base simulators. It has occurred not only during simulator exposure but, in some individuals, has lasted several hours post-exposure (Frank, Kennedy, McCauley, Root, Kellogg, and Bittner, 1984). Moreover, simulator aftereffects may be delayed as much as 10 hours post exposure and include visual flashbacks (Kellogg, Coward, and Castore, 1980).

The reports on simulator sickness, although numerous, are generally not very informative. Only a handful of formal systematic evaluations of simulator sickness have taken place in which the stimulus environment was specified. The vast majority of reports can be classified as incidence reports, wherein a quick survey was conducted to "get a feel" for the magnitude of the problem (e.g., Frank, 1981). The remainder of the reports on simulator sickness fall into a category that can be labeled "asides." In this category authors mention the occurrence of simulator sickness in the context of being a hindrance to the real purpose of the study. For example, Miller and Riley (1977), in investigating the effects of time delays between the motion and visual systems of a simulator on operator control performance, reported that some subjects exhibited nausea.

In order to facilitate comparisons among the different reports of simulator sickness, Casali and Frank (in press) have compiled a set of tables defining the engineering aspects of several simulators in which simulator sickness has been reported. In addition, Casali and Frank developed a set of companion tables designed to summarize the data collection methods and findings of the field and laboratory studies on simulator sickness.

Table 1 presents the various design characteristics of the driving simulators, while Table 2 annotates the respective procedures and findings. In a similar fashion, Tables 3 and 4 present information on flight simulators. Blanks in the body of a table indicate that the information was either not evaluated nor reported in the study. The section of Tables 2 and 4 labeled "significant effects" refers to statistically significant ($\underline{p} < .05$) findings.

Not all the reports on simulator sickness were amenable to the format of Tables 1 through 4. For example, the engineering characteristics of a simulator may be listed but, since the data were only incidence data, no corresponding annotation could be made in the companion table. Consequently, Table 5 presents the relative incidence of simulator sickness in 13 additional simulators which were not amenable to the format of Tables 2 and 4. The incidence rates reported by Kennedy, Dutton, Ricard, and Frank (1984) for the flight simulators represent very preliminary results from a large comprehensive field study that is still ongoing.

As can be seen in 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 ms (Evans, Scott, and Pfeiffer, 1984). Ninety-eight percent of the throughput

Table 1. Driving simulator characteristics[1] (From Casali and Frank, in press).

Sim. Designation	Goodyear Aerospace I	Goodyear Aerospace II	UCLA I	General Motors Technical Center
Actual Vehicle	automobile	automobile	automobile	automobile
Type Vehicle	full-size sedan	full-size sedan	full-size sedan	general
Application	research	research	research & driver rehab.	research
Visual System				
Type	CCTV projection	CCTV monitor	motion picture	motion picture
Image Source	model board	model board	film	film
Medium	spherical screen	CRT	spherical screen	spherical screen
Infinity ∞ cueing	viewing distance	reflective ∞ optics	viewing distance	reflective optics
Lighting Cond.	daylight	daylight	adj. by film	adj. by film
H/V FOV (deg)[2]	50/39	54/unk.	150/unk	77-90/unk.
Scene Content	road & periphery	road & periphery	film of actual road	film of actual road
Motion System				
Type	fixed-base	fixed-base	fixed-base	cascade
Deg of Freedom[2]	-	-	-	tilt sim. of LN,LT accel.
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	-	-	yes	yes
Cockpit Environ.				
Cab type	car body	car body	car body	enclosed custom
No. Crew	driver	driver	driver, passenger	driver
Audio	engine, drivetrain	engine, drivetrain	engine, drivetrain	engine, drivetrain, tire
Operating Proced.				
Part/Whole Task	whole	whole	whole	whole
Typ. Task Length	30 min.	30 min.	unk.	unk.
Freeze Capa.	-	-	-	-
Slew/Reset Capa.	-	-	-	-
Ext.View Allowed	unk.	unk.	unk.	unk.
Other Characteristics				

[1] as existing in studies referenced in Table 2.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

Table 1. Driving simulator characteristics.[1] (Continued)

Sim. Designation	General Precision Sim-L-Car	North American Rockwell	VPI&SU
Actual Vehicle	automobile	automobile	automobile
Type Vehicle	general	general	adjustable car
Application	research	research	research
Visual System			
Type	point-light proj.	CCTV projection	CGI
Image Source	transparency	model board	hybrid CGI
Medium	flat, rear-projected screen	screen	monochrome CRT
Infinity ∞ cueing	refraction, 6 ft. viewing distance	unk.	refractive ∞ optics
Lighting Cond.	sunset	unk.	dusk, night
H/V FOV (deg)	45/unk.	~ 39/52	~ 48/30
Scene Content	road & objects	road & signs	road & periphery, other vehicles
Motion System			
Type	fixed-base	cascade	cascade
Deg of Freedom[2]	-	V; tilt sim. of LN, LT accel.	R, Y, LN, LT
g-seat/g-suit	-	-	-
g-display dim	-	-	-
Vibration	-	yes	yes
Cockpit Environ.			
Cab type	car components	enclosed custom	open/enclosed custom
No. Crew	driver, passenger	driver	driver
Audio	engine, drivetrain	engine, road noise	engine, drivetrain road noise, tire
Operating Proced.			
Part/Whole Task	whole	whole	whole
Typ. Task Length	10 min.	unk.	20 min.
Freeze Capa.	-	-	-
Slew/Reset Capa.	-	-	-
Ext.View Allowed	unk.	unk.	not by subjects
Other Characteristics			operation in dark room

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[1] as existing in studies referenced in Table 2.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

Table 2. Driving simulator study summary (From Casali and Frank, in press).

Author(s)	Barrett & Nelson (1965)	Barrett & Nelson (1966)	Barrett & Nelson (1968)
Simulator Designation	Goodyear Aerospace I	Goodyear Aerospace II	Goodyear Aerospace I & II
Type Report	Laboratory	Laboratory	Laboratory
Intent	simulator evaluation	virtual image display evaluation	perceptual style differences[5]
Simulator Tasks			
Scenario	freeway driving w/stops	freeway driving w/stops	freeway driving w/stops
Duration	30-50 min.[5]	30-50 min.[5]	30-50 min.[5]
Subjects			
Type	male engineering dept. employees	male engineering dept. employees	male engineering dept. employees
Number	25	25	46
Active/Passive	active	active	active
Independent Variables	emergency stop, speed	emergency stop, speed	emergency stop, speed
Dependent Measures[1]	D,S	D,S	D,S,Q
% Incidence Sickness	64	72	
% Leaving Simulator	44	56	50
Signs/Symptoms[2]			
Queasiness			
Sweating	x	x	
Nausea	x	x	
Emesis	x		
Eyestrain		x	
Headache		x	
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation	x		
Visual Dysfunction			
Ataxia			
Dizziness	x	x	
Vertigo			
Aftereffects			
Other	upset stomach faint feelings		Subject rating of discomfort, subject estimate of discomfort duration, No. trials subject able to stay in sim., rod & frame test
Habituation Effects[3]			
Experience Effects[4]			
Instructor/Student Effects			
Significant Effects			Extremely field independent, more susceptible

[1] How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] This was a post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson (1965, 1966) data.

[6] Estimated from Barrett and Nelson (1965, 1966).

Table 2. Driving simulator study summary. (Continued)

Author(s)	Testa (1969)	Reason & Diaz (1971)	Casali & Wierwille (1980)
Simulator Designation	UCLA I	Sim-L-Car	VPI&SU
Type Report	Laboratory	Laboratory	Laboratory
Intent	simulator sickness	simulator sickness	simulator sickness
Simulator Tasks			
Scenario	two-lane winding mountain road	winding perimeter road	freeway driving
Duration		10 min.	20 min.
Subjects			
Type	male college students	students/technicians	students
Number	40	15 male/16 female	64
Active/Passive	active	passive	active
Independent Variables	perceptual style instructional set	restricted vision sex driving experience	lateral accel. cueing delayed dynamic feedback simulator enclosure perceptual style
Dependent Measures[1]	R,Q	Q	Q,R
% Incidence Sickness	100	90	
% Leaving Simulator		1 case	
Signs/Symptoms[2]			
Queasiness			
Sweating	x	29	
Nausea		42	
Emesis			
Eyestrain			
Headache		45	
Pallor		29	x
Respiration Changes	x		x
Skin Resistance Changes			x
Heart Rate Changes			
Fatigue/Drowsiness		3	
Disorientation			
Visual Dysfunction			
Ataxia			
Dizziness		71	
Vertigo			
Aftereffects			
Other	galvanic skin response rod & frame test embedded figures test instructional set	Bodily warmth-48% stomach awareness-42% increased salivation-19% drymouth-6%	pulse rate arithmetic proficiency yaw standard deviation steering reversals
Habituation Effects[3]			
Experience Effects[4]		x	
Instructor/Student Effects			
Significant Effects	sweating, respiration, perceptual style instructional set	females more susceptible experienced more susceptible	pallor, skin resistance, respiration rate, yaw deviation, no.steering reversals

[1] How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] This was a post-hoc analysis of the effects of field independence/dependence on the Barrett and Nelson (1965, 1966) data.

[6] Estimated from Barrett and Nelson (1965, 1966).

Table 3. Flight simulator characteristics[1] (From Casali and Frank, in press).

Sim. Designation	2-FH-2	V/STOL	2F87F I	2F87F II
Actual Vehicle	Bell HTL-4	General V/STOL	P-3C turboprop	P-3C turboprop
Type Vehicle	helicopter	jet-lift	patrol	patrol
Application	hover training	research	training	training
Visual System				
Type	point-light proj.	point-light proj.	CCTV monitor Rediffusion Duoview	CGI MDEC[4] Vital IV
Image Source	transparency	transparency	model board	digital CGI
Medium	curved screen	spherical screen	CRTs	calligraphic CRTs
Infinity ∞ cueing	refraction, 6-12 ft. viewing distance	reflection, viewing distance	reflective ∞ optics	reflective ∞ optics
Lighting Cond.	dim, daylight	daylight	day, dusk, night	dusk, night
H/V FOV (deg)[2]	260/75	100/30	48/36[3]	48/36[3]
Scene Content	sky, earth	sky, earth, objects	sky, earth	sky, earth
Motion System				
Type	fixed-base	unk.	synergistic	synergistic
Deg of Freedom[2]	-	P, R, Y	all 6	all 6
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	yes	unk.	-	-
Cockpit Environ.				
Cab type	open	unk.	enclosed, A/C cab	enclosed, A/C cab
No. Crew	2	1	3	3
Audio	engine	unk.	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	unk.	takeoff & land	takeoff & land
Typ. Task Length	30 min.	unk.	4 hr.	4 hr.
Freeze Capa.	yes	yes	unk.	unk.
Slew/Reset Capa.	yes	-	unk.	unk.
Ext.View Allowed	unk.	unk.	unk.	unk.
Other Characteristics	control lag noted	orig. fixed-base, motion added		flight engr. had off-axis display view—caused sickness

[1] as existing in studies referenced in Table 4.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

[3] one window FOV; monochrome display added for flight engr. in Brunswick, ME, device (no. II).

[4] McDonnell-Douglas Electronics Corporation.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	(2 cockpits) SAAC	CP 140 FDS	2E6 ACM (2 cockpits)	2F112
Actual Vehicle	F-4 jet	Aurora turboprop (P-3C)	F-14/F-4 jet	F-14 jet
Type Vehicle	fighter	patrol	fighter	fighter
Application	air-air combat training	training, limited research	air-air combat training	air-air combat & misc. training
Visual System				
Type	CGI mosaic[3]	CGI	point-light proj.[3] MDEC	point-light proj.[4]
Image Source	digital CGI	digital CGI	2 transparency spheres	2 transparency spheres
Medium	8 monochrome raster CRTs	2 CRTs	40 ft. dia. dome	40 ft. dia. dome
Infinity ∞ cueing	reflective ∞ optics	unk.	20 ft. viewing distance	20 ft. viewing distance
Lighting Cond.	unk.	dusk, night	day, dusk, night	day, dusk, night
H/V FOV (deg)[2]	~ 296/180	unk.	~ 350/280	~ 350/280
Scene Content	sky, earth, A/C	sky, earth, objects	sky, earth, A/C	sky, earth, objects, carrier
Motion System				
Type	synergistic	synergistic	fixed-base	fixed-base
Deg of Freedom[2]	all 6	all 6	-	-
g-seat/g-suit	both	-	both	both
g-display dim	yes	-	yes	yes
Vibration	-	-	control stick vib.	control stick vib.
Cockpit Environ.				
Cab type	actual cockpits w/ canopies	enclosed	actual cockpit w/ canopies	actual cockpit w/ canopy
No. Crew	1 ea. cockpit	3	2 ea. cockpit	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	in-air combat	whole flight	in-air combat	whole flight
Typ. Task Length	45-60 min.	30 min.-2 hr.	45 min.-1 hr.	1-1.5 hr.
Freeze Capa.	yes	yes	yes	yes
Slew/Reset Capa.	yes	yes	yes	yes
Ext.View Allowed	unk.	unk.	no	no
Other Characteristics	0.2-0.4 Hz motion spectrum component apparent		gentry handrails in view of cockpit	

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[1] as existing in studies referenced in Table 4.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

[3] CCTV camera model target projectors.

[4] CCTV camera model target projectors and CGI carrier for landing via MDEC Vital IV.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	2F106	2F64C	2F110	2F117
Actual Vehicle	SH-2F	SH-3	E-2C turboprop	CH-46E
Type Vehicle	helicopter	helicopter	AEW/tactical	helicopter
Application	training	training	training	training
Visual System				
Type	CGI MDEC Vital III	CGI MDEC Vital IV	CGI Rediffusion Noroview SP1	CGI Rediffusion CT5
Image Source	digital CGI	digital CGI	digital CGI	digital CGI
Medium	calligraphic CRTs	calligraphic CRTs	calligraphic CRTs	raster CRTs
Infinity ∞ cueing	reflective ∞ optics	reflective ∞ optics	reflective ∞ optics	reflective ∞ optics
Lighting Cond.	night	dusk, night	dusk, night	day, dusk, night
H/V FOV (deg)	~ 144/32	130/30 & chin window	~ 139/35	200/50 & chin window
Scene Content	sky, earth, ships, objects	sky, earth, ships, objects	sky, earth, carrier, objects	sky, earth, ships, objects
Motion System				
Type	synergistic	synergistic	synergistic	synergistic
Deg of Freedom[2]	all 6	all 6	all 6	all 6
g-seat/g-suit	-	-	-	-
g-display dim	-	-	-	-
Vibration	yes, multiple	yes	yes	yes
Cockpit Environ.				
Cab type	enclosed helo. cab	enclosed helo. cab	enclosed A/C cab	enclosed helo. cab
No. Crew	2	2	2	2
Audio	yes, multiple	yes, multiple	yes, multiple	yes, multiple
Operating Proced.				
Part/Whole Task	whole flight	whole flight	whole flight	whole flight
Typ. Task Length	1.5 hr.	unk.	2-2.5 hr.	1.5-2 hr.
Freeze Capa.	yes	yes	yes	yes
Slew/Reset Capa.	-	yes	yes	yes[3]
Ext.View Allowed	yes	unk.	yes	yes
Other Characteristics				

[1] as existing in studies referenced in Table 4.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

[3] crew instructed not to view display during reset.

Table 3. Flight simulator characteristics.[1] (Continued)

Sim. Designation	2F121	2E7 ACTT (2 cockpits)	2F132
Actual Vehicle	CH-53D	F-18 jet	F-18 jet
Type Vehicle	helicopter	fighter	fighter
Application	training	air-air combat & tactics	training
Visual System			
Type	CGI Rediffusion CT5	CGI[4] IMI generator	CGI MDEC Vital IV
Image Source	digital CGI	CGI	digital CGI
Medium	raster CRTs	raster TV proj. on 35 ft. dia. dome	raster TV proj. onto dome
Infinity ∞ cueing	reflective ∞ optics	viewing distance	viewing distance
Lighting Cond.	day, dusk, night	day, dusk, night	dusk, night
H/V FOV (deg)[2]	200/50 & chin window	~ 360/150	~ 48/32
Scene Content	sky, earth, ships, objects	sky, earth, A/C	sky, earth, carrier objects
Motion System			
Type	synergistic	fixed-base	fixed-base
Deg of Freedom[2]	all 6	-	-
g-seat/g-suit	-	both	both
g-display dim	-	yes	unk.
Vibration	yes	yes	-
Cockpit Environ.			
Cab type	enclosed helo. cab	actual cockpits w/canopies	actual cockpit w/canopy
No. Crew	2	1	1
Audio	yes, multiple	yes, multiple	yes, multiple
Operating Proced.			
Part/Whole Task	whole flight	in-air combat	takeoff & land
Typ. Task Length	1.5-2 hr.	unk.	unk.
Freeze Capa.	yes	yes	yes
Slew/Reset Capa.	yes[3]	unk.	yes
Ext.View Allowed	yes	unk.	-
Other Characteristics			dynamic replay seat buffet carrier takeoff/ landing

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[1] as existing in studies referenced in Table 4.

[2] H-horizontal, V-vertical, FOV-field-of-view.
P-pitch, R-roll, Y-yaw, LN-longitudinal, LT-lateral, V-vertical (6 total).

[3] crew instructed not to view display during reset.

[4] CGI target projection via Rediffusion CT5.

Table 4. Aircraft simulator study summary (From Casali and Frank, in press).

Author(s)	Havron & Butler (1957)	Miller & Goodson (1958,1960)	Ryan, Scott, & Browning (1978)
Simulator Designation	2-FH-2	2-FH-2	2F87F 1
Type Report	field study	field study	field study
Intent	training effectiveness eval.	simulator sickness	transfer of training
Simulator Tasks			
Scenario	footnote 5	footnote 5	landing
Duration	30 min.	30 min.	4 hrs.
Subjects			
Type	instr./student pilots	instr./student pilots	instr./student pilots
Number	36	10	47
Active/Passive	active	active	active
Independent Variables			motion/no motion
Dependent Measures[1]	Q	Q,I	Q
% Incidence Sickness	78[6]	60 instructor, 12 student	11
% Leaving Simulator			
Signs/Symptoms[2]			
Queasiness			
Sweating	x		
Nausea	x		
Emesis			
Eyestrain			
Headache	x		6
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			
Disorientation			
Visual Dysfunction			
Ataxia			11
Dizziness			
Vertigo	x	x	
Aftereffects	x	x	
Other			
Habituation Effects[3]	x	x	
Experience Effects[4]	x	x	
Instructor/Student Effects	x	x	
Significant Effects			

[1] How obtained: Q-Questionnaire, I-interview, R-instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] Two scenarios--low level (55') or high level (500') maneuvers.

[6] In addition, 11 instructors were assigned to the simulator, but 7 had to quit because of sickness.

Table 4. Aircraft simulator study summary. (Continued)

Author(s)	Crosby & Kennedy (1982)	Kellogg, Castore, & Coward (1980)	Hartman & Hatsell (1976)
Simulator Designation	2F87F II	SAAC	SAAC
Type Report	field study	field observation	field study
Intent	simulator sickness	simulator sickness	simulator sickness
Simulator Tasks			
Scenario	patrol mission	air combat maneuvering	air combat maneuvering[5]
Duration	4 hrs.	about 60 min.	about 60 min.
Subjects			
Type	flight engineers	pilot	pilot
Number	20 plus	48	100-114
Active/Passive	passive	active	active
Independent Variables	field-of-view		
Dependent Measures[1]	D,Q,I	I	Q,I
% Incidence Sickness	50	88	52
% Leaving Simulator			
Signs/Symptoms[2]			
Queasiness			
Sweating		54	
Nausea		79	14
Emesis			2
Eyestrain			50
Headache			
Pallor			
Respiration Changes			
Skin Resistance Changes			
Heart Rate Changes			
Fatigue/Drowsiness			38
Disorientation			52
Visual Dysfunction			
Ataxia	50	60	
Dizziness			
Vertigo			
Aftereffects	x		
Other		spinning sensations-54% maneuver. sensations-25% headache, leans, dizziness or loss of situational awareness-23% vivid involuntary flashbacks-35% vivid dreams, daydreams-35% inverted visual field-10%	
Habituation Effects[3]		x	
Experience Effects[4]			
Instructor/Student Effects			
Significant Effects			

[1] How obtained: Q-Questionnaire, I-Interview, R-Instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] Also had a maximum maneuvering scenario.

Table 4. Aircraft simulator study summary. (Continued)

Author(s)	Money (1980)	McGuinness, Bouwman & Forbes (1981)
Simulator Designation	CP 140 FDS	2E6[7]
Type Report	field study	field survey
Intent	simulator sickness	simulator sickness
Simulator Tasks		
Scenario		air combat maneuvering
Duration		30-45 min.
Subjects		
Type	pilots	pilots/navigators
Number	14	66
Active/Passive	active	active/passive
Independent Variables		
Dependent Measures[1]	Q	Q
% Incidence Sickness	43[5]	27
% Leaving Simulator		
Signs/Symptoms[2]		
Queasiness		
Sweating		
Nausea	x[6]	9
Emesis		
Eyestrain		
Headache		7
Pallor		
Respiration Changes		
Skin Resistance Changes		
Heart Rate Changes		
Fatigue/Drowsiness		11
Disorientation		
Visual Dysfunction		8
Ataxia		
Dizziness		17
Vertigo		11
Aftereffects		x
Other		leans-9% discomfort-8% other-9%
Habituation Effects[3]	x	
Experience Effects[4]		x
Instructor/Student Effects		
Significant Effects		

[1] How obtained: Q-Questionnaire, I-interview, R-instrumentation, D-Direct observation, S-Subject comment.

[2] A number indicates % incidence; x-occurrence reported, but not by %.

[3] Lessens with exposure.

[4] More experienced real-world vehicle operators more susceptible.

[5] Three other individuals experienced symptoms while working, observing, or flying the simulator.

[6] Slight discomfort to mild nausea.

[7] Both F-4 and F-14 cockpits evaluated.

TABLE 5. Simulator sickness incident reports (From Casali and Frank, in press).

Simulator Designation	Vehicle	Active/Passive	Sample Size	Incidence
General Motors Technical Center[1]	generic auto	active	50 plus[2]	2 cases plus[2]
North American Rockwell[3]	generic auto	active	40	3 cases
V/STOL[4]	jet-lift	active	1	1 case
2F112[5]	F-14	active	65	16%
2F106[5]	SH-2F	active	28	13%
2F64C[5,6]	SH-3	active	36	13%
2F64C[5,7]	SH-3	active	153	55%
2F110[5]	E-2C	active	75	49%
2F117[5]	CH-146E	active	160	29%
2F87[5]	P-3C	active	55	44%
2F121[5]	CH-53D	active	208	36%
2E-7[5]	F/A-18	active	102	33%
2F132[5]	F/A-18	active	26	23%

[1] Beinke and Williams (1968)

[2] Precise figures not provided

[3] Breda, Kirkpatrick, and Shaffer (1972)

[4] Sinacori (1967)

[5] Kennedy, Dutton, Ricard, and Frank (1984)

[6] Simulator located on west coast

[7] Simulator located on east coast

delays were between 155 and 285 ms. For the west coast simulator, the average visual throughput delay was 167 ms.

As previously mentioned, Havron and Butler (1957) were the first individuals to document the occurrence of simulator sickness. Havron and Butler were performing a training effectiveness evaluation of the 2-FH-2 helicopter trainer. The trainer was designed to approximate the Bell HTL-4 helicopter. The 2-FH-2 became operational in the U.S. Navy in 1956 at Ellyson Field, Pensacola, Florida. Its purpose was to train hovering and autorotation.

The 2-FH-2 had a point-source visual system which provided a 260 deg horizontal by 75 deg vertical field of view. The transparency plate could be changed to simulate either low-altitude (16.78 m) or high-altitude (152-5 m) maneuvers. The simulator was fixed-base, but provided vibration of unknown frequency to the operator's seat. Havron and Butler reported that 78% of the individuals exposed to the simulator reported some type of symptomatology. In addition, of the 11 instructor pilots assigned to the simulator, seven had to quit because of sickness. Havron and Butler believed that the conflict between the lack of physical motion and presence of visual motion was the cause of the sickness.

Miller and Goodson (1958, 1960) also studied the 2-FH-2 simulator in an attempt to isolate the specific causal factors of simulator sickness. Miller and Goodson reported that 60% of the instructors demonstrated symptomatology, whereas only 12% of the student pilots showed symptomatology. Havron and Butler (1957) had also noted that there appeared to be an experience effect.

Miller and Goodson (1958, p. 9) reported the occurrence of delayed effects in one instructor pilot who became "so badly disoriented in the simulator that he was later forced to stop his car, get out, and walk around in order to regain his bearings enough to continue driving." Miller and Goodson attributed the simulator sickness to several apparent distortions in the visual system.

Barrett and Nelson (1965, 1966) reported the occurrence of simulator sickness in a series of studies using the Goodyear Aerospace driving simulator. As can be observed from Table 1, two versions of the Goodyear Aerospace simulator were used, differing only in the type of visual system. A closed-circuit television model-board system, which projected the image onto a large spherical screen yielding a 50 deg by 30 deg field of view, was used in the Goodyear Aerospace I. The Goodyear Aerospace II system used a virtual image projection system providing a 54 deg horizontal field of view.

Using the Goodyear Aerospace I simulator, Barrett and Nelson (1965) found that 11 of 25 subjects (44%) were too ill to continue the driving experiment. Two subjects (8%) reached emesis while in the simulator. In addition, of the 14 who completed the study, five (36%) reported that they felt some nausea. Similar results were reported by Barrett, Kobayashi, and Fox (1968).

When subjects were exposed to the virtual image display under similar driving scenarios, 14 of the 25 subjects (56%) became too ill to continue. Four of the 10 subjects (40%) who completed the study reported some nausea (Barrett and Nelson, 1966). Barrett and Nelson

(1966) asked the subjects to rate discomfort on a 10 point scale, where 0 was no discomfort and 10 was extreme discomfort. The average discomfort score for those subjects who completed was 3.6, whereas the average discomfort score for those who did not complete was 6.5.

Barrett and Nelson (1966) also compared the rates of simulator sickness between the virtual-image display and those reported in 1965 to the real-image display. They found a slightly higher incidence for the virtual-image display, but the difference was not statistically significant.

Barrett and Thornton (1968a, b) collected data on the perceptual style of the subjects who participated in the Barrett and Nelson (1965, 1966) studies. (This statement is not made in their reports, but it is evident when the data between the Barrett and Nelson and Barrett and Thornton studies are compared.) Using the Rod-and-Frame Tests as their measure of perceptual style, Barrett and Thornton (1968b) reported that extremely field independent subjects were more susceptible to simulator sickness than were those who were extremely field dependent. (A more detailed discussion of perceptual style will be presented later).

Testa (1969) reported a relationship between perceptual style and simulator sickness using the UCLA I driving simulator. The UCLA simulator consisted of a real car positioned on a dynamometer, with a 150 deg horizontal field of view, as seen on a wide, curved screen in front of the simulator. A screen located at the rear of the car provided a projected image that could be viewed by the simulator operator through his rear-view mirror (i.e., a virtual image). Testa found respiration rate and perspiration rate to be reliable indicators of simulator sickness.

Jex and Ringland (1973) reported that incidents of "vertigo" occurred in a closed-circuit television version of the UCLA simulator. The simulator differed from that reported by Testa (1969) only in terms of the visual display. The visual system was described as a "projected TV image of endless belt" (Jex and Ringland, 1973, p. 3) with a 40 deg horizontal field of view.

While examining route guidance techniques, Breda, Kirkpatrick, and Shaffer (1972) reported that three of their 40 subjects (8%) suffered acute illness. The North American Rockwell driving simulator consisted of an actual car body positioned on a motion system. A terrain model board TV projection system, having a 39 deg horizontal field of view, provided the visual stimulus.

Up until this point, all the reports on simulator sickness have two things in common. All simulators were fixed-base (excluding Breda et al., 1972), and all subjects were active participants in the "control" of the vehicle being simulated. Reason and Diaz (1971) investigated simulator sickness in passive observers.

The simulator used by Reason and Diaz was the Sim-L-Car. It had a point light source projection system which provided a 45 deg horizontal field of view, rear projected on a screen located six feet in front of the subject. The visual scene depicted "driving on a perimeter track and intersecting roads of a deserted airfield" (Reason and Diaz, 1971, p. 4). The subjects sat in the passenger seat of the automobile simulator and were told to keep their eyes on the screen throughout the 10-min exposure. Since other objects besides the projected visual scenes could be seen from the simulator, about one-half of the subjects were fitted with blinders to block everything but the moving visual scene from view.

Twenty-eight of the 31 subjects (90%) exhibited symptomatology ranging from mild dizziness to severe nausea. Reason and Diaz also found that women were significantly more disrupted than men. This is not surprising considering that the motion sickness literature indicates females are more susceptible to motion sickness (Money, 1970; Reason and Brand, 1975).

Somewhat more surprising, however, was the finding that the blinders had no effect. The ambient visual system is dominant over the focal visual system in terms of body orientation. It is also highly sensitive to movement perception (Leibowitz and Post, 1982b). It would, therefore, be expected that a restriction of the field of view would affect the incidence of symptomatology. However, in the Reason and Diaz study, the blinders did not reduce the dynamic visual scene field of view; only the presence of extraneous visual inputs was reduced. Effectively, there was no difference between the group with blinders and the group without, especially when it is recalled that the subjects were instructed to attend to the screen and ignore everything else.

The Reason and Diaz study also indicated that passive subjects were more susceptible to simulator sickness. Again, this is not surprising. As mentioned earlier, it is well-known that visual vection alone can induce disorientation, ataxia, and emesis. Benfari (1964), for example, induced simulator-like sickness in subjects who passively observed a driving scene which varied in the amount of field structure, peripheral flicker, and speed in a 165 deg ciné dome. Parker (1964) presented similar findings.

The only study to systematically investigate several design alternatives and their effects upon the occurrence of simulator sickness and simulator-operator control performance was conducted by Casali and Wierwille (1980). Casali and Wierwille used the VPI&SU driving simulator which has a four degree-of-freedom motion base (roll, yaw, lateral and longitudinal translation) and a 48 deg horizontal by 39 deg vertical virtual-image display.

In early automobile simulators, angular rotation and pitch were used to simulate lateral and longitudinal translation, respectively (e.g., Beinke and Williams, 1968; Breda, Kirkpatrick, and Shaffer, 1972). Casali and Wierwille found that using angular rotation to simulate lateral translation produced poorer control performance (number of steering reversals) and increased pallor and respiration rate as compared to true lateral translation. Similarly, a delay of 300 ms in the onset of the visual and motion systems yielded significantly more control yaw deviations and increased respiration rate. The authors also found that the presence of a cab enclosing the simulator operator produced increased respiration and decreased forehead skin resistance compared to an "open" vehicle. These latter differences were not due to increased temperature and humidity in the cab since adequate flow-through ventilation was provided. Casali and Wierwille also blocked subjects according to a Hidden Figures test of perceptual style and found no performance or simulator sickness effects due to this factor.

Two studies in the U.S. Air Force Simulator for Air-to-Air Combat (SAAC) have been performed. The SAAC is an F-4 air combat maneuvering trainer that has a canopy formed by a mosaic of eight CRTs, yielding a 296 deg horizontal by 180 deg vertical field of view. In the first of these studies, Hartman and Hatsell (1976) evaluated approximately 100 questionnaires and interviewed 14 pilots. Fifty-two percent of the pilots reported some type of symptomatology ranging from fatigue to two cases of emesis. Hartman and Hatsell also performed a power spectral analysis on the heave motion of the six degree-of-freedom synergistic motion system. The majority of the energy fell between 0.02 and 0.04 Hz. This is of special interest because it has been well established that the greatest motion sickness symptomatology occurs at a frequency resonance of 0.2 Hz (McCauley and Kennedy, 1976; Money, 1970). It is readily apparent that the SAAC simulator would be expected to induce true motion sickness because of this feature alone. Frank et al. (1983) have emphasized the importance of the simulator energy spectrum as a possible contributory factor and have presented envelopes from which design decisions can be made.

The second study performed on the SAAC was by Kellogg, Castore, and Coward (1980). Since about 1978, the motion system on the SAAC has not been used because of a study indicating that it did not provide any transfer of training benefit. Consequently, the Kellogg et al. study was performed on the SAAC in a fixed-base configuration. Kellogg et al. found that 88% of the 48 aircrew members they interviewed experienced simulator sickness. Nausea was the most prevalent symptom occurring in 79% of the subjects. The severity ranged from very mild to bordering on emesis.

Of particular interest was the finding that several pilots exhibited aftereffects occurring anywhere from 30 min to 10 hr following simulator exposure. Aftereffects of spinning or being rotated through an orthogonal plane were reported by 29% of the pilots. Other aftereffects included the sensation of climbing and turning (as in the aircraft) while watching TV, or experiencing a 180 deg inversion of the visual field while lying down. Other symptoms and their respective percentages can be seen in Table 4.

The differences in symptomatology and rates observed between the Hartman and Hatsell (1976) study and the Kellogg et al. field study cannot be totally attributed to the presence or lack of an active motion base. In the Hartman and Hatsell study, the subjects were involved in a less strenuous training regimen. In the Kellogg et al. study, the pilots received 12 hr of simulator exposure over a five-day period of time, averaging 550 air combat maneuvering engagements. Thus, the subjects in the Kellogg et al. study received a higher exposure rate and a higher level of stimulus intensity. (By stimulus intensity, it is meant that more visual stimulation was taking place.)

An early investigation of simulator sickness in the U.S. Navy's 2E6 Air Combat Maneuvering Simulator (ACMS) found that 27% of the aircrew reported some symptomatology (McGuinness, Bouwman, and Forbes, 1981). The ACMS is a domed simulator which can have either an F-4 cockpit or an F-14 cockpit inserted. This fixed-base simulator provides a 350 deg horizontal by 280 deg vertical field of view.

In the McGuinness et al. study, both F-4 and F-14 pilots and radar intercept officers (RIOs) were surveyed through a questionnaire and interview procedure. McGuinness et al. appropriately pointed out that the F-4 aircrews had not used the ACMS within 30 days of the conduct of the interviews and that it had been over 90 days since the F-14 aircrews had used the ACMS. Nevertheless, their findings indicated that 43% of the F-4 aircrews exhibited symptomatology, whereas only 28% of the F-14 aircrews did. The reason for this difference is unknown.

McGuinness et al. also found that 36% of the pilots reported simulator sickness as compared to only 15% of the RIOS. McGuinness et al. postulated that the reason for this difference is that RIOs have learned not to attend to disparity in the visual and proprioceptive cues. From the very early days of flight training, the RIOs are positioned in the back of aircraft, such as the T-39, without any outside visual reference. Even when in a fighter aircraft, RIOs frequently have to function in a "head-down" mode. Learning to disregard body sensations would lead to less airsickness. Pilots, on the other hand, have learned to build stronger associations between the visual and proprioceptive sensory systems.

An interesting finding of this study is that 50% of those aircrew with over 1500 flight hours experienced symptomatology, whereas only 28% of those with less than 1500 flight hours experienced symptomatology. This finding is consistent with the reports of Miller and Goodson (1958, 1960) and Reason and Diaz (1971) that experience in the real vehicle is related to simulator sickness susceptibility.

Because the visual systems vary considerably between the SAAC and the ACMS, and because of differences in the levels and intensity of exposure experienced by the aircrew, it is not meaningful to attempt to explain why a greater incidence of simulator sickness occurred in the SAAC as opposed to the ACMS.

Crosby and Kennedy (1982) have reported cases of simulator sickness in the U.S. Navy P-3 flight simulator (2F87), particularly in the flight engineers. In the P-3 simulator (see Table 3, 2F87 II), both the pilot and copilot have a digital CIG/CRT display yielding a 48 deg horizontal by 36 deg vertical field of view. The pilot also has a side view CIG/CRT display for use during landing. The flight engineer, who is positioned between and slightly aft of the pilot and copilot, does not have a visual display designed for his use. However, he can monitor either the pilot's or copilot's display even though he is 30 deg off the viewing axis. Crosby and Kennedy found that about 50% of the flight engineers demonstrated ataxia and other signs of simulator sickness.

Crosby and Kennedy found that inserting a baffle, which occluded the flight engineer's view of either the pilot's or copilot's display, eliminated the sickness. In addition, the presence or absence of the six degree of freedom motion system had no effect. In a second phase of their field study, Crosby and Kennedy installed a Hewlett-Packard monochrome repeater CRT in front of the flight engineer. In some cases, the baffle remained in place, occluding the pilot's and copilot's displays from the flight engineer. In other cases, the baffle was removed. The findings indicated that there were no differences between the baffle alone and baffle-plus-display conditions, and that the display alone condition was no different than the unbaffled condition.

Ryan, Scott, and Browning (1978) reported that 11% of their subjects experienced simulator sickness while conducting a transfer of training study on the 2F87-I, which is a modelboard closed circuit TV system.

Money (1980) found a 43% incidence of simulator sickness in the Aurora (CP 140 FDS) flight simulator, which is the Canadian version of the American P-3 (2F87).

In a recent study, Kennedy, Frank, McCauley, Bittner, Root, and Binks (1984) investigated two helicopter simulators in a pilot effort to test some field protocols for a larger survey to be conducted by the U.S. Navy. Thirty-six naval aviators flew the SH-3 helicopter simulator and 28 different naval aviators flew the SH-2 helicopter simulator. The SH-2 simulator (device 2F106) has a 144 deg horizontal by 32 deg vertical field of view which is generated by a "Vital III" calligraphic CIG. The display was a four-window, three-channel, folded on-axis virtual image. The SH-3 simulator (device 2F64C) had a 130 deg horizontal by 30 deg vertical field of view which was generated by a five-channel, "Vital IV" calligraphic CIG. The display was a seven-window, five-channel, folded on-axis virtual image CRT display. Both simulators had six degrees-of-freedom, synergistic motion-base systems.

All subjects were administered a motion sickness history questionnaire, a postural equilibrium test, and a commercially available air combat maneuvering Atari video game prior to their exposure to the simulator.

The ACM game was used because it was a two-dimensional pursuit tracking task which had been shown to be stable, related to other traditional manual control tasks, and was thought to be a useful measure of pilot skills (cf. Lintern and Kennedy, 1984). Following simulator exposure, subject reports on symptomatology, objective experimenter recordings of motion/simulator sickness signs and symptoms, postural disequilibrium tests, and the ACM performance task were administered.

There were no significant differences between the two simulators on the dependent measures. Overall, 80% of the subjects reported at least one symptom, 40% reported two or more symptoms, and 13% reported symptomatology related to discomfort of considerable magnitude. There were no significant differences in postural disequilibrium or on the ACM game. Motion sickness history was only slightly predictive.

Three other instances of simulator sickness reported by Kennedy et al. (1984) are especially worth noting. In the first, a pilot reported that he experienced disequilibrium on the evening following a 4-hr, moving-base CH-53 helicopter simulator ride, while he was in a movie theater. The disequilibrium occurred when the scene panned a landscape. In a second incident involving the same simulator, an aviator experienced a feeling of "detachment" while driving home about a half-hour following a 4-hr simulator exposure. He stated that he "found it mandatory to pull off to the side of the road to avoid being a hazard to the normal flow of traffic" (Kennedy et al., 1984, p. 34-9). An even more graphic report comes from an instructor pilot with more than 500 hrs in the simulator. He stated that, while attempting to land in formation in the real CH-53 helicopter, he had the illusory feeling of being in the simulator, which "landed high" in comparison to the real aircraft, and had trouble setting his helicopter down. Just as he was about to relinquish control to his copilot, the helicopter made contact with the ground and the disorientation subsided.

In September, 1983, the National Academy of Sciences/National Research Council, Committee on Human Factors held a workshop on simulator sickness. The proceedings of that workshop (McCauley, 1984) provide a very complete overview of the simulator sickness problem, promising dependent variables, remedial actions to ameliorate simulator sickness, and a list of some 60 independent variables thought to contribute toward simulator sickness. With the exception of the discussion on the vestibulo-ocular reflex (VOR), the content of that workshop has been covered in detail in this review and, therefore, requires no special annotation. For those interested in simulator sickness, however, the workshop proceedings are the recommended first reading.

Because so few of the studies on simulator sickness have defined the stimulus conditions under which the event occurred, it is difficult to draw firm conclusions. Nevertheless, based upon the data cited and the information detailed in Tables 1 through 5, the following tentative statements appear warranted:

(1) Delays in cue synchronization between the onset of the motion subsystem and the visual subsystem appear to be provocative.

(2) Simulator motion frequencies in the range of 0.2 - 0.4 Hz can induce sickness.

(3) The greater the intensity of stimulation and/or the greater the duration of exposure, the greater the likelihood of occurrence.

(4) Although not a linear relationship, in general the more experienced an individual is in operating the real-world vehicle being simulated, the more susceptible the individual is to simulator sickness.

(5) Females appear to be more susceptible than males.

(6) Motion sickness history appears to be modestly predictive.

Perceptual Style

The perceptual style concept of field dependence-independence has been extensively studied by Witkin and his colleagues (e.g., Witkin, Lewis, Hertzman, Machover, Meissner, and Wapner, 1954). Field dependent (FD) individuals are influenced more than field independent (FI) individuals by the context in which a perceptual judgement is to be made. Field independent individuals are better able to separate out or "disembed" an element of a stimulus array than are FD individuals. Prior to a discussion of field dependence-independence as it relates to simulator sickness, a brief background of its measurement is necessary.

Tests of perceptual style. Several metrics are available to ascertain a person's perceptual style. An early test of perceptual style, used by Witkin and his colleagues, was the Body Adjustment Test (BAT). The apparatus used for this test consisted of a boxlike room which could be tilted to either the right or the left. Within the room there was a chair for the subject, which also could be tilted to the right or left, independent of the room's position. On half of the trials, the room and chair were tilted in the same direction, and on half of the trials, the room and chair were tilted in opposite directions. The room and chair were always tilted to different angular settings. During the BAT, the subject's task was to direct the movement of his/her chair to the upright. The BAT could be administered with either the eyes open or closed.

Two other popular tests, because of their relative ease of administration, are the Embedded Figures Test (EFT) and the Hidden Figures Test (HFT). These two tests have a Pearson product-moment correlation of $\underline{r} = -0.55$ (Spotts and Mackler, 1967). In the EFT, a subject is presented with a card with a geometrical figure printed on it. The subject typically identifies the figure orally and then traces the shape with a stylus. This card is removed and a second card containing a complex geometrical pattern is presented. Embedded in this design is the geometric figure presented on the previous card. The subject's task is to correctly trace the original figure. Time to identify the figure is the dependent measure. Field-independent individuals take less time than FD individuals to perform the task.

The HFT is a variant of the EFT and was designed for group administration. Subjects are presented a set of simple figures (typically five). The subjects are then presented more complex figures (usually 32), each of which has one of the simple figures embedded within it. The subject's task is to identify the simple figure within the embedding context. The dependent variable is the number of figures correctly identified. Thus, FI individuals obtain higher scores than FD individuals. A major difference between the HFT and the EFT is that the HFT figures are achromatic, whereas, the EFT figures are colored.

The classic test of perceptual style is the Rod-and-Frame Test (RFT). In the RFT, the subject sits in a darkened room and is presented with a rectangular luminous frame surrounding a luminous rod. The frame can be set to any angle by the experimenter. The subject's task is either to remotely adjust the rod until he or she perceives it to be vertical, or to report when the rod is vertical as the experimenter moves it. The subject's score is represented by the angle between the subject's final positioning of the rod and true vertical. Three series of RFT can be administered. The Series 1 RFT consists of the subject and frame being tilted 28 deg to the same side (either right or left). In the Series 2 RFT, the subject and frame are tilted 28 deg to opposite sides. The Series 3 RFT is administered with the subject erect and the frame tilted 28 deg to either side.

Perceptual style and simulator sickness. It has been suggested by Barrett and others (e.g., Barrett and Thornton, 1968b; Testa, 1969) that FI individuals are more susceptible to simulator sickness than FD individuals because they are more sensitive to body cues or the lack thereof. It is conjectured that because FI people are more sensitive to body cues, they would be affected to a greater degree by a conflict that occurs between the visual and proprioceptive senses in a fixed-base simulator (i.e., visual signaling movement, proprioception signaling no movement). It is true that early work by Witkin and his colleagues suggested that FI individuals were more sensitive to body cues than FD. However, as Witkin, Dyk, Faterson, Goodenough, and Karp (1962, p. 42) later stated: "...it soon became clear that the body-sensitivity hypothesis also was untenable." For example, performance on stabilometer body-steadiness tests, which heavily involved the use of body cues, had little relation to the Witkin et al. (1962) orientation tests (i.e., RFT, EFT). According to Witkin et al.

(1962), the most reasonable hypothesis explaining their consistent findings on the FI-FD continuum is that there are individual differences in the ability to overcome an embedding context. In addition to being discrepant with the Witkin et al. (1962) findings, the Barrett and Thornton (1968) hypothesis does not account for the lack of sickness in several fixed-base simulators.

Barrett and Thornton (1968) were the first authors to report a relationship between simulator sickness and perceptual style. In their study, half of the subjects were exposed to the Goodyear Aerospace driving simulator, which consisted of a fixed-base, closed circuit television model-board system that projected the image onto a large spherical screen yielding a 50 deg by 30 deg field of view. The other half of the subjects were exposed to the same simulator, except the display consisted of a virtual-image projection providing a 54 deg horizontal field of view. For both groups, the driving task consisted of driving the simulator at a requested speed and making an emergency stop for a dummy pedestrian.

Using the RFT, Barrett and Thornton classified the subjects into perceptual-style types. Extremely FI and extremely FD subjects were those who were either one standard deviation above or below the mean of the Witkin et al. (1954) adult standardization sample for the Series 3 RFT.

Barrett and Thornton found no significant differences between the virtual-image and projected-image displays and pooled the data for purposes of analysis. They indicated that the reciprocal of the subjects' Series 3 RFT scores was significantly correlated with four measures of discomfort (reciprocal transformations on the RFT scores were performed to approximate linearity in the perceptual-style measure). Scores on the Series 1 and Series 2 RFT were not significantly correlated with any of the four measures. While Barrett's and Thornton's correlation analysis showed a positive association between FI and simulator sickness, several FD subjects also left the simulator early. This can be seen in Table 6, which presents the number of subjects who left the simulator before the end of the experimental run as a function of perceptual-style classification.

Examination of Table 6 reveals that 39 of the 46 subjects were classified as FI. In theory, this clearly non-Gaussian sample distribution should not affect the Barrett and Thornton correlation results as long as the subjects represent a random sample, which they do. Nevertheless, proportionally it can be seen that only 46% of the FI subjects left the simulator early, while nearly 71% of the FD subjects left. Consequently, the present author performed tests for significant differences between two proportions (Bruning and Kintz, 1968) on the data in Table 6. The proportion of extremely FI subjects who left the simulator (12/12) was significantly greater than the proportion of extremely FD subjects who left (3/5), $z = 3.36$, $p < 0.01$, supporting the Barrett and Thornton conclusion. In contrast, the proportion of all FD subjects who left early (5/7) was significantly greater than the proportion of all FI subjects who left, (18/39), $z = -2.54$, $p < 0.01$. Similarly, the proportion of all FI subjects who

Table 6

Number of Subjects Leaving Simulator Early as a Function of Perceptual-Style Classification (From Barrett and Thornton, 1968)

Subject	Extremely FI	FI	FD	Extremely FD
Left Simulator	12	6	2	3
Remained in Simulator		21		2

remained in the simulator (21/39) was significantly greater than the proportion of all FD subjects who remained (2/7), $\underline{z} = 2.54$, $\underline{p} < 0.01$. Considering the results revealed by the Barrett and Thornton correlation analysis, the proportion analysis herein, and the non-Gaussian nature of the perceptual-style variable, it appears that, on the basis of this data alone, no firm conclusion can be made regarding the relationship between perceptual style and simulator sickness.

In a follow-on study to the one just reviewed, Barrett, Thornton, and Cabe (1969) administered the EFT to most of the subjects who participated in the Barrett and Thornton (1968) study. The subjects were tested on the EFT six months following administration of the RFT, the RFT having been administered to the subjects six months after completing experimentation in the Goodyear Aerospace driving simulator.

Barrett, Thornton, and Cabe (1969) found that, whereas the correlations between RFT and simulator sickness had ranged from 0.33 to 0.55 in the 1968 study, the correlations between the EFT and simulator sickness were nonsignificant, ranging between 0.10 and 0.29. The correlation between the RFT and the reciprocal of the EFT was 0.83. Barrett, Thornton, and Cabe suggested several plausible reasons which, either alone or in combination, could account for the low correlation between simulator sickness and EFT scores. For example, the EFT and the RFT may assess slightly different perceptual dimensions.

Alexander and Barrett (1975) performed an experiment in which FI subjects and FD subjects watched a film (developed by Parker, 1964) of a high-speed automobile drive down a curving mountain road, as seen from the driver's seat. Half of the subjects in each perceptual-style group passively viewed the film while seated. The other half of the subjects were also seated, but had their feet positioned on a floor platform which could be tilted to either the right or left by movement of the subject's respective foot. The subjects were instructed to press to the floor the foot that corresponded to the direction they anticipated the car in the film was going to turn. This latter condition was designated the active-viewing condition. Thus, there were four experimental treatment conditions: FI passive viewing, FI active viewing, FD passive viewing, and FD active viewing.

Skin conductance was measured at the volar surface of the forearm and the axillae inner surface of the upper arm. Difference scores between the last two minutes of the stimulus film and a two-minute pre-film period were calculated for each subject for each of the two electrode sites. (See Alexander and Barrett, 1975, for specifics of how the skin conductance measures from each site were computed.) The subjects were also required to fill out a seven-item questionnaire which assessed the motion sickness sensations the subjects experienced.

The statistical analysis employed by Alexander and Barrett is somewhat difficult to interpret. For example, Alexander and Barrett state that they performed a single-factor analysis of variance (ANOVA) to assess if the FI passive-viewing group showed a greater change in forearm skin conductance than the FD passive-viewing group. Since there were 10 subjects in each group, a single-factor ANOVA would have 1 degree of freedom for the treatment (perceptual style) condition and 18 degrees of freedom for the error term (subjects nested within perceptual style condition). But Alexander and Barrett report 1 and 36 degrees of freedom for the treatment and error terms, respectively. An analysis using the upper arm skin conductance for this comparison was not reported. In a second analysis, Alexander and Barrett performed a single-factor ANOVA between the two active-viewing groups. Again, they reported 1 and 36 degrees of freedom for the treatment and error terms, respectively, for a test involving 2 groups of 10 subjects each. In another analysis, Alexander and Barrett contend that, since they were unable to reject the null hypothesis that the FI passive and FI active groups were equal in forearm skin resistance, this result supported the contention that they were equal. Although Alexander and Barrett noted that the ANOVA had a power of 89% to detect a difference of the magnitude found between the two groups, "proving the null" hypothesis provides no interpretive value.

Alexander and Barrett (p. 510) also reported that "...a post hoc analysis was performed to test the field-independent passive group against the other three groups. This post hoc analysis showed the mean of the field-dependent group in the passive condition to be significantly lower than the means of the other three groups, $\underline{F}(3,36) = 16.1$ $\underline{p} < .005$." The reported degrees of freedom for this analysis were 3 and 36. A significant F value with 3 and 36 degrees of freedom would only indicate that there existed at least one significant difference among the four means (assuming a simple-randomized design).

Alexander and Barrett also reported that two of the questionnaire items significantly correlated with both of the skin conductance measures: discomfort and illusory motion. Analysis of variance on the experimental groups for each sensation response produced no significant results. The RFT correlated 0.35 with the HFT. Analysis of the intercorrelations among HFT, the two measures of skin conductance, and the self reports of sensations experienced were nonsignificant.

From a description of the analyses performed by Alexander and Barrett, it is apparent that not all possible comparisons were made, particularly the interaction between perceptual style and subject activity level. It is also noteworthy that, for one analysis only, the forearm skin conductance dependent variable was assessed; for another, it appears that the mean value of the upper arm and forearm skin conductance measures was the dependent variable -- but it is uncertain. The "post-hoc" analyses were performed for both the upper arm and lower arm skin conductance measures.

Because of the questions regarding the statistical analyses addressed above, the Alexander and Barrett interpretation of the results is somewhat tenuous. The only "hard" data provided in their report show that the rank-order of the mean log skin conductance levels in micromhos was: FD passive (0.0724), FD active (0.1604), FI passive (0.1745), and FI active (0.2021). Thus, skin conductance was slightly greater for FI subjects, but it cannot be determined, based upon the reported analyses, whether there was a significant difference between FI and FD subjects.

In another study, Barrett, Thornton, and Cabe (1970) used an experimental device modelled after Wood's (1895) famous "haunted swing." The analogous device consisted of an enclosed boxlike swing in which the subject sat. An aperture in the front surface of the enclosed swing permitted a view of a distant brick-faced wall. Although the enclosed box appeared to the subject to be capable of side-to-side swinging movement, it actually remained stationary throughout the experiment.

The illusion of movement was provided by swinging what the subject believed to be an intact brick wall from side-to-side. Thus, the subject sat in a stationary swing, viewing a moving wall through an aperture. This situation is analogous to a fixed-base simulator in which there are visual cues of movement, but not proprioceptive. Barrett et al. (1970) predicted that the results of this study would parallel those found by Barrett and Thornton (1968) in the Goodyear driving simulator, that FI subjects were more susceptible to simulator sickness. (Recall that the review herein of the 1968 article indicates that the results were inconclusive).

In this swing study, Barrett et al. (1970) measured perceptual style using both the RFT and the HFT. The subjects were also administered the Kinesthetic Figural Aftereffects Test (KFAET), which consists of measuring an individual along a perceptual augmentation-reduction continuum, and three questionnaires assessing each subject's past motion sickness history and simulator sickness sensations.

The results of Barrett et al. (1970) surprisingly demonstrated that FD individuals experienced the sensations of movement and discomfort more than FI individuals, which was in contrast to their hypothesis. Series 2 and Series 3 of the RFT positively correlated with stomach effects and sensations of motion. No significant relationship was found between the KFAET and any of the dependent measures, nor was the HFT correlated with discomfort.

Barrett, Thornton, and Cabe (1970) suggested that, since Witkin et al. (1962) demonstrated that FD individuals are more suggestible than the FI individuals, this finding could help explain why FD individuals experienced more discomfort in a cue-conflict situation. In this study, the subjects were told that the swing was going to move. However, the visual-vestibular conflict experienced by the subjects of Barrett et al. (1970) is basically the same as that experienced in a fixed-base simulator. Thus, the explanation of suggestibility should also apply to fixed-base simulator studies regardless of whether the subjects were told to expect movement.

Testa's (1969) study has been cited as demonstrating that extremely FI persons are more likely to experience symptoms of simulator sickness than are extremely FD individuals. Testa used the UCLA driving simulator which consisted of a real car positioned on a dynamometer. The simulator had a 150 deg horizontal field of view, as seen on a wide, spherical screen in front of the subject. A screen located at the rear of the car provided a projected motion-picture image that could be viewed by the simulator operator through his rear-view mirror.

Testa evaluated two independent variables: perceptual style and instructional set. For the perceptual-style variable, 60 subjects were tested on both the RFT and a short-form EFT. Raw scores on each of these tests were converted to standard scores and added together for each subject. Individuals falling either plus or minus one standard deviation from the mean were classified as extremely FD or extremely FI, respectively. For purposes of statistical analysis, Testa assessed only the extremely FI and extremely FD subjects.

For the instructional set variable, subjects were given either a null (neutral) set of instructions regarding use of the driving simulator, or the subjects were given a set of instructions which notified them that, in the past, some people had become ill in the simulator and, if they felt unable to continue, to notify the experimenter. This latter set of instructions was referred to as the positive set. Thus, the overall design was a 2 by 2 factorial.

Testa performed step-wise multiple regression analyses, Chi-square analyses, and various ANOVAs on his data. Only the ANOVAs will be reviewed here since they are considered the more pertinent and revealing. Testa performed all possible one-way ANOVAs on the data and reported that FI subjects demonstrated a significantly greater incidence of simulator sickness as measured by sweat rate, respiration, GSR, and a motion sickness questionnaire for various combinations of instructions and perceptual set. He also reported that extremely FD subjects were more affected by the positive instructional set than were the extremely FI subjects.

It is important to emphasize that although Testa performed the more appropriate two-way ANOVAs, these findings are based upon one-way ANOVAs and are the results most frequently cited from Testa supporting a difference between susceptibility to simulator sickness in FI and FD people. Results from the two-way ANOVAs revealed that *there was a significant interaction between perceptual style and instructional set* for the dependent measures of sweating rate and respiration. Of course, a main effect in a factorial experiment will be the same as the treatment effect in a single-factor experiment only when there is no interaction in the factorial. Consequently, Testa's data do not clearly indicate that FI individuals are more likely to become simulator sick than are FD individuals.

There was a main effect of perceptual style for the two-way ANOVAs on the GSR and post-simulator sickness questionnaire measures. Field-independent subjects had higher post-simulator sickness questionnaire scores than FD subjects. But, interestingly, for the GSR measure, skin resistance was higher for the FI subjects than for the FD subjects. These two findings, then, appear to contradict one another.

It is important to recognize that, as the number of ANOVAs in an experimental analysis increases, there is a concomitant increase in the probability of a Type I error. Testa performed four two-way ANOVAs (one for each dependent variable). Consequently, his criterion level of $\alpha = 0.05$ was inflated to an $\alpha = 0.185$ (i.e., $1.0 - 0.95^4$). One method to guard against inflating the Type I error is to perform a multivariate analysis of variance (MANOVA). A MANOVA assesses the sensitivity of a set of dependent variables to the manipulation of the independent variables. When a significant MANOVA effect is found, subsequent univariate ANOVAs may be performed to isolate the pertinent dependent variable(s). If a MANOVA effect is nonsignificant, univariate tests are not used to interpret that effect. (It is quite possible to have an ANOVA signify a significant effect when the MANOVA does not or, on the other hand, to have a MANOVA mask an inherently significant ANOVA.)

A re-analysis of Testa's data was performed on the extremely FI and extremely FD subjects using a two-way MANOVA with perceptual style and instructional set as the independent variables. Following Testa, GSR, log respiration, log perspiration, and post-simulator questionnaire scores served as the dependent measures.

Table 7 summarizes the results of the MANOVA. Assuming Testa selected $\alpha \leq 0.05$ level, no significant effects were found, though the perceptual style main effect and perceptual style by instructional set interaction approached significance. This analysis fails to show a clear-cut, significant relationship between perceptual style and simulator sickness in Testa's (1969) data.

It should be noted that, when Testa performed his study in 1969, he apparently calculated all his statistical analyses by hand. Hand

Table 7

Multivariate Analysis of Variance Summary Table on Testa's (1969) Data

Source	df	*F*	*p*
Perceptual Style (PS)	1	2.94	0.0619
Instructional Set (IS)	1	0.81	0.5407
PS x IS	1	2.76	0.0731
Error	16		

calculation of a two-way MANOVA would have been an awesome undertaking. Today, the convenience of a large mainframe and the Statistical Analysis System (SAS) software makes such multivariate analysis more feasible.

The review of the literature relating perceptual style to simulator sickness reveals considerable contradictory evidence. Insight into the actual relationship between these two factors is further hampered by the lack of raw data presented in the studies, Testa's (1969) dissertation being the notable exception. Barrett and Thornton (1968) and Alexander and Barrett (1975) also provide a modicum of raw data, some of which were reproduced in this review.

One plausible interpretation of the literature on simulator sickness is that perceptual style may be unrelated to simulator sickness susceptibility. Casali and Wierwille (1980) found scores on the HFT to be unrelated to operator physiological measures and performance indicants of simulator sickness in a moving-base automobile simulator. In a related factor-analytic study on the physiological and psychological correlates of motion sickness, Bick (1983) found perceptual style, as measured by the EFT, to be unrelated to any of the other measures used, such as tests of balance and suggestibility. From these data, one would not expect perceptual style and simulator sickness to be related.

It should also be emphasized that many of the studies, such as Testa's (1969), focus at the extreme of the FI-FD continuum; using subjects which score at least a standard deviation from the mean. For perceptual style to be a meaningful predictor, a mapping against simulator sickness needs to be made over the entire perceptual-style continuum. Only then can meaningful threshold scores be obtained and used for prediction purposes. None of the studies reviewed approach being able to define such a "sickness-susceptibility" threshold. And, as has been shown, because of statistical deficiencies, the Alexander and Barrett (1975), Barrett and Thornton (1968), and Testa (1969) studies do not convincingly support the contention that there is a relationship between FI and susceptibility. In fact, two studies indicate either no relationship (Casali and Wierwille, 1980) or the opposite relationship to FD (Barrett, Thornton, and Cabe, 1970).

An interesting point was made by Kennedy and Frank (1985), who noted that it is well established that women, as a group, are more susceptible to motion sickness than men. Yet, women are predominately FD. (In all the studies reviewed, with the exception of Casali and Wierwille, all subjects were male.)

A paper by Kennedy (1975) reported that FI was significantly related to success in naval aviation training. Kennedy stated that scores on a motion sickness history questionnaire were also predictive of success in naval aviation. Although these two findings stem from separate experiments, it is reasonable to speculate that an FI individual would be less susceptible to motion sickness (therefore, simulator sickness) than an FD individual.

Ebenholtz and Benzschawel (1977) have demonstrated that, as the distance from the frame increased, the magnitude of the Rod and Frame effect (RFE) decreased as an approximately linear function of distance. In a second study, Ebenholtz (1977) verified that the retinal image size is directly related to the size of the RFE. According to Ebenholtz, retinal images of 10 deg or less will result in RFE less than 2 deg. At small retinal images then, everyone becomes FI.

It is interesting to note that the Witkin et al. (1954) adult RFT norms are based upon a 42-inch (106.68 cm) square frame positioned 7 feet (213.36 cm) from the subject. Yet, these conditions were not reproduced in any of the simulator sickness studies reviewed. For example, Barrett and Thornton (1968) used a 40-inch (101.6 cm) square frame positioned 8 feet (243.84 cm) from their subjects, while Barrett, Thornton, and Cabe (1970) used a 42-inch frame 8 feet away. Testa (1969) positioned a 40-inch frame 7 feet from his subjects. As can be seen from Table 8, each of these frame-size-distance combinations results in a smaller visual angle and retinal-image size than the Witkin et al. RFT. From Ebenholtz's (1977) work, it is obvious that the smaller retinal-image size inherent in these studies introduces a bias towards field independence. This bias may explain, in part, why Barrett and Thornton (1968) had such a skewed distribution of perceptual style scores (see Table 6), especially when it is recalled that they classified their subjects according to the Witkin et al. (1954) norms.

Ebenholtz's work suggests that FD subjects may have an ambient visual system dominance while FI individuals may have a dominant focal visual system. This was effectively demonstrated by Ebenholtz and

Table 8

Comparison of Frame Size, Test Distance, Visual Angle, and Retinal-Image Size in Four Studies

Study	Frame Size (cm)	Test Distance (cm)	Visual Angle (deg)	Retinal-Image Size (mm)
Witkin et al. (1954)	106.68	213.36	28.07	8.35
Barrett and Thornton (1968)	101.60	243.84	23.54	6.96
Barrett, Thornton and Cabe (1970)	106.68	243.84	24.68	7.31
Testa (1969)	101.60	213.36	26.78	7.95

Utrie (1983). They showed that, when a luminous circle surrounds the frame in the RFT, errors in setting the rod to egocentric vertical are significantly reduced. When a luminous circle is inscribed within the frame, no such effect is observed. This work indicated that it is not retinal eccentricity that is critical to the control of egocentric orientation but, rather, the most peripheral contour. Ebenholtz's and Utrie's work has the further implication that the ambient visual system is also involved in the inhibition of visual spatial orientation.

These latter data lead to the logical argument that an individual exhibiting the FI phenotype would be much more disposed to adapt to a perceptual conflict than an FD individual would (Barrett, Thornton, and Cabe, 1970; Kennedy, 1975). For example, Ebenholtz's work suggested that when the retinal image produced by a rod and frame stimulus was restricted to the focal visual system, all subjects became FI. This would imply that the ambient visual system dominates in FD individuals and that the focal visual system dominates in the FI person. Consequently, an individual who is FD would be more likely to have a conflict between the visual and proprioceptive systems than a FI person. This is particularly true when it is recalled that FD individuals cannot overcome an embedded context. Because the review of the literature on perceptual style as a predictor of simulator sickness indicated considerable contradictory evidence and is perhaps best interpreted as being nonsupportive of a relationship between FI and simulator sickness, it was decided that perceptual style need not be examined as a major independent variable in this study. However, it was felt that it would be remiss not to ascertain each subject's perceptual style and unambiguously assess its influence in a secondary analysis.

Selection of Independent Variables

The review of the literature established that visual-motion coupling delays in vehicle simulators degrade operator control performance. Data were also presented indicating that these delays can cause simulator sickness. Although several parametric studies have been performed investigating the influence of visual-motion coupling delays on operator performance, no study has been conducted exploring the relationship between transport delay and simulator sickness.

It was also noted that with the exception of two studies (Casali and Wierwille, 1980; Shirachi and Shirley, 1977), all of the performance studies on delay were conducted in simulators in which the motion subsystem led the visual subsystem. It was argued that this design philosophy, which is mandated by the Federal Aviation Administration for Phase II and III flight simulators, may only be valid when suprathreshold proprioceptive stimuli are presented.

It is advisable to perform a parametric study on visual-motion coupling transport delays from which design recommendations can be made to optimize control performance and minimize simulator sickness. The goal of this dissertation is to develop an empirical model and concomitant response surfaces from which design recommendations can be derived.

Consequently, two independent variables were selected for study in the Virginia Polytechnic Institute and State University (VPI&SU) driving simulator: motion-system delay and visual-system delay. Because "...transport delays are inherent in the updating of digitally generated visual displays..." (Simon and Roscoe, 1984, p. 594), transport delays were investigated in this experiment.

Review of the literature on transport delays in operational vehicle simulators reveals that delays up to 400 ms have occurred, with most falling below 300 ms (Evans, Scott, and Pfeiffer, 1984; Puig, 1984). To be able to statistically generate second-order response surfaces for later analysis, three levels of delay are both necessary and sufficient. Transport delays of 0, 170, and 340 ms were evaluated in this experiment. The selection of these levels of delay was based upon the literature reviewed, the desire to have a statistically orthogonal response surface design, and the limitations imposed in quantizing the delays. Delay quantization will be addressed in a later section.

Of secondary interest were two other independent variables: perceptual style and past motion sickness history. As previously mentioned, a subject's perceptual style was not expected to influence susceptibility to simulator sickness. However, it was felt that a clearer interpretation of its role might be ascertained in this study. Similarly, an individual's past motion sickness history has been shown to be moderately predictive of future motion sickness (Reason and Brand, 1975) and simulator sickness (Kennedy, Frank, McCauley, Root, Bittner, and Binks, 1984).

Although several motion sickness questionnaires have been developed, perhaps one of the most thoroughly studied and widely implemented is the Pensacola Motion Sickness Questionnaire (MSQ). The Pensacola MSQ is based upon one described by Reason and Brand (1975), and consists of an omnibus, anamnestic form that has been item analyzed, empirically validated, and cross-validated against a laboratory procedure for the prediction of motion sickness (the dial test). Moreover, MSQ scores have been found to be related to success in U.S. Naval flight training (Hutchins and Kennedy, 1965) and have been used to categorize subjects on the basis of motion sickness susceptibility (May, Cullen, Harbison and Holt, 1984). Appendix C presents the Pensacola MSQ.

Selection of Dependent Variables

As previously noted, this study is concerned with the effects of temporal delay and motion cueing delay order on an operator's performance and physical well-being. Correspondingly, four classes of dependent variables were selected which were believed to be sensitive indexes of simulator driving performance and simulator sickness.

Driving performance measures. It is readily apparent from the literature reviewed that delays in the visual and motion systems of a simulator degrade operator control performance and, in some cases, induce simulator discomfort. Two measures of driving performance, the number of steering wheel reversals and yaw standard deviation, and one simulator measure of driver discomfort, the number of seat movements, were selected for use in this study.

Casali and Wierwille (1980) have reported yaw standard deviation and the number of steering reversals to be sensitive measures of operator performance in a driving simulator sickness study. Other authors have also reported steering reversals to be a reliable measure of driver performance and vehicle controllability (McLane and Wierwille, 1975; McLean and Hoffman, 1975). More recently, Dingus, Hardee, and Wierwille (1986) demonstrated that steering reversals and yaw variance correlated significantly with other objective measures of alcohol level and drowsiness in a driving simulator study.

It might also be hypothesized that when individuals are exposed to a motion sickness-provocative environment, they become more restless and "squirm" about. It could then be expected that the number of seat movements might be a sensitive measure of simulator uneasiness. This conjecture is given support by the results of Dingus et al. (1986) which showed the number of seat movements in a driving simulator to be a reliable predictor of alcohol consumption and drowsiness.

Physiological measures. The most common observable signs of motion sickness, in their usual order of occurrence, are drowsiness, pallor, cold sweating, (i.e., sweating in the absence of thermal stimulation), and emesis (Money, 1970). A similar response order appears to hold for simulator sickness (Kennedy and Frank, 1985). Review of the literature reveals that three physiological measures — skin resistance, pallor, and respiration — appear to be reliable indicators of simulator sickness.

(1) Skin resistance. As noted, cold sweating is a cardinal sign of motion sickness which can be observed as a decrease in skin resistance or as an increase in skin conductance (conductance is the inverse of resistance). Several studies investigating simulator sickness have observed excessive perspiration by their subjects (e.g., Barrett and Nelson, 1965, 1966; Kellogg, Coward, and Castore, 1980). Parker (1971) reported sweating from the volar surface to be a highly sensitive indicator of motion sickness susceptibility to a visually moving stimulus (viz., a film of a drive down a winding mountain road as viewed from the driver's seat). Testa (1969) reported skin resistance to be a reliable index of simulator sickness, although Casali and Wierwille (1980) found it to be less sensitive than measures of respiration and pallor.

Because the subjects in this study were actively driving the simulator, the forehead was selected as the site for skin resistance measurement. Although the forehead has about twice as many eccrine sweat glands per unit area as the limbs (Weiner and Hellman, 1960), McClure and Fregly (1972) have suggested that the forehead may not be the best location to monitor skin resistance changes during motion sickness. This suggestion stems from their finding that a sweat response was not observed immediately at the time of a vestibular stimulus onset. McClure and Fregly reported that the response profile of forehead skin resistance demonstrates a relatively long latency to sweat onset followed by a gradually rising level of response. This response profile is compatible with the design of this experiment since a subject's skin resistance score consists of a difference score between the mean of the last five minutes of an experimental run and the mean of a baseline, pre-stimulus exposure period. Details of the measurement and scoring techniques will be addressed in later sections of this report.

(2) Pallor. Pallor is the result of restricted blood flow to the head which is exhibited as "paleness" in the subject. Casali and Wierwille (1980) found that objective measurement of opacity changes in a subject's ear was a reliable measure of uneasiness for certain experimental manipulations in a driving simulator study.

(3) Respiration. The motion sickness literature strongly indicates that changes in respiration are likely to occur when a subject is exposed to a motion sickness provocative situation. However, the literature is contradictory as to whether respiration rate will increase or decrease. For example, Parker (1964) found a decrease in respiration, whereas Crampton (1955) found an increase in respiration. Likewise, Testa (1969) found that respiration rates increased with the onset of simulator sickness.

In order to circumvent the problem of individual differences in respiration changes, Casali and Wierwille (1980) used an absolute difference score between baseline respiration rate and the simulator exposure respiration rate. Using this procedure, they found respiration to be a highly reliable measure of simulator discomfort.

Postural disequilibrium tests. Postural stability is a frequently used measure of vestibular disruption following exposure to altered sensory environments. Crosby and Kennedy (1982), for example, found significant ataxia problems in aircrew following exposure to the Navy's P-3 simulator (2F87 I). During exposure to an altered sensory environment, such as a simulator, visual and vestibular adaptation occurs. This adaptation disrupts an individual's balance upon return to the "normal" environment. Moreover, it has been conjectured that aftereffects are proportional to the amount of adaptation (Kennedy and Frank, 1985). Recently, Thomley, Kennedy, and Bittner (in press) experimentally evaluated modified forms of four classical postural disequilibrium tests for the specific use in simulator-sickness studies. Thomley et al. recommended the use of the "stand-on-leg" tests as a method of first choice for the determination of highly transitory effects such as might occur following simulator exposure. Thus, the following two postural disequilibrium tests were used in this study: Stand-On-Preferred-Leg (SOPL) and Stand-On-Nonpreferred Leg (SONPL). Specifics of each test are given in the method section.

Simulator sickness severity index (SSSI). Subjects' self-evaluation forms following sickness-provocative stimulation have been shown to be valuable tools in assessing an individual's well-being (Kennedy, Frank, McCauley, Bittner, Root, and Binks, 1984; Reason and Brand, 1975; Testa, 1969). Wiker, Kennedy, McCauley, and Pepper (1979) developed a self-evaluation questionnaire and diagnostic categorization technique which permits a rater of a subject's questionnaire to classify the subject into one of eight categories indicative of motion sickness severity. Wiker et al. have shown this technique to be easy to use by different raters and to yield an inter-rater reliability of *r* = 0.956. In addition, point-biserial correlations between the dichotomous criterion of vomit/no vomit and the subject's symptomatology were significant and average *r* = 0.63 between the subjects' recording of their own symptoms and experimental observations of subject emesis. More recently, Kennedy, Frank, McCauley, Bittner, Root, and Binks (1984) have demonstrated the utility of this procedure in field studies of flight simulator sickness. Details of the self-evaluation questionnaire and categorization procedure will be presented in the method section.

RESEARCH OBJECTIVES AND EXPECTED RESULTS

As previously mentioned, the goal of this research was to develop empirical models and concomitant response surfaces from which design recommendations can be derived. Specific concerns of this research included:

1. What is an acceptable delay range over which performance is maximized and simulator discomfort minimized? Is this range symmetrical across the two independent variables?
2. Is control performance better when the visual subsystem leads motion, or when the motion subsystem leads visual?
3. What physiological measures are reliable indicators of discomfort?
4. Does perceptual style show a relationship to simulator sickness and operator control performance?

Based upon the review of the literature, the following results were expected:

1. Control performance will decrease as delay increases for both independent variables.
2. Optimal control performance will be obtained for asynchronous delays less than 100 ms.
3. Symptomatology will increase as transport delay increases over the range to be studied.
4. The results of the different driving measures will closely parallel each other.

5. The measures of simulator sickness will vary in their sensitivity.
6. For moderate levels of delay a more pronounced effect is expected on performance measures, whereas simulator sickness measures may exhibit subtle changes.

METHOD

Experimental Design

Primary design. A two-factor, between-subjects, orthogonal, second-order, response surface central composite design, with equal replication was the primary design in this study. Response surface methodology (RSM) consists of a group of statistical techniques which can be used to study empirically the relationships between one or more measured responses and a number of independent variables. Response surface methodology has several advantages: it uses central-composite design techniques to collect data efficiently; and first-order and second-order polynomial equations can be generated to describe the response surface.

An orthogonal design was used to provide uncorrelated estimates of the response model regression coefficients, thereby facilitating the interpretation of possible second-order effects. A between-subjects design was selected to eliminate the possible occurrence of learning, practice, or order effects across treatment conditions.

Although equal replication across the design is not as economical as replication at the center point, Williges (1981) and Clark and Williges (1973) have noted that responses across subjects may be so variable that an estimate of the error from only the center point may not be judicious. Using a between-subjects response surface design, Williges and Baron (1973) demonstrated that replication at the center and replication across the entire design yielded essentially equivalent first-order polynomials, but that the reliability of the regression weights was greater for the equal replication error estimate.

The two independent variables of prime interest were visual delay and motion delay. For an orthogonal RSM design with only two independent variables, it can be readily shown that this design is equivalent to a conventional 3 x 3 factorial design with nine treatment conditions. Figure 1 schematizes the experimental design and Table 9 presents the coded and uncoded treatment conditions.

Secondary design. In addition to the above design, a secondary design appropriate for assessing perceptual style and sex was employed. Although, based upon the literature review, it was not expected that a subject's perceptual style would influence his or her susceptibility to simulator sickness, it was decided to block the subjects according to perceptual style to enable unambiguous interpretation of the data.

The subjects' scores on the RFT were independently rank-ordered for each sex and divided into thirds. This procedure yielded nine subjects per third for each sex. One subject from each third for each sex was randomly assigned to one of the nine treatment conditions. The secondary analysis thus consisted of a Motion Delay x Visual Delay x Sex x Perceptual Style (3 x 3 x 2 x 3) between-subjects factorial design. Also of interest were the intercorrelations among the various independent and dependent variables. A multiple correlation analysis was therefore performed.

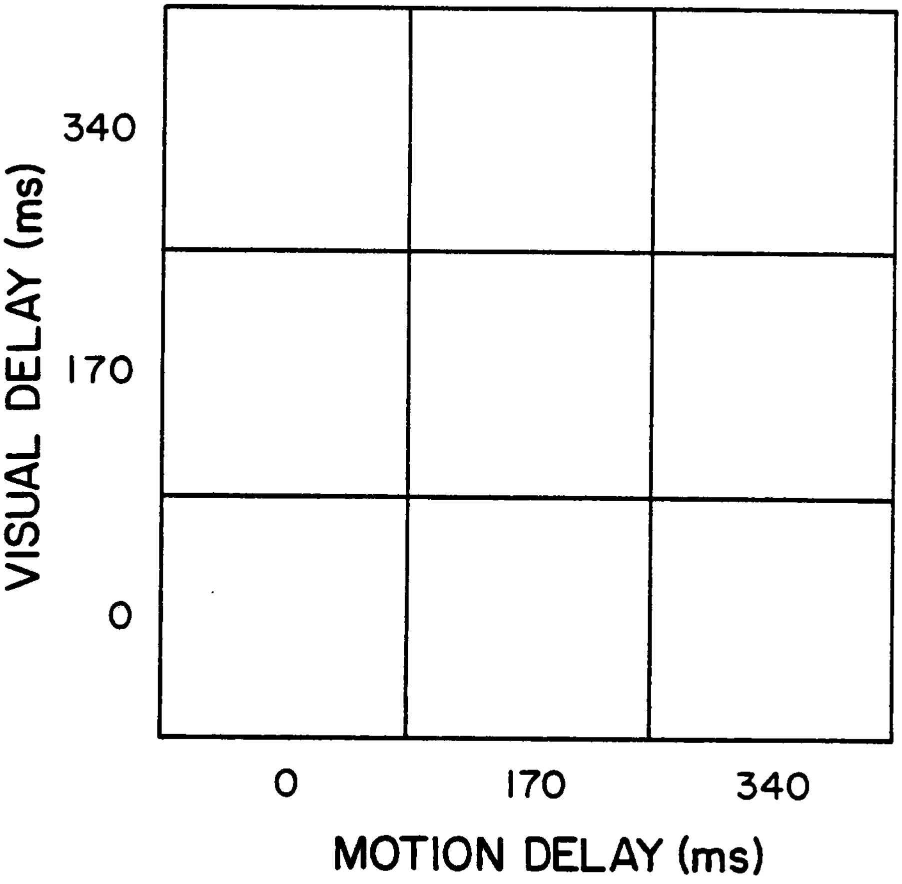

Figure 1. Schematic of the between-subject, central-composite, experimental design.

Table 9

Coded and Uncoded Values for the Nine Treatment Conditions of the Central Composite Design

Treatment Condition	Coded Values		Uncoded Values	
	Visual Delay	Motion Delay	Visual Delay	Motion Delay
1	-1	-1	0	0
2	-1	0	0	170
3	-1	1	0	340
4	0	-1	170	0
5	0	0	170	170
6	0	1	170	340
7	1	-1	340	0
8	1	0	340	170
9	1	1	340	340

Subjects

The subjects were 27 male and 27 female paid volunteers aged between 18 and 48 years, with a mean age of 25.68 years. The distance driven per year per subject ranged from 644 to 40,234 km (400 to 25,000 miles) with a mean of 13,724 km (8,528 miles). None of the subjects had previous simulator experience. All subjects had a valid drivers license and a minimum of 20/30 far static visual acuity as measured by a wall chart Landolt-C test.

All subjects were directed to abstain from drugs and to attain a normal night's rest before the second experimental session, which included the simulated driving task.

Driving Simulator Apparatus

The primary apparatus used in this study consisted of a computer-controlled automobile simulator located in the VPI&SU Vehicle Simulation Laboratory. A detailed description of the simulator has been reported elsewhere (Wierwille, 1975).

In brief, the simulator mimics a current, midsize, rearwheel-drive American sedan. It has been validated by Leonard and Wierwille (1975) against a comparable instrumented automobile. Four major subsystems comprise the simulator: a motion platform, a visual display, an audio subsystem, and a hybrid analog/digital computer control subsystem.

The simulated car interior was outfitted with a seat belt, steering wheel, brake and accelerator foot pedals, a dashboard fitted with a speedometer, and a display system. The simulated car interior was positioned on a hydraulically activated, servo-controlled, motion platform which provided four degrees of freedom consisting of roll, yaw, lateral translation, and longitudinal translation. A motor with an eccentric mass provided simulator drivetrain vibration.

A computer-generated visual display provided a dynamic presentation of a two-lane highway at an apparent distance of 10.1 m (33 ft). The roadway scene depicted a dashed center-line and side-lane markings, and horizontal lines which gave the road the appearance of being embedded in the horizontal plane (Dingus, Hardee, and Wierwille, 1985).

A black and white image, which emanated from a 58.42 cm (23 in) diagonal CRT, was viewed by the subject through a curved plexiglass windscreen and a Fresnel lens with a focal length of 50.8 cm (20 in). When viewing the visual display, the subject also saw a simulated automobile hood. The field-of-view of the subject was 48 deg horizontally by 39 deg vertically. Visual roadway movement included longitudinal velocity, lateral translation, yaw, roll, and the inverse radius of curvature.

An audio system produced sound simulating aerodynamic and chassis-road-produced sounds, engine and drivetrain noise, tire screech during severe breaking, and tire squeal during severe cornering. Each of these simulations was produced over a separate channel.

The vehicle dynamics were controlled by an analog computational subsystem (EAI TR48). Inputs from potentiometers located on the steering column, brake, and accelerator pedal mounting brackets, plus road curvature and wind gust signals, were received by the computational system. The inputs were processed and appropriate output signals were sent to the visual, motion, and audio subsystems.

In addition to the above features, two analog-to-digital, digital-to-analog (A-D/D-A) interfaces were installed to permit the use of two microcomputers (TRS-80 Model III). One digital computer was used to control visual and motion system delay while the second was used for programming visual display roadway curvature and on-line data processing of the driving measures.

Delay Quantization

Because different time delays were used in this study, it is important to consider the manner in which the delays were quantized. In the present experiment, analog signals from the simulator are converted to digital signals via the 8-bit A-D/D-A interface, sampled, and stored in a digital computer for a specified amount of time (i.e., delayed), and finally outputted via the A-D/D-A interface in analog form to the simulator's motion base and visual display.

Conceptually, when the first sample of the analog signal occurs at time t(0), it is stored in digital memory cell 1. At time t(1), when sample two takes place, sample two is stored in memory cell 1, and the value that was in memory cell 1 is transferred to memory cell 2, where it is now stored, and so on. Delay thus becomes a function of the sample rate and the number of storage cells each sample is transferred through before it is outputted from the digital computer to the simulator. Consequently, delay can be quantized either by using a constant sample rate and varying the number of storage cells that each sample must pass through to produce the desired delay, or by maintaining a fixed number of storage locations and varying the sampling rate. In the constant sampling rate method, the more cells that are "stepped" through, the longer the delay.

The major advantage of the fixed storage method is that less memory is required compared to the constant sampling rate method. However, the constant sampling rate method has the very pronounced advantage of depicting the analog waveform with equal precision, regardless of delay length (i.e., precision and delay are independent). In the fixed storage approach, as delay increases, sample rate decreases, and the precision of waveform estimation decreases.

To avoid spurious results due to differences in precision of waveform reproduction for the different time delays used in this study, the constant sampling rate method of quantization was used.

By selective sampling of acceleration, display roll, display yaw, display lateral translation, display velocity, motion roll, motion yaw, and motion lateral and longitudinal translation, visual and motion system delays of 0, 170, or 340 ms could be accomplished. Two separate Basic language programs were required to program the various delay treatment conditions. The first program sampled six channels and could implement a constant delay of 170 ms in both systems or asynchronous delays of 0 and 170 ms or 170 and 340 ms between the two systems. The second program sampled four channels and resulted in a constant delay of 340 ms in both systems or an asychronious delay of 0 and 340 ms between the two systems. Although the two software programs differed in the number of channels they sampled, the programs were carefully constructed to ensure sampling symmetry and quantization. The mean sample rate for each program was 14 samples/s.

The sensitivity of the simulator inertial and visual dynamics, coupled with only 256 steps of resolution in the 8-bit A-D/D-A interface, resulted in perceptible "jerks" in the movement of the visual-display and motion-base systems when delay was introduced. To obviate this problem, analog output signals from the A-D/D-A interface were filtered. Essentially, the filter network applied a double low-pass filtering of the analog signal before it was fed back to the simulator. This network resulted in an additional 87 ms of delay, which was embedded in the final desired delay value (170 or 340).

The Basic program sampled a voltage input, delayed that input for a desired length of time, then outputted the original voltage value. Thus, since the constant sampling rate method was used, the overall delay was comprised of three elements: an internal machine (program) delay, a sample-hold delay, and a delay imposed by the filter network. The relationships among a voltage input, the internal machine delay, the sample-hold delay, and the filter delay are depicted in Figure 2. The straight, solid line represents an increasing voltage input. The distance between this line and the straight, short-dashed line represents the internal machine (program) delay. The horizontal distance of the solid step-like line represents the sample-hold delay range. The best estimate of the sample-hold line is its mean value.

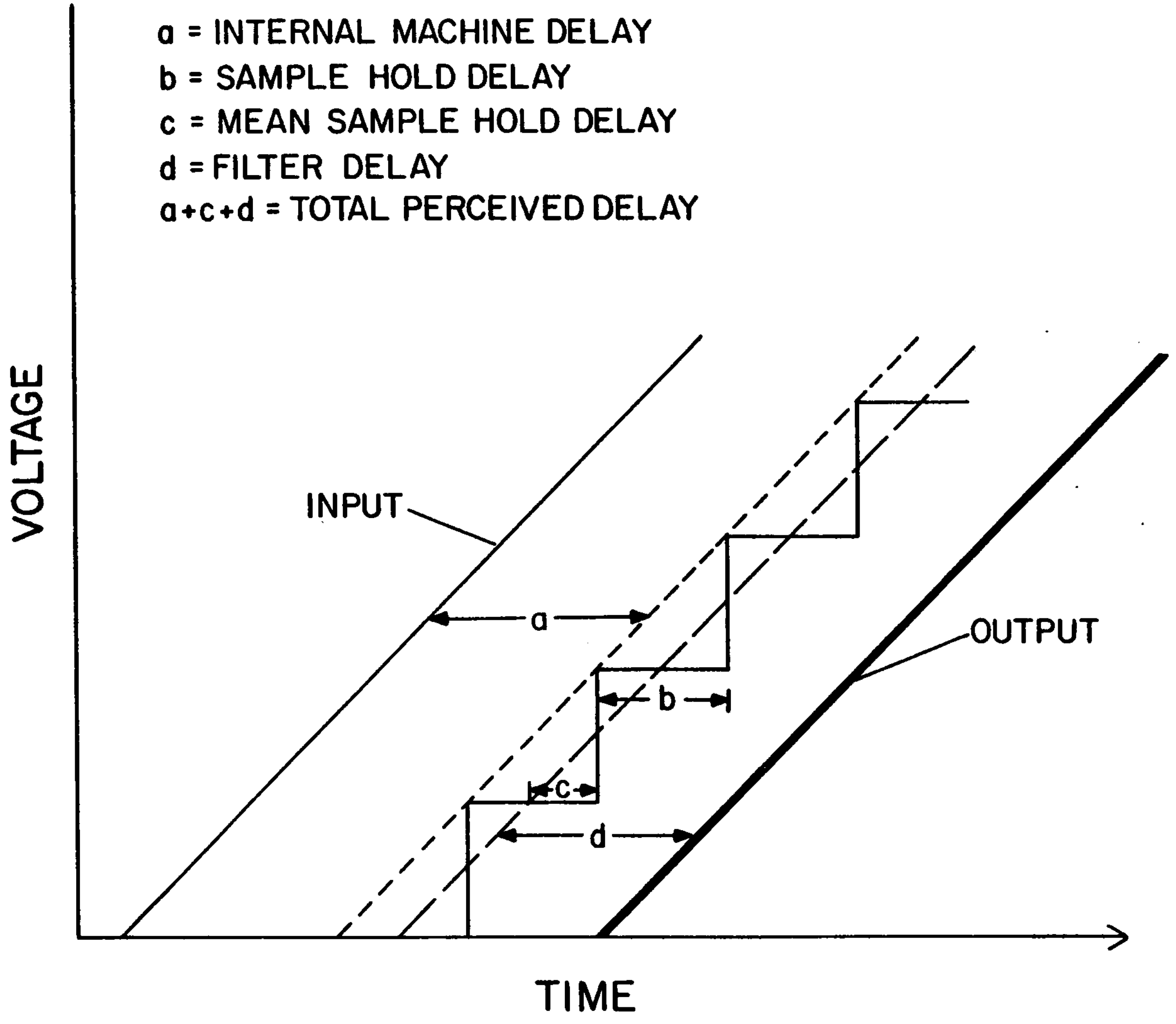

Figure 2. Schematic relationship among internal machine delay (program), sample-hold delay, filter delay, and total perceived delay.

This is represented by the long-dashed line. The horizontal distance between this line and the thick line on the far right is the filter delay. The perceived delay is the horizontal distance between the solid input line on the left and the thick output line.

In the present experiment, the 340 ms delay consisted of a 218 ms internal machine (program) delay plus a mean sample-hold delay of 35 ms plus a filtering delay of 87 ms. Similarly, the 170 ms short delay consisted of a 48 ms internal machine delay, a mean sample-hold delay of 35 ms and a filtering delay of 87 ms.

Measurement Apparatus

Rod and Frame. The rod-and-frame apparatus consisted of a square frame, 1.08 m (42.75 inches) on a side and within it a rod 1.02 m (40.50 inches) long. Both the rod and the frame were constructed from 19 mm (0.75 inch) tubular pipe covered with reflective tape.

The frame was attached to a 1.22 m (48 inch) diameter circular piece of wood painted flat black. At the center of the wood support, a shaft was attached which permitted rotation of the frame. A second shaft ran through the center of the shaft of the frame, thereby permitting rotation of the rod. Consequently, the frame and the rod pivoted at the same center, yet could be independently rotated. At the back of the rod and frame, observable only to the experimenter, the shafts passed through the center of a protractor. Alignment indicators from the two shafts permitted the experimenter to easily set the rod and the frame to their desired angular positions and read the subject's error in setting the rod to vertical within 0.5 deg of accuracy.

The rod-and-frame apparatus was housed in a 3.20 m (10.5 feet) long, 1.42 m (56 inches) wide, 1.98 m (6.5 feet) high structure covered in a double layer of opaque black "ground cloth." The interior corners of the enclosure were curved to eliminate possible cues to verticality. This structure was, in turn, housed in an air-conditioned room. During experimentation, the room lights were turned off and a black ground cloth tarpaulin was taped over the room door to prevent light leaks from the door jam. The rod-and-frame were illuminated by an ultraviolet light source (G.E. F15T8.BLB). During testing, the subject sat in a chair with an adjustable headrest inside the light-proof structure. The eye-to-frame distance was 2.17 m (85.5 inches). This distance was selected to ensure that the frame's retinal-image size was the same as that of Witkin et al. (1954). During experimentation, only the rod and frame were visible to the subject.

<u>Driving simulator measures.</u> The driving measures were as follows:

(1) Number of steering reversals. Steering wheel position was measured as an analog signal and sampled every 0.10 s by one of the digital microcomputers. Two measures of steering reversals were computed: large steering reversals (LREV) and small steering reversals (SREV). Large steering reversals were defined as the number of times the magnitude of the steering movement exceeded 5 deg or more after steering wheel velocity passed through zero, summed over a 5-min interval. Similarly, SREV were defined as the number of times the magnitude of the steering movement exceeded 2 deg or more after

steering wheel velocity passed through zero, summed over a 5-min interval.

(2) Yaw standard deviation. Vehicle yaw was given by the angle in the horizontal plane between the simulated vehicle longitudinal axis and the instantaneous roadway tangent. This value was sampled every 0.10 s by one of the microcomputers. Yaw standard deviation was computed over a 5-min interval.

(3) Frequency of seat movement. Seat movement was measured as a change in seat pad and backrest pressure of the simulator operator's seat. One transducer (linear potentiometer) in each location was connected to a GP-6 analog processor which, in turn, was interfaced to a Sanborn 350 stripchart recorder. Each seat movement was represented by a spike mark on the stripchart. The signal amplitude was set to ensure that only driver movements and not simulator vibrations were recorded.

Physiological sensors. Three physiological measures were used in this study:

(1) Skin resistance. Skin resistance was measured by two metallic electrodes incorporated into a rubber headband worn by the subject. The electrodes could be adjusted on the headband for desired positioning on the forehead. Saline solution was used to ensure electrical contact with the skin. A floating battery-powered circuit was used to apply a nominal current of 20 microamperes. Skin conductance was displayed on and recorded from the 20-VDC scale of a Micronta 22-191 digital multimeter. Conductance values were later converted to resistances (ohms) for data analysis.

Since pallor measures were also recorded from the same multimeter as used for skin resistance, a switch, which permitted easy and quick selection of either measure to be read from the digital multimeter, was used. The digital multimeter was operated in its battery mode to eliminate any possibility of A.C. line voltage electrical hazard.

(2) Pallor. Pallor was measured by a small photoelectric module attached to the antihelix of the subject's right ear. The sensor body was attached to the headband containing the skin resistance electrodes. The pallor sensor essentially consisted of an earpiece module with two separate facing sides. One half of the earpiece contained a light source which was thermally isolated from the ear by fiber optics. The other half of the earpiece contained a photosensitive cell (phototransistor). During experimentation, the light source remained on, focusing light through the skin of the ear to the phototransistor. The amount of light sensed at any moment was a function of the volume of blood in the antihelix (top of the pinna) of the ear. When ear blood volume increased, the amount of light passing through the ear decreased. This decrease in light incident upon the phototransistor was seen as a decrease in voltage output. Similarly, as decrease in blood volume resulted in an increase in transmissivity and an increase in voltage output.

Since pallor is a decrease in transmissivity due to increased blood volume over time, the transducer was designed to be insensitive to rapid volume changes such as are produced by a single heartbeat. Pallor was displayed and measured from the same multimeter used for skin resistance. Pallor was displayed as a D.C. voltage on the 20-volt scale. Using a rheostat, the initial pallor phototransistor output was adjusted to 2.5 volts for each subject at the beginning of the baseline data collection period.

(3) Respiration. The apparatus used for the measurement of respiration frequency has been described in detail elsewhere (Casali et al., 1983). Briefly, the device consisted of a proximity transducer housed in a 45 mm long, 5 mm diameter rigid plastic tube. In turn, the tube was attached to a belt formed of malleable aluminum. The belt was split at the back, which enabled it to be "slipped" around the subject's waist. When the belt was properly positioned on the subject, the 15 x 20 mm aluminum antenna plate of the proximity transducer was located approximately 20 mm from the subject's abdominal area and 80 to 100 mm below the xiphoid process. The plastic housing tube was friction fitted to the belt to allow adjustment of the proximity transducer's antenna plate relative to the subject's abdomen.

The respiration frequency apparatus essentially functioned as follows: the subject's abdominal region and the transducer formed a capacitive coupling with the subject's body, functioning as an antenna for electromagnetic noise. The proximity transducer antenna plate was also sensitive to this noise. Because it was capacitively coupled with the subject's body, the amount of noise it sensed was related to its distance from the subject's abdomen. When the subject inhaled, the distance lessened, and an increase in electromagnetic noise was sensed. When the subject exhaled, the distance increased and the detected noise level decreased. The voltage output signals were conditioned and recorded on a Sanborn 350 chart recorder. Respiration frequency was obtained by counting the number of pairs of peaks wherein a single breath consisted of one peak for inhalation and one peak for exhalation. Visually, inhalation and exhalation were seen as peaks in opposite polarities of the strip-chart recording and, therefore, consecutive peaks with the same polarity represented respiration periods.

Postural disequilibrium. For the stand-on-preferred-leg (SOPL) test, the subjects were instructed to stand erect with their arms crossed, to cross their other foot behind their preferred knee, and then to close their eyes. The subjects were timed with a Cronus 4 time-out stopwatch from the moment they closed their eyes until they made a major shift in posture, began to fall, or opened their eyes. The stand-on-non-preferred-leg (SONPL) test was administered and scored in the same manner as the SOPL test. Each subject received three trials on each test, alternating between standing on their preferred-leg and non-preferred leg, with approximately 30 s between each trial. Half of the subjects received the SONPL test first, the other half received the SOPL test first. All subjects were tested while wearing flat-soled shoes or in their stocking feet.

Simulator sickness severity index. The self-evaluation form used in this study was a version by Wiker et al. (1980) which has been modified by Kennedy, Dutton, Ricard, and Frank (1984) for specific use in simulator sickness studies. Appendix A presents the self-evaluation form. The only changes to the Wiker et al. scoring format are that the symptoms were grouped as "pathognomic" (only vomiting), "major," "minor," or "other," and that a family of visual symptoms was added to the "minor" category because of the prevalence of such symptoms in simulators. Appendix B presents the diagnostic categorization score sheet.

Motion sickness history questionnaire. As previously described, the Pensacola MSQ was used to assess past motion sickness history of the subjects and is presented in Appendix C.

Procedure

Screening. Upon volunteering to participate in the study and verification of a valid drivers license, each subject was given a static visual acuity test, using Landolt-C rings as the test stimuli. All subjects were required to have a minimum visual acuity of 20/30 (corrected or uncorrected) to ensure that all roadway stimuli and vehicle instrumentation readings were adequately visible to the subject.

In order not to introduce an extraneous variable into the study, no individual who had prior experience in a driving or flight simulator was used in this study.

Upon satisfactory completion of the vision test, each subject was asked to read the participant's rights and consent form which included a general description and instructions of the experiment (Appendix D). The experimenter then attempted to clarify any questions the volunteer had. If the volunteer desired to participate in the experiment, he or she was asked to sign the consent form. After written consent had been obtained from the subject, the subject was administered the RFT.

Rod-and-Frame Test. Before entering the RFT enclosure, the subject was told that the purpose of the enclosure was to attenuate unwanted light leaks during the perceptual test. The subject was asked to stand in front of the enclosure while the experimenter turned off the room lights. Construction of the enclosure prevented the subject from seeing inside. After the lights were off, the experimenter led the subject into the enclosure with the aid of a small pen light. The subject was seated in the chair and the headrest was adjusted. The subject was then asked to wear a pair of light attenuating goggles which consisted of welder's goggles covered with black, opaque paper. The experimenter then removed a cover from the RFT apparatus, turned on the light source, and left the chamber to position the tarpaulin over the room door. The experimenter then read the instructions for the RFT to the subject. These standardized instructions are presented in Appendix E.

The subjects were told that the experimenter was manually moving the rod and that he would attempt to do so in equal increments. They were also informed that there was no time limit on the test, and that the experimenter would continue to adjust the rod in either direction until they were completely satisfied that it was vertical.

At the beginning of a trial, the subject stated which direction the rod and the frame were both tilted. The subject then directed the experimenter in positioning the rod to vertical in accordance with the subject's instructions. The experimenter manually moved the rod in about 1.5 deg increments. When the subject was satisfied that the rod was vertical, the experimenter asked the subject to close his/her eyes until told to open them. The subject was told that the experimenter must turn on a light to take a measurement and that his/her dark adaptation would be ruined if his/her eyes did not remain closed. When the subject reported his/her eyes closed, the experimenter used a small, shielded pen light to read the subject's error in setting the rod to vertical and then set the RFT for the next trial. Following the method of Oltman (1968) and Testa (1969), the Series 3 of the RFT of Witkin et al. (1954) was given to each subject. Each subject received 8 trials with the frame and the rod initially tilted 28 deg in the following sequence: frame, LLRRLLRR; rod, LRRLLRRL (L = left; R = right). At the end of the RFT, the subject was scheduled to return to the laboratory for the second portion of the experiment, which included driving the simulator.

Pre-simulator exposure. Prior to entering the simulator, each subject was administered the postural disequilibrium tests in accordance with the protocol already described. Each subject was then assisted into the simulator and instructed to fasten the seat belt. The physiological sensors were fitted to the subject after showing the subject each sensor. To avoid any spurious physiological readings as a result of the subject attending to the specific physiological measures being recorded, the subject was not told the specific purpose of each sensor, but just that they reflected their bodily reactions. The subject was then asked if the physiological sensors were comfortable. If they were not, they were readjusted by the experimenter.

Each subject was then given a sheet of written instructions for the driving task (shown in Appendix F) and asked to read them carefully. The subjects were told to relax and rest while the experimenter calibrated the recording equipment. Room illumination was reduced to approximate twilight and the physiological monitoring system was checked to ensure that it was functioning properly.

After approximately 5 min, the experimenter returned to the subject, retrieved the written instructions, and orally briefed the subject on the driving task. If the subject had any questions, the experimenter attempted to answer them. The physiological sensors were once again checked. The subject was again told to relax for about another 10 min and that the experiment would then begin.

After the subject had been sitting for at least 10 min in the deactivated simulator, baseline measures of respiration, skin resistance, pallor, and number of seat movements were taken every minute over a 5-min period. A 10-min stabilization period has been reported by Casali (1979) to be satisfactory before measurement of baseline physiological responses in a similar driving simulator study.

Simulator exposure. At the appropriate time, the subjects were advised that the simulator was being activated and that they would have a 2-min practice session to "get the feel" of the simulator. During this 2-min interval, the subject was told to change lanes and to accelerate and decelerate several times to help the subject meet this objective. At the end of 2 min, the experimenter told the subject that the experimental driving session was beginning, to accelerate to 55 mph (88.5 km/hr), and to try to maintain that speed and the right-hand lane position throughout the remainder of the experiment.

The preprogrammed driving scenario alternated between curved and straight stretches of road. Appendix G details the 21-min driving scenario.

Post-simulator exposure. Upon completion of the simulated driving task, the physiological sensors were removed from the subject, the seat belt was unbuckled, and the subject was assisted from the simulator. The subject was immediately administered the postural disequilibrium tests and then asked to fill out the self-evaluation form for use by the experimenter in the simulator sickness severity index (SSSI) calculation. Following this, the subject filled out the motion sickness history questionnaire.

If requested by the subject, he or she was debriefed on the experiment and asked not to discuss or disclose any aspect of the experiment with anyone else for a period of 60 days. Upon determination of the subject's well-being, he or she was paid and allowed to leave.

Data Reduction

The following methods were employed to reduce the raw data derived for each measure to a form appropriate for statistical analysis.

Rod-and-Frame Test. For each subject, the mean number of degrees by which the rod deviated from true vertical was computed across the eight experimental trials.

Driving measures. As previously detailed, yaw standard deviation (YAW), small steering reverals (SREV), and large steering reversals (LREV) were sampled every 0.10 s and computed on a microcomputer every 150 s of the 21-min simulator exposure. A subject's yaw deviation score was calculated as the mean value of the two yaw standard deviation values computed during the final 5 min of the experimental run. The numbers of SREV and LREV were represented by the cumulative total of the number of times steering reversals equaled or exceeded 2 deg or 5 deg, respectively, over the final 5 min of the 21-min simulator exposure. For seat movement, the total number of seat movements during the 5-min baseline period was subtracted from the total number of seat movements during the last 5 min of the simulated driving task. This difference score was referred to as SEAT. In addition, the total number of seat movements made during the 21-min driving scenario was also computed (TSEAT).

Physiological measures. For each physiological measure, a single difference score was computed between the subject's mean baseline value and his or her mean value during the final 5 min of the simulated driving task. Specific reduction procedures for each measure were as follows:

(1) Pallor. As will be recalled, pallor was recorded every minute as a voltage reading using the apparatus discussed previously.

Pallor as a function of voltage was plotted during system calibration. Over the range of interest, this function exhibited a linear characteristic. A subject's pallor score (PAL) was computed as the difference in the mean voltage of the 5 min baseline period and the mean voltage of the last 5 min period of the simulated driving session.

(2) Forehead skin resistance. Voltage output was converted to resistance and a subject's skin resistance score (SR) was computed by substracting his or her mean resistance baseline score from the mean resistance over the final 5-min period of the simulated driving task. A positive score indicated an increase in resistance or a decrease in perspiration. Conversely, a negative score indicated a decrease in resistance or an increase in perspiration.

(3) Respiration. The number of breaths taken per unit of time were determined from the stripchart recorder. Only those portions of the stripchart recording that were clearly interpretable were included. Again, the subject's score was represented by the difference between his or her number of breaths during the final 5 min of driving and that of the baseline period. Since the motion sickness literature indicated that respiration may either increase or decrease, depending upon the individual, the absolute value of the breath cycles per second (BCS) difference score was used.

Postural disequilibrium. As will be recalled, for both the SOPL and SONPL ataxia tests, the subject's score was the total time, in seconds, that he or she stood erect. To avoid ceiling effects, the mean of the three trials for each test was used (Thomley et al., in press). The difference between a subject's score on the post-simulator exposure test and a subject's score on the pre-simulator exposure test yielded each subject's stability measure, in seconds.

A combined score (COMB) was also formed by adding the results of the SOPL and SONPL tests and computing a mean. The combined score also represented a difference score between the pre-simulator and post-simulator tests.

While administering the ataxia tests, a large variability in the subject's ability to maintain stability on the pre-simulator exposure test was observed. Because of this, it was felt that a percentage score might produce a more sensitive measure of any vestibular disturbance induced by the experimental treatments. Consequently, a percentage SOPL (PSOPL), percentage SONPL (PSONPL), and percentage combined (PCOMB) score were computed by forming a ratio of the respective post-simulator exposure mean score to the pre-simulator exposure mean score, subtracting this value from 1.0, and multiplying by 100.

Simulator sickness severity index. Following the procedure of Kennedy, Dutton, Ricard, and Frank (1984), each subject's responses to the self-evaluation form shown in Appendix A were transposed into the divisions presented in Appendix B. Once the symptoms were gathered for each subject according to Appendix B, he or she was appropriately assigned to one of the eight diagnostic categories shown in Appendix H. Thus, each subject's final symptomatology categorization score consisted of an integer value between 0 and 7, inclusive. In addition, the total number of symptoms reported by the subject was also tallied (TSYM).

Motion sickness history questionnaire. Appendix I, taken from Moore, Lentz, and Guedry (1977), provides the detailed procedure for scoring the Pensacola MSQ. In general, each section of the MSQ is scored separately and added together to form a single composite score.

For ease of reference, Table 10 presents a list of the experimental dependent measures and their abbreviations. The MSQ represents an independent variable and is therefore not included in Table 10.

Table 10

A List of the Experimental Dependent Measures and Their Abbreviations

Yaw Standard Deviation	(YAW)
Small Steering Reversals	(SREV)
Large Steering Reversals	(LREV)
Difference in Seat Movements	(SEAT)
Total Number of Seat Movements	(TSEAT)
Difference in Pallor	(PAL)
Difference in Skin Resistance	(RES)
Difference in Breath Cycles Per Second	(BCS)
Simulator Sickness Severity Index	(SSSI)
Total Number of Symptoms Reported	(TSYMP)
Stand-on-Preferred Leg Test	(SOPL)
Stand-on-Non-Preferred Leg Test	(SONPL)
Combined Stand-on-Leg	(COMB)
Percent Stand-on-Preferred-Leg	(PSOPL)
Percent Stand-on-Non-Preferred-Leg	(PSONPL)
Percent Combined Stand-on-Leg	(PCOMB)

RESULTS

Primary Analyses

The response surface methodology data analysis essentially consisted of two statistical analyses. First, a least-squares multiple-regression analysis was performed to determine the first-order polynomial model. Second, an analysis of variance (ANOVA) was performed on the derived regression model. In the present experiment, an orthogonal central-composite design was used to ensure that there would be uncorrelated estimates of the regression coefficients for both first-order and second-order polynomial models. For the 3 x 3 between-subjects, central-composite design used in this study, the ANOVA partitioned the sums of squares into variation due to regression, lack-of-fit, and error. A significant lack of fit on the first-order polynomial suggested that the model was an inadequate representation of the data, and that higher-order terms needed to be included to improve the model. If a significant lack of fit was revealed, the next step was to generate a second-order regression equation (which the central-composite design permits) and test its adequacy.

Following this procedure, a first-order model was derived for each dependent variable (all regressions were conducted on coded values). Subsequently, an ANOVA was performed on each of the 16 models. Ten of the models were found to be significant ($\underline{p} < 0.05$). Table 11 presents each significant model. Recall that the coded values for each treatment were presented in Table 9 and ranged between -1.0 to 1.0,

Table 11

Significant First-Order Models (V = visual delay, M = motion delay)

Dependent variable	Regressors†
Breath cycles/s* =	0.042 + 0.004V + 0.030M
Yaw standard deviation* =	8.542 + 1.298V + 0.587M
Small steering reversals* =	247.167 + 24.000V + 8.389M
Large steering reversals* =	48.685 + 18.583V + 12.306M
Simulator sickness severity index** =	3.481 + 0.361V + 0.250M
Stand-on-preferred-leg*** =	-3.722 - 2.323V - 0.309M
Stand-on-non-preferred-leg*** =	-3.835 - 0.543V - 1.903M
Combined stand-on-leg*** =	-3.986 - 1.242V - 1.343M
Percent stand-on-preferred-leg**** =	25.059 + 21.103V + 1.092M
Percent combined stand-on-leg**** =	33.398 + 12.889V + 4.108M

† Model is significant at $p < 0.05$
* Total number occurring during 5-min period
** Value between 0 to 7, inclusive
*** Time, in seconds
**** Percent decrement

inclusive. Tables 12 through 21 present first-order regression ANOVA summary tables for each significant model. As can be observed from the ANOVA summary tables, lack of fit was nonsignificant across all models, suggesting that the introduction of higher-order effects would not meaningfully improve each model's description of the functional relationship between performance and the independent variables. Significant models were derived for respiration (BCS), driving performance (YAW, SREV, LREV), simulator sickness symptomatology (SSSI), and postural stability (SOPL, SONPL, COMB, PSOPL, PCOMB). For ease of comparison, Table 22 summarizes the results of the ANOVAs for all 10 models. Only the significant regressors from each model are presented.

As seen from this table, only in the model predicting large steering reversals were both the visual and motion delay regressors significant contributors. In each of the other models, only one regressor was statistically significant. It is apparent from Table 22 that visual delay and motion delay do not equally predict the various dependent measures. It is also apparent that more than one model is required to predict both an individual's control performance and well-being as a function of visual and motion delays.

Although none of the ANOVAs on the first-order polynomial equations yielded a significant lack of fit, Myers (1976) has cautioned that a nonsignificant lack of fit does not necessarily indicate that the best model has been achieved. Review of the ANOVAs performed on the first-order regressions indicates that the proportion of variance

Table 12

First-Order Regression Analysis of Variance Summary Table for Breath Cycles per Second

Source	df	SS	MS	F
Regression	(2)	0.034	0.0167	3.375*
Visual delay	1	0.001	0.0007	0.156
Motion delay	1	0.033	0.0325	6.620*
Residual	(51)	(0.242)		
Lack of fit	6	0.021	0.0036	0.728
Error	45	0.221	0.0049	
Total	53	0.275		

* $p < 0.05$

Table 13

First-Order Regression Analysis of Variance Summary Table for Yaw Standard Deviation

Source	df	SS	MS	*F*
Regression	(2)	73.040	36.520	7.296*
Visual delay	1	60.645	60.645	12.115**
Motion delay	1	12.395	12.395	2.476
Residual	(51)	232.857		
Lack of fit	6	7.549	1.266	0.253
Error	45	225.259	5.006	
Total	53	305.097		

* $p < 0.01$
** $p < 0.001$

Table 14

First-Order Regression Analysis of Variance Summary Table for Small Steering Reversals

Source	df	SS	MS	*F*
Regression	(2)	23269.444	11634.722	6.584*
Visual delay	1	20736.000	20736.000	11.734*
Motion delay	1	2533.444	2533.444	1.4336
Residual	(51)	86718.055		
Lack of fit	6	7194.889	1199.148	0.679
Error	45	79523.166	1767.181	
Total	53	109987.500		

* $p < 0.01$

Table 15

First-Order Regression Analysis of Variance Summary Table for Large Steering Reversals

Source	df	SS	MS	F
Regression	(2)	17883.611	8941.805	7.361**
Visual delay	1	12432.250	12432.250	10.235**
Motion delay	1	5451.361	5451.361	4.488*
Residual	(51)	60518.037		
Lack of fit	6	5856.537	976.089	0.804
Error	45	54661.500	1214.700	
Total	53	78401.648		

* $p < 0.05$
** $p < 0.01$

Table 16

First-Order Regression Analysis of Variance Summary Table for Simulator Sickness Severity Index

Source	df	SS	MS	*F*
Regression	(2)	6.944	3.472	3.300*
Visual delay	1	4.694	4.694	4.463*
Motion delay	1	2.250	2.250	2.139
Residual	(51)	56.537		
Lack of fit	6	9.204	1.533	1.458
Error	45	47.333	1.052	
Total	53	63.482		

* $p < 0.05$

Table 17

First-Order Regression Analysis of Variance Summary Table for Stand-on-Preferred-Leg

Source	df	SS	MS	*F*
Regression	(2)	197.771	98.885	3.51*
Visual delay	1	194.324	194.324	6.888*
Motion delay	1	3.447	3.447	0.122
Residual	(51)	1412.644		
Lack of fit	6	143.116	23.853	0.845
Error	45	1269.528	28.212	
Total	53	1610.415		

* $p < 0.05$

Table 18

First-Order Regression Analysis of Variance Summary Table for Stand-on-Non-Preferred-Leg

Source	df	SS	MS	*F*
Regression	(2)	140.997	70.499	3.457*
Visual delay	1	10.634	10.634	0.0521
Motion delay	1	130.363	130.363	6.392*
Residual	(51)	953.112		
Lack of fit	6	35.306	5.884	
Error	45	917.805	20.396	
Total	53	1094.109		

* $p < 0.05$

Table 19

First-Order Regression Analysis of Variance Summary Table for Combined Stand-on-Leg

Source	df	SS	MS	*F*
Regression	(2)	120.528	60.264	4.141*
Visual delay	1	55.565	55.565	3.818
Motion delay	1	64.964	64.964	4.464*
Residual	(51)	683.544		
Lack of fit	6	28.719	4.787	0.328
Error	45	654.824	14.552	
Total	53	804.072		

* $p < 0.05$

Table 20

First-Order Regression Analysis of Variance Summary Table for Percent Stand-on-Preferred-Leg

Source	df	SS	MS	*F*
Regression	(2)	16074.683	8037.342	5.154*
Visual delay	1	16031.780	16031.780	10.263**
Motion delay	1	42.903	42.903	0.0274
Residual	(51)	73617.167		
Lack of fit	6	3320.300	553.384	0.354
Error	45	70296.866	1562.153	
Total	53	89691.850		

* $p < 0.05$
** $p < 0.01$

Table 21

First-Order Regression Analysis of Variance Summary Table for Percent Combined Stand-on-Leg

Source	df	SS	MS	*F*
Regression	(2)	6588.067	3294.033	4.626*
Visual delay	1	5980.444	5980.444	8.399**
Motion delay	1	607.623	607.623	0.853
Residual	(51)	33955.444		
Lack of fit	6	1914.825	319.137	0.4482
Error	45	32040.615	712.014	
Total	53	40543.509		

* $p < 0.05$
** $p < 0.01$

Table 22

Significant Regressors From Each of Ten Empirical Models

Dependent Measure	Source	*F*	Model R^2
Breath cycles/s	Motion delay	6.620*	0.1207
Yaw standard deviation	Visual delay	12.115***	0.2388
Small steering reversals	Visual delay	11.734**	0.2116
Large steering reversals	Visual delay Motion delay	10.235** 4.488*	0.2281
Simulator sickness severity index	Visual delay	4.463*	0.1094
Stand-on-preferred-leg	Visual delay	6.888*	0.1228
Stand-on-Non-preferred-leg	Motion delay	6.392*	0.1288
Combined stand-on-leg	Motion delay	4.464*	0.1499
Percent stand-on-preferred-leg	Visual delay	10.266**	0.1792
Percent combined stand-on-leg	Visual delay	8.399**	0.1622

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

accounted for by each model varied from about 11% to 23% (see Table 22). Consequently, second-order polynomial models were derived in an attempt to improve predictive power. Table 23 compares the coefficients of determination (R^2) for the respective first-and second-order models for each dependent measure. As can be seen from this table, with the exception of two models, only slight improvement in R^2 is obtained by going to a second-order model. Parsimony would dictate retention of the first-order models for all dependent variables except perhaps SSSI and SOPL. It should be recalled that one problem with the use of R^2 as a criterion for model selection is that R^2 can never decrease in value as further regressors are added and will almost always increase in size.

Table 24 and Table 25 summarize the ANOVAs on the second-order models for predicting SSSI and SOPL, respectively. Both second-order models were nonsignificant ($p > 0.05$), although they approached significance. Visual delay was the only significant regressor in each model. The question arises as to whether the significant first-order models or the higher R^2 second-order models are the "better" predictors. To gain insight, Mallow's C_p statistic (Mallows, 1973) was computed for each model in question. The C_p statistic is basically a composite value which incorporates variance and bias. The lower the C_p value, the better the model. For the SSSI dependent measure, the first-order model had a C_p value of 8.24, whereas the second-order model had a C_p value of 6.00. For the SOPL variable, the first-order and second-order models had C_p values of 4.79 and 6.00, respectively.

Table 23

Coefficients of Determination for First-Order and Second-Order Models

Dependent variable	First-Order R^2	Second-Order R^2
Breath cycles/s	.1207	.1576
Yaw standard deviation	.2387	.2558
Small steering reversals	.2116	.2194
Large steering reversals	.2281	.2368
Simulator sickness severity index	.1094	.2025
Stand-on-preferred-leg	.1228	.2048
Stand-on-non-preferred-leg	.1288	.1293
Combined stand-on-leg	.1498	.1780
Percent stand-on-preferred-leg	.1797	.1981
Percent combined stand-on-leg	.1625	.1734

Table 24

Second-Order Regression* Analysis of Variance Summary Table for Simulator Sickness Severity Index

Source	df	SS	MS	*F*
Regression	(5)	15.227	3.045	2.894
Visual delay (V)	1	4.694	4.694	4.462**
Motion delay (M)	1	2.250	2.250	2.139
VxV	1	3.343	3.343	3.178
MxM	1	1.565	1.565	1.483
VxM	1	3.375	3.375	3.208
Residual	(48)	48.255		
Lack of fit	3	0.921	0.307	0.292
Error	45	47.333	1.052	
Total	53	63.481		

* SSSI = 4.074 + 0.361V + 0.250M - 5.28VxV - 0.361MxM - 0.375VxM.
** $p < 0.05$

Table 25

Second-Order Regression* Analysis of Variance Summary Table for Stand-on-Preferred-Leg

Source	df	SS	MS	*F*	R^2
Regression	(5)	(326.081)	65.216	2.311	.2048
Visual delay (V)	1	194.324	194.324	6.887**	.1206
Motion delay (M)	1	3.447	3.447	0.122	.0021
VxV	1	50.485	50.585	1.709	.0313
MxM	1	59.170	59.170	2.097	.0367
VxM	1	18.656	18.656	0.661	.0116
Residual	(48)	(1284.333)			
Lack of fit	3	14.805	4.935	0.174	.001
Error	45	1269.528	28.212		.7883
Total	53	1610.415			

* SOPL = −3.609 − 2.323V − 0.309M + 2.051VxV − 2.221MxM − 0.882VxM
** $p < 0.05$

Based on these results, it is recommended that the second-order model be used for prediction of SSSI and that the first-order model be used to predict SOPL performance.

To gain a better intuitive appreciation of the 10 models presented, the response surface of each uncoded model was plotted over the range of delays investigated in this study. The nine first-order models for predicting BCS, YAW, SREV, LREV, SOPL, SONPL, COMB, PSOPL, and PCOMB are presented in Figures 3 through 11, respectively. The second-order model for SSSI is shown in Figure 12. These figures will be assessed in the discussion section. Table 26 presents the formulae for the 10 uncoded models. Due to the small magnitude of some regressor coefficients (e.g., BCS), all values are carried out to six decimal places.

For the uncoded models, motion and visual delay values between 0 and 340 ms, inclusive, are used for prediction. It should be noted that, regardless of whether the coded or uncoded model for a particular dependent variable is used, they will both result in the same predicted outcome. Differences between the constants (intercepts) of the coded and uncoded models, shown in Tables 11 and 26, respectively, reflect the range of values over which each model is applied (i.e., -1 to 1 or 0 to 340).

The univariate analyses provide an assessment of how the combined influence of the independent variables affect a specific dependent variable. Multivariate techniques can be used to test the effects of several dependent variables, thereby helping to isolate underlying behavioral dimensions.

Table 26

Significant Uncoded Regression Models (V = visual delay, M = motion delay)

Dependent variable	Regressors
Breath cycles/s =	0.000777 + 0.000027V + 0.000171M
Yaw standard deviation =	6.657954 + 0.007635V + 0.003452M
Small steering reversals =	214.77778 + 0.141176V + 0.049346M
Large steering reversals =	17.796296 + 0.109314V + 0.072386M
Simulator sickness severity index =	2.199074 + 0.010539V + 0.007925M - 0.000018VxV - 0.000012MxM - 0.000013VxM
Stand-on-preferred-leg =	-1.089259 - 0.013667V - 0.001820M
Stand-on-non-preferred-leg =	-1.389222 - 0.003197V - 0.011197M
Combined stand-on-leg =	-1.400491 - 0.007308V - 0.007902M
Percent stand-on-preferred-leg =	2.864814 + 0.124143V + 0.006422M
Percent combined stand-on-leg =	16.400926 + 0.075817V + 0.024167M

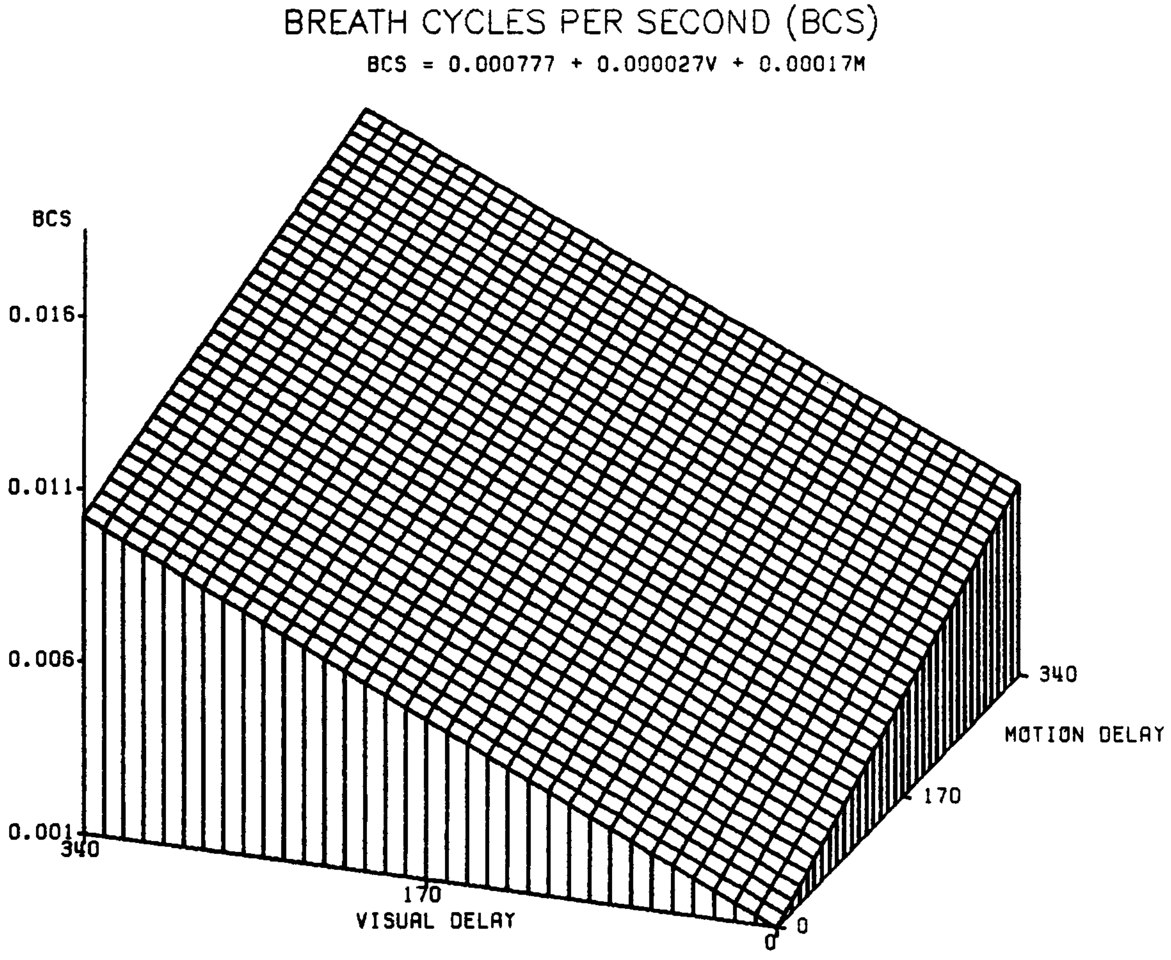

Figure 3. First-order response surface for breath cycles per second.

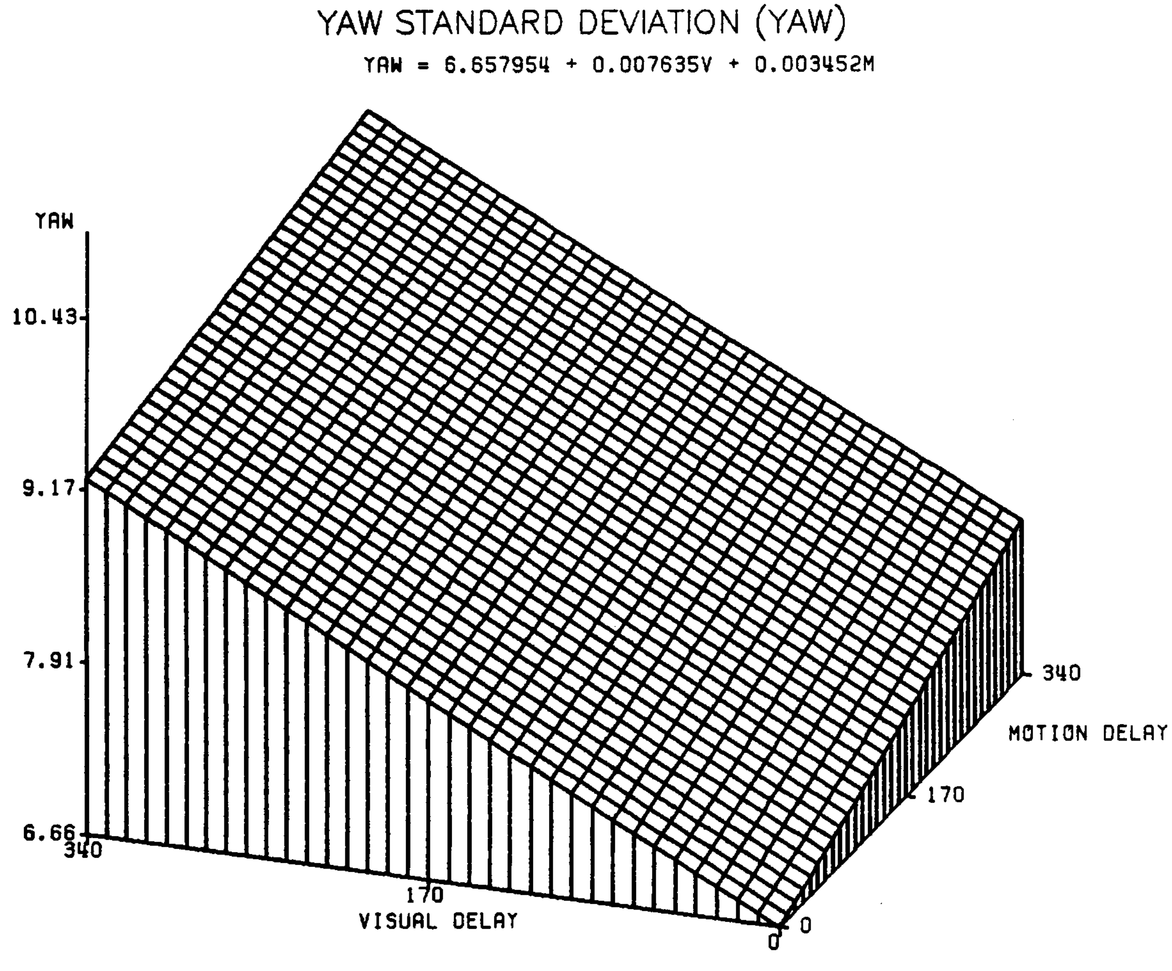

Figure 4. First-order response surface for yaw standard deviation.

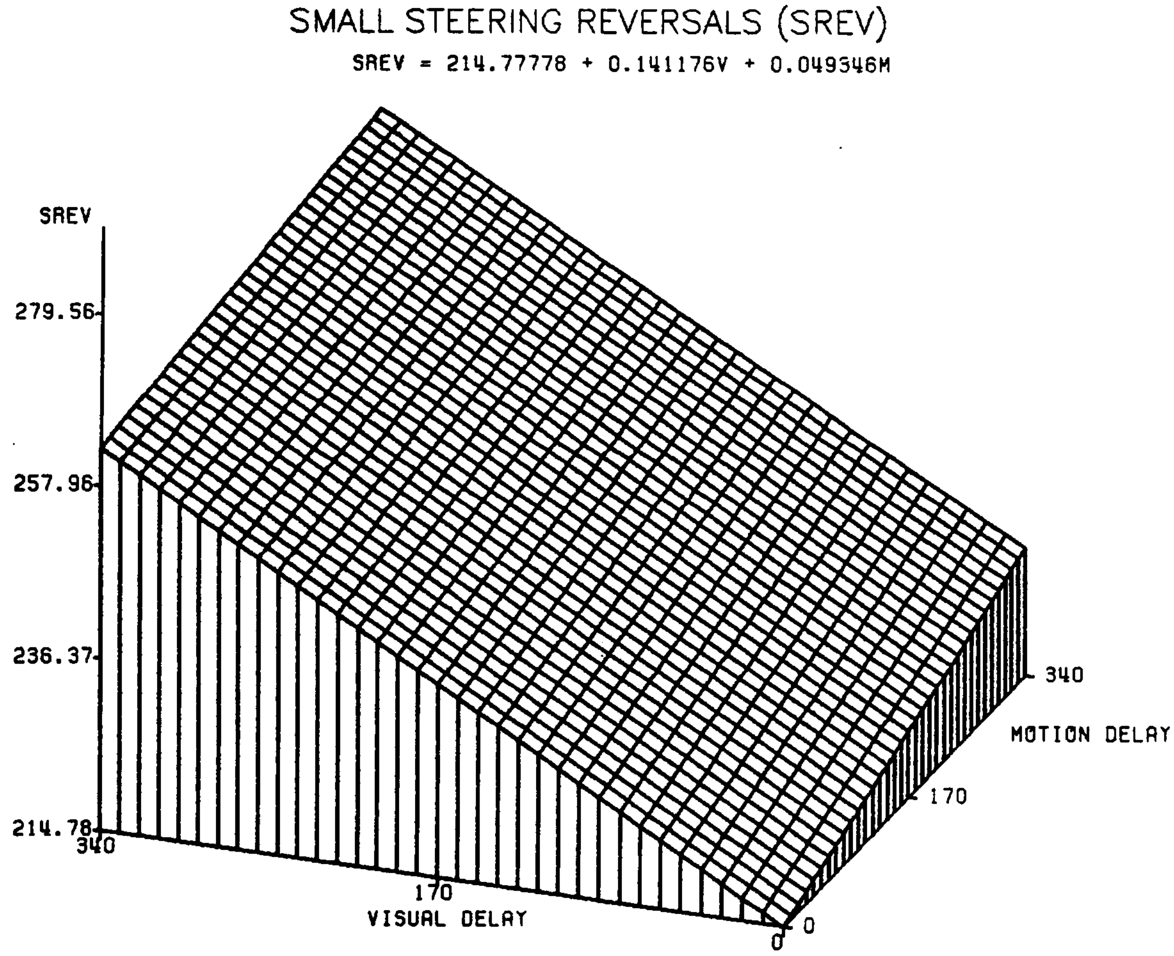

Figure 5. First-order response surface for small steering reversals.

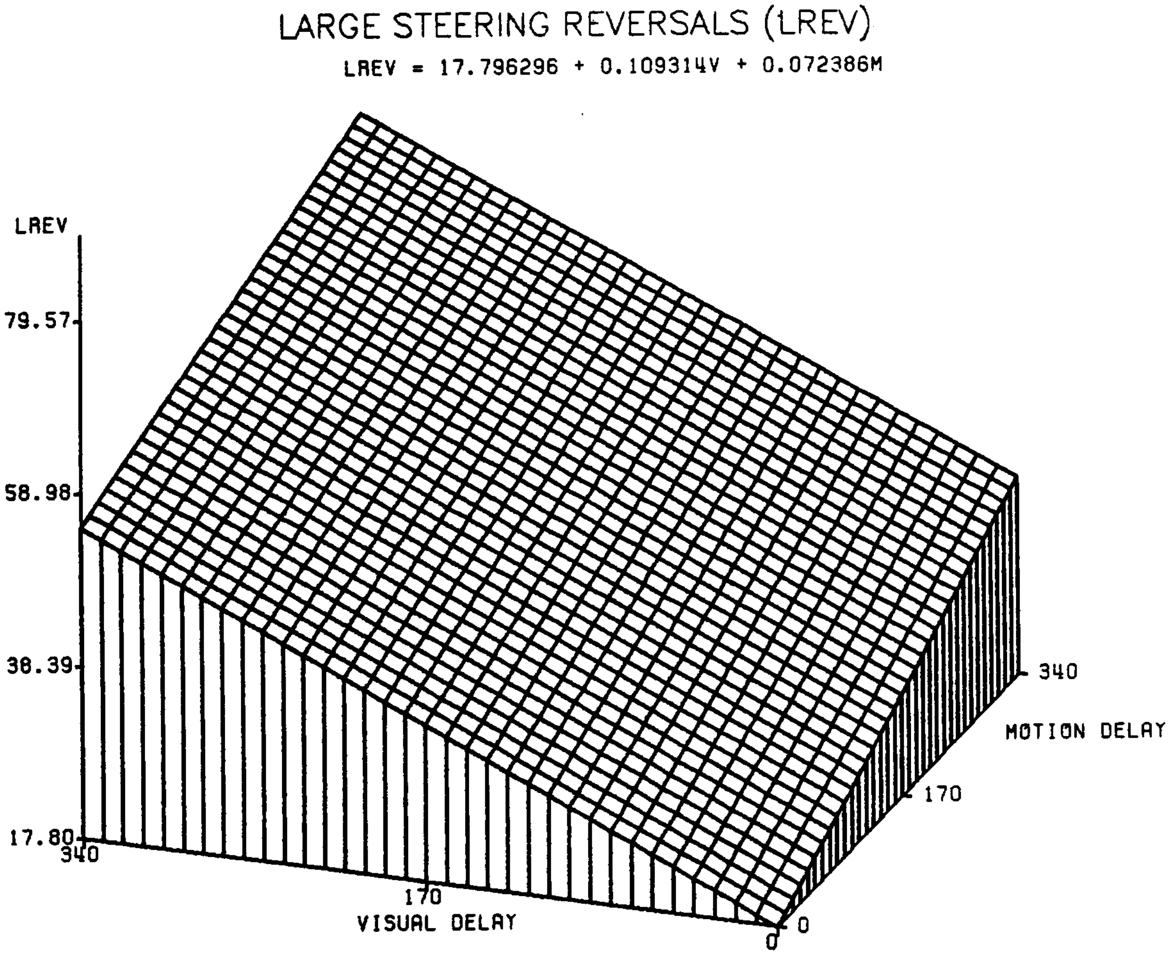

Figure 6. First-order response surface for large steering reversals.

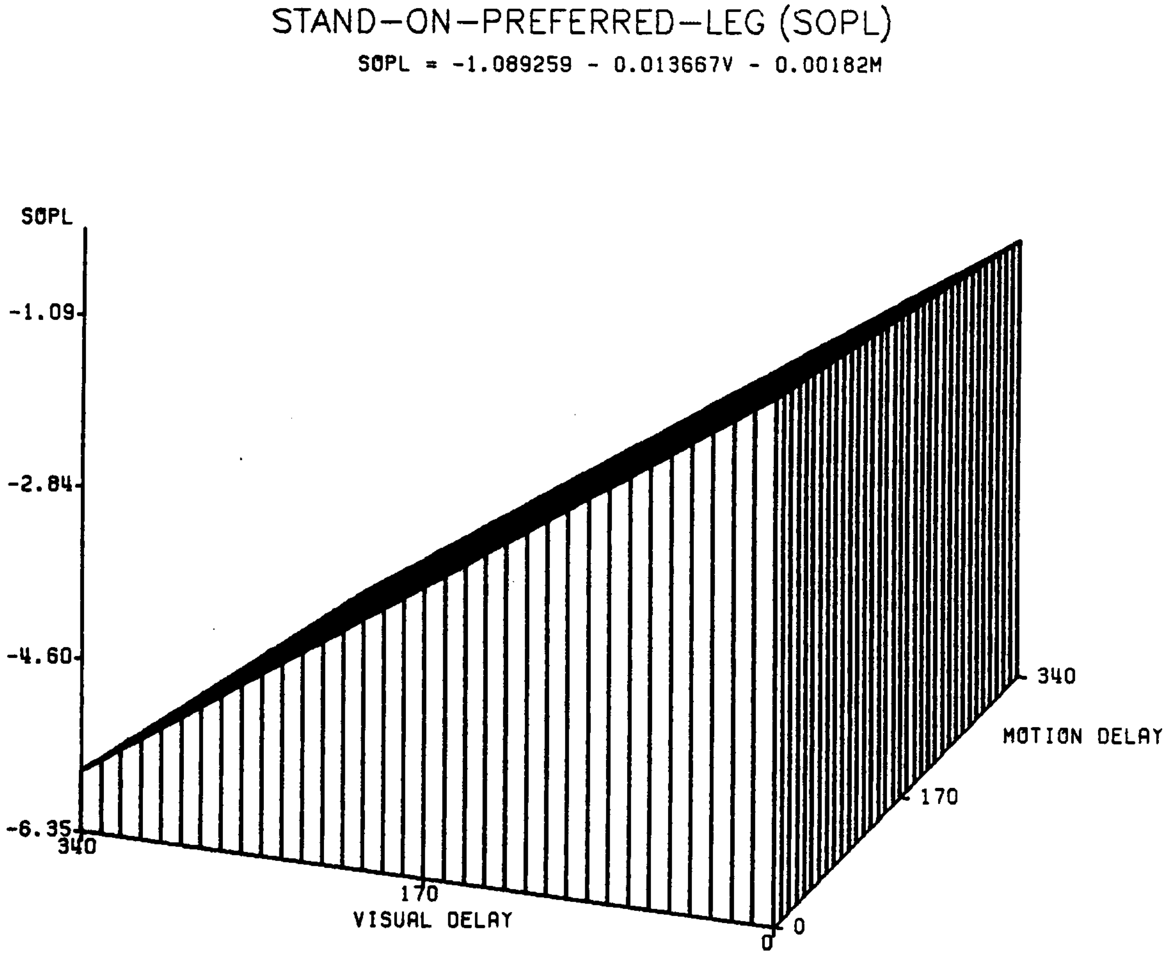

Figure 7. First-order response surface for stand-on-preferred-leg.

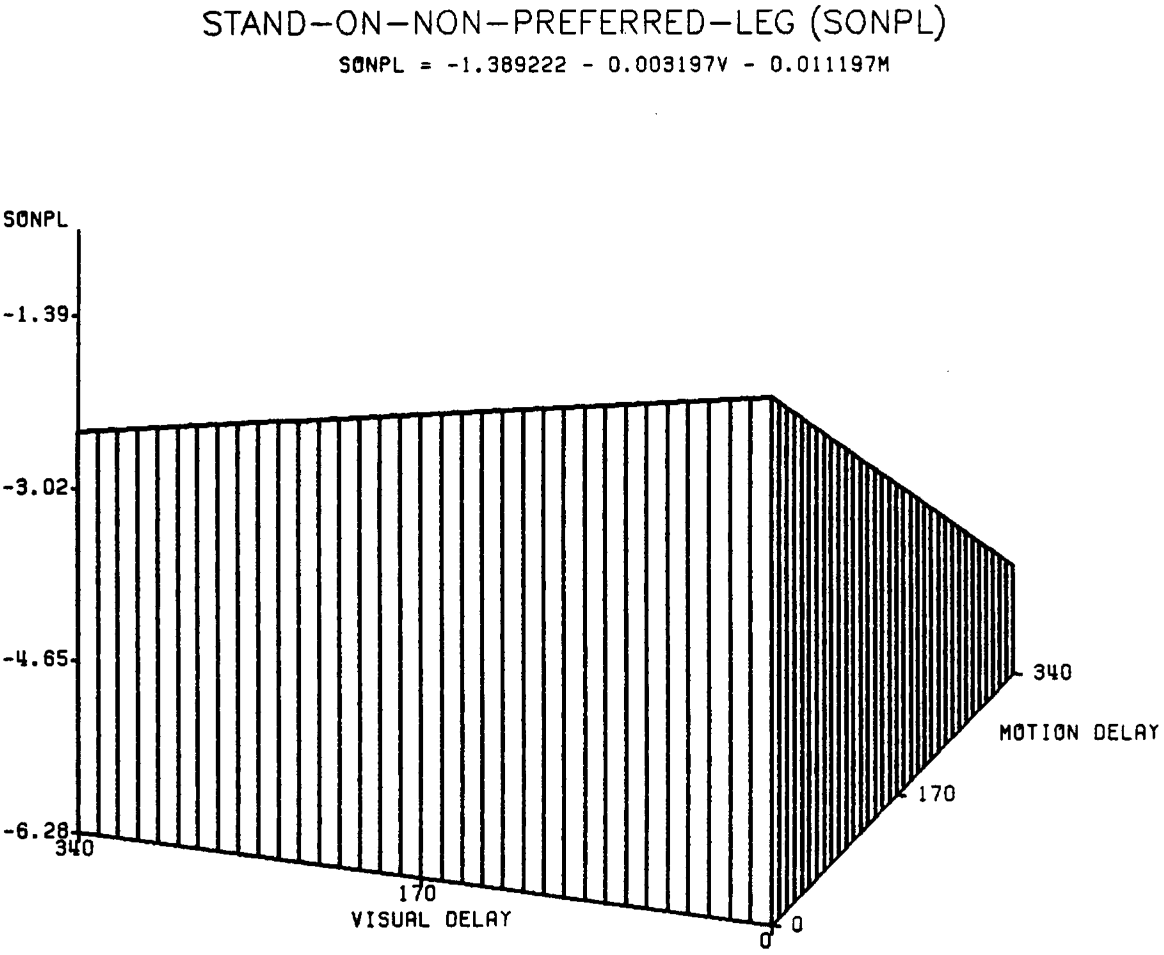

Figure 8. First-order response surface for stand-on-non-preferred-leg.

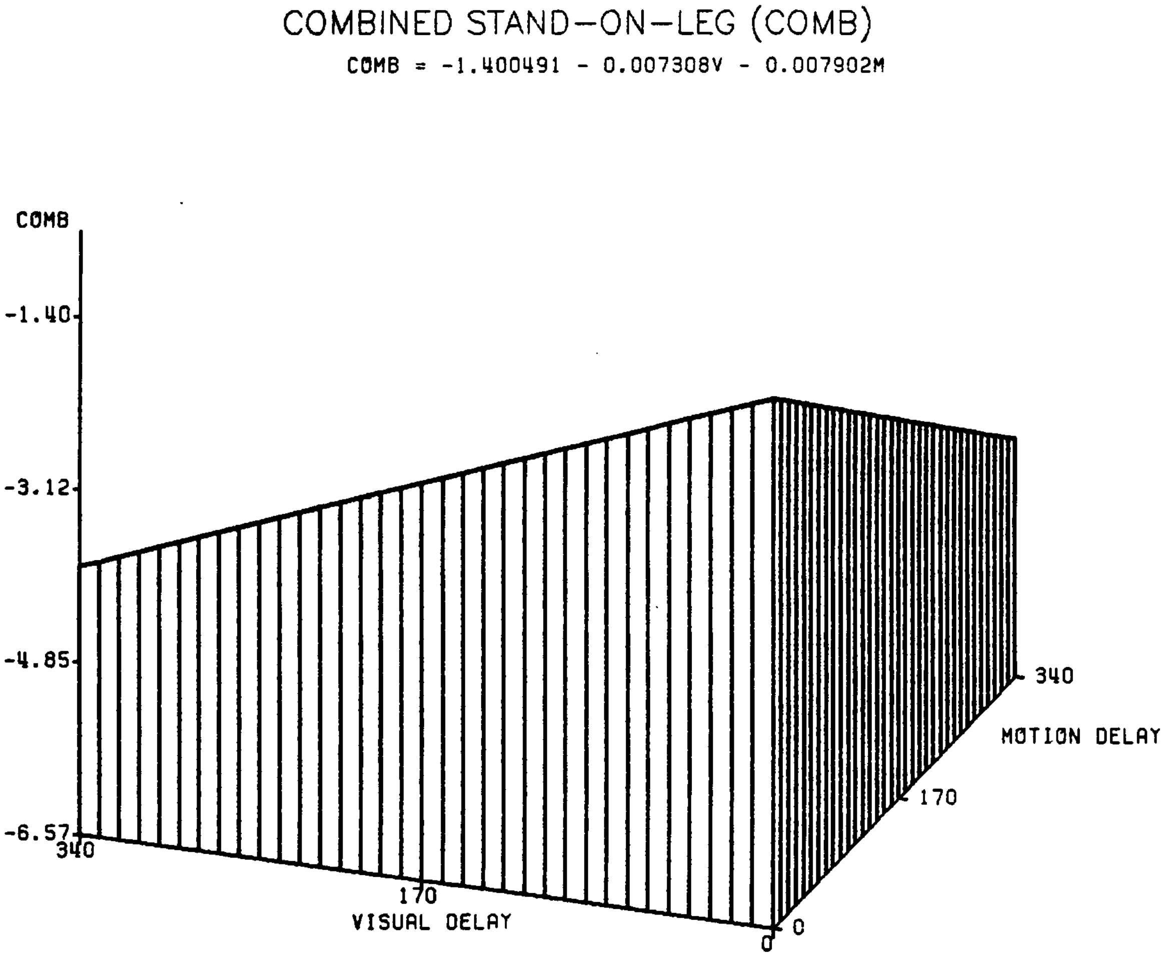

Figure 9. **First-order response surface for combined stand-on-leg.**

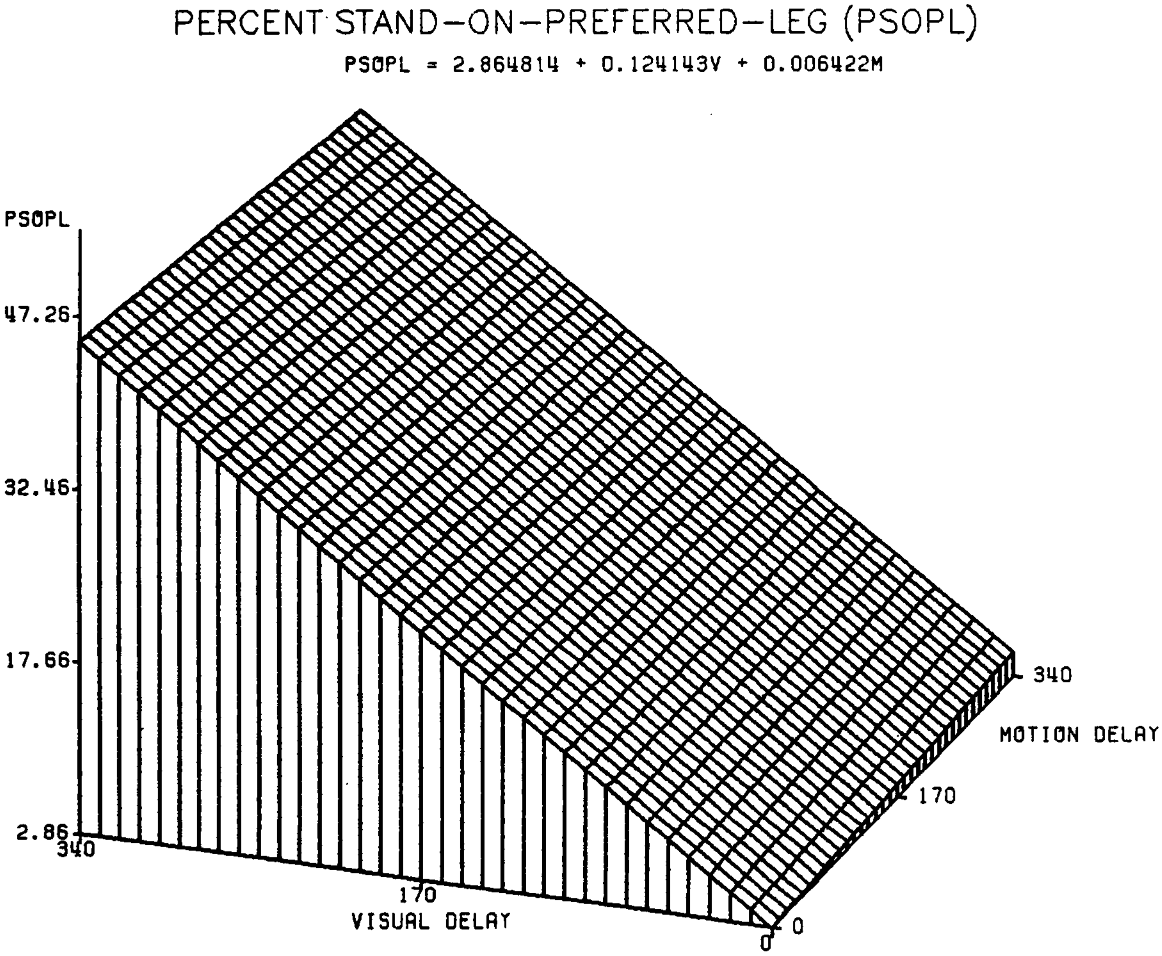

Figure 10. First-order response surface for percent stand-on-preferred-leg.

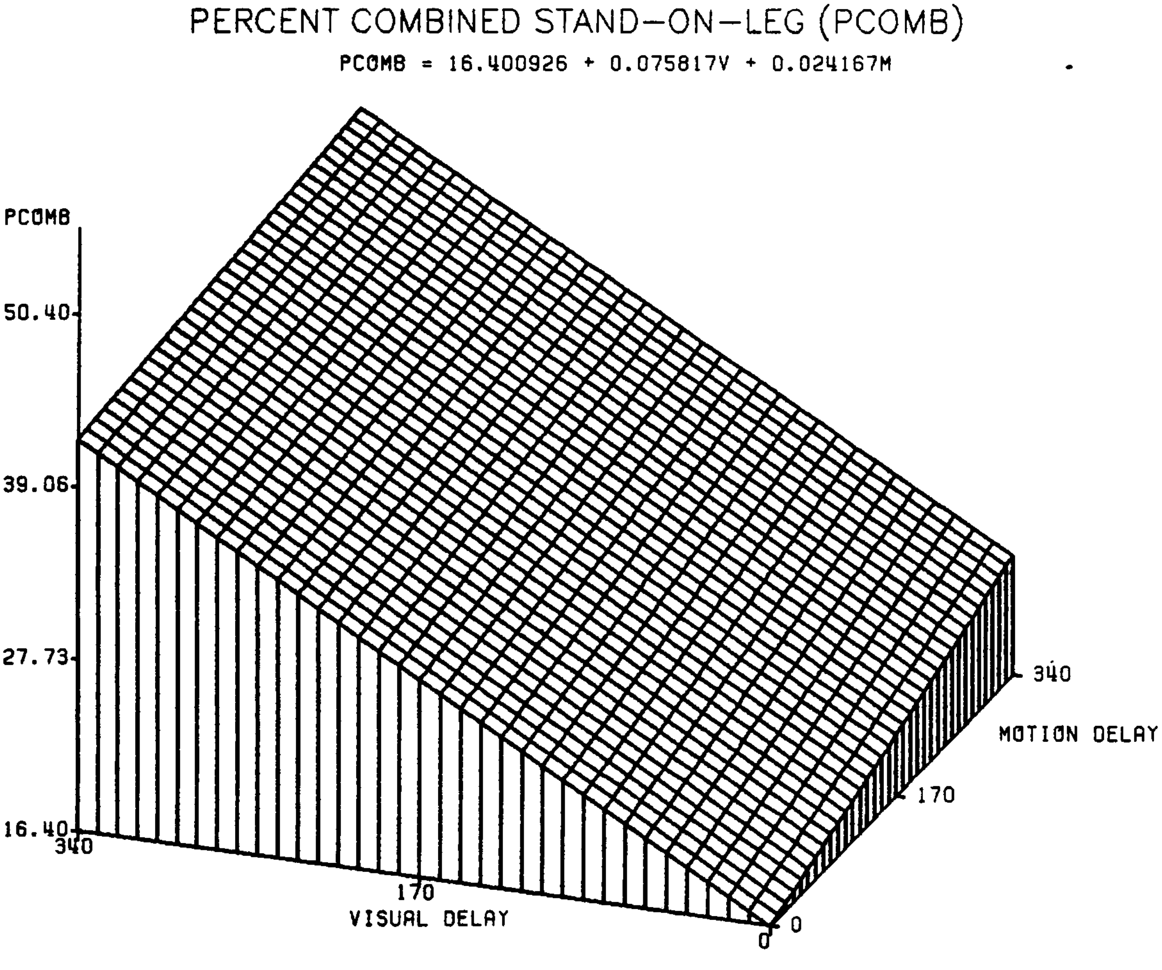

Figure 11. First-order response surface for percent combined stand-on-leg.

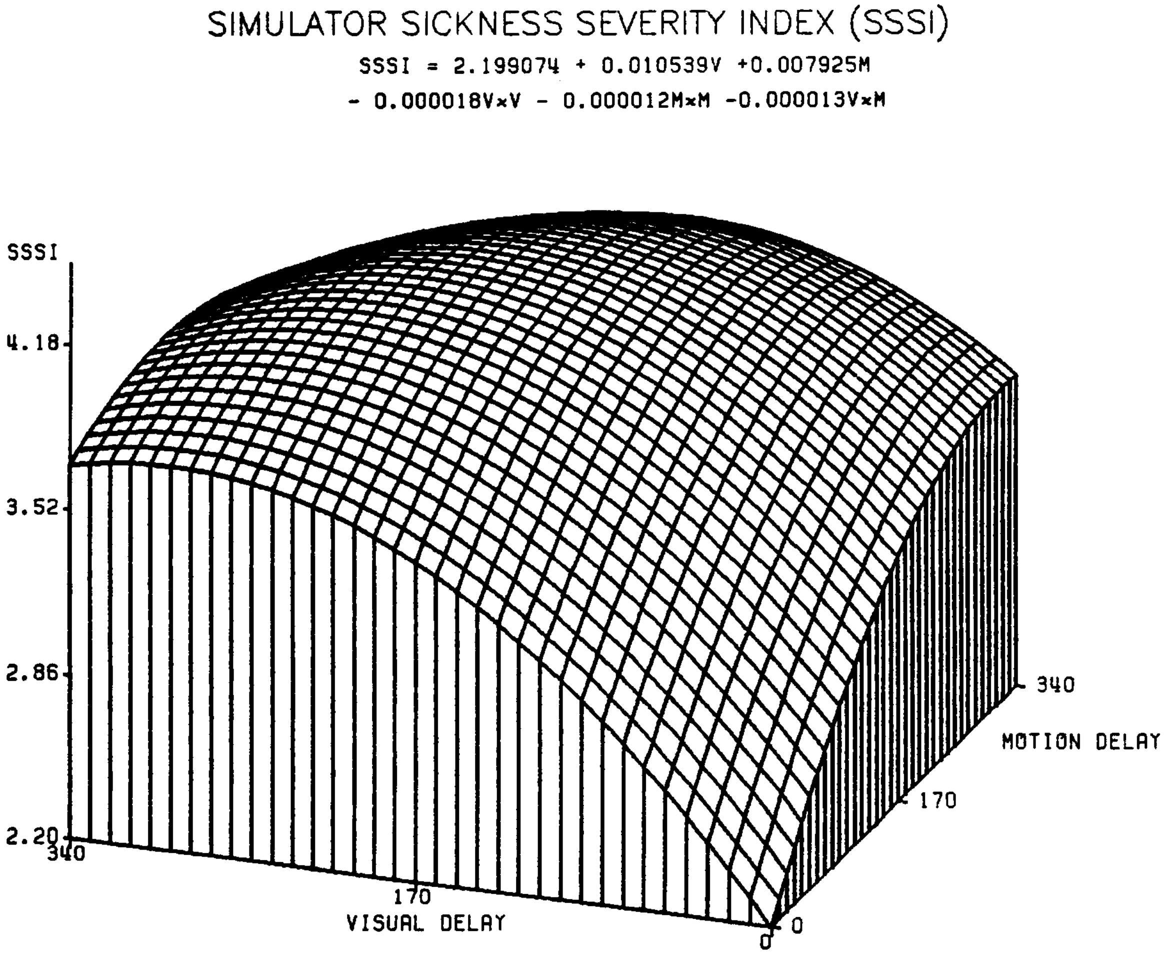

Figure 12. Second-order response for simulator sickness severity index.

Williges and Williges (1982) successfully used principal components analysis to transform an originally large set of variables into a smaller set of linear combinations that accounted for most of the variance of the original set. Williges and Williges (1982) then used the resultant component scores as the dependent variables in subsequent polynomial regression analyses. The same technique was applied herein to the 10 significant regression models (i.e., dependent measures) previously discussed. The rationale for using principal components analysis is parsimony—attempting to explain as much of the total variance as possible with the fewest factors.

Because the variance of a variable is not independent of scale (Dillon and Goldstein, 1984), the principal components analysis was performed on the correlation matrix. Table 27 presents the eigenvalues and proportion of variance accounted for by each component. Use of the Kaiser (1958) criterion of retaining only those components with an eigenvalue greater than or equal to 1.0 would result in three components being retained. These components account for about 69% of the variance. However, as seen in Table 27, the addition of the fourth component would account for over 78% of the variance. The addition of further components obviously increases the proportion of variance accounted for, but negates the attempt to gain parsimony. Thus, four components were considered for further analysis.

Table 28 presents the component loadings based upon the correlation matrix. From this table, it can be seen that the variables loading highest on component 1 are the various measures of postural

Table 27

Eigenvalues and Proportion of Variance Accounted for by Each Component

Component	Eigenvalue	Proportion of Variance	Cumulative Proportion of Variance
1	3.805	0.3805	0.3805
2	2.102	0.2102	0.5907
3	1.076	0.1076	0.6983
4	0.885	0.0885	0.7868
5	0.845	0.0845	0.8713
6	0.719	0.0719	0.9432
7	0.258	0.0250	0.9690
8	0.160	0.0160	0.9850
9	0.135	0.0135	0.9985
10	0.148	0.0015	1.000

Table 28

Component Loadings Based on Correlation Matrix

Variable	Component 1	Component 2	Component 3	Component 4
Breath cycles/s	-0.21690	0.60141	-0.25756	0.01130
Yaw standard deviation	0.44738	0.57132	-0.25367	-0.46981
Small steering reversals	0.16331	0.59158	0.11967	0.74424
Large steering reversals	0.43525	0.79612	-0.18492	-0.01794
Simulator sickness severity index	0.21290	0.50857	0.49169	-0.25572
Stand-on-preferred-leg	-0.82631	0.19345	-0.10010	0.03546
Stand-on-non-preferred-leg	-0.66943	0.23556	0.49833	-0.10057
Combined stand-on-leg	-0.88418	0.25637	0.28966	-0.02723
Percent stand-on-preferred-leg	0.75940	-0.06429	0.54648	-0.07459
Percent combined stand-on-leg	0.89825	-0.09296	0.11789	0.16465

stability which indicate vestibular disruption. The variable loadings on component 2 fall into two groups. The first is on the driving performance measures of YAW, SREV, and LREV. The second group of BCS and SSSI depict a subject's discomfort. Because this component reflects both subject control performance and subject physiological performance, it was labeled "degraded performance." The third factor loaded highest on PSOPL, followed by SONPL and SSSI, and was therefore labeled "discomfort." The fourth factor's highest loadings were on SREV and YAW, with moderate loadings across the remaining variables. This component appears to reflect general driving performance and subject comfort and was therefore labeled "general."

A first-order multiple regression model was generated for each of the four principal components. Analyses of variance on the coded regressions revealed that only the first two principal component regressions were significant. Tables 29 and 30 summarize the analyses of variance and present the respective coded regression equations for vestibular disruption (component 1) and degraded performance (component 2). The R^2 values for vestibular disruption and degraded performance were 0.2654 and 0.2102, respectively. Although there was not a significant lack-of-fit effect for either regression model, examination of the second-order polynomials for these two components revealed that both second-order models were significant. These analyses are presented in Tables 31 and 32. However, the coefficients of determination increased negligibly for each component: $R^2 = 0.2895$ for vestibular disruption and $R^2 = 0.2119$ for degraded performance. Examination of Mallow's C_p statistic also favored the first-order

Table 29

First-Order Coded Regression* Analysis of Variance Summary Table for Principal Component 1 (Vestibular Disruption)

Source	df	SS	MS	*F*
Regression	(2)	53.252	26.626	8.529**
Visual delay (V)	1	43.013	43.013	13.777**
Motion delay (M)	1	10.239	10.239	3.279
Residual	(51)	147.411		
Lack of fit	6	6.941	1.157	0.370
Error	45	140.470	3.122	
Total	53	200.663		

* Vestibular Disruption = $-0.00002 + 1.093V + 0.5333M$
** $p < 0.05$

Table 30

First-Order Coded Regression* Analysis of Variance Summary Table for Principal Component 2 (Degraded Performance)

Source	df	SS	MS	*F*
Regression	(2)	22.522	11.261	6.601***
Visual delay (V)	1	14.755	14.755	8.649***
Motion delay (M)	1	7.572	7.572	4.438**
Residual	(51)	83.911		
Lack of fit	6	7.133	1.189	0.697
Error	45	76.778	1.706	
Total	53	106.238		

* Degraded Performance = 0.0185 + 0.6402V + 0.4586M
** $p < 0.05$
*** $p < 0.01$

Table 31

Second-Order Coded Regression* Analysis of Variance Summary Table for Principal Component 1 (Vestibular Disruption)

Source	df	SS	MS	*F*
Regression	(5)	58.101	29.050	9.305**
Visual delay (V)	1	43.013	43.013	13.778**
Motion delay (M)	1	10.239	10.239	3.279
VxV	1	3.704	3.704	1.186
MxM	1	1.114	1.114	0.357
VxM	1	0.030	0.030	0.009
Residual	(48)	142.563		
Lack of fit	3	2.093	0.6979	0.223
Error	45	140.470	3.122	
Total	53	57.985		

* Vestibular Disruption = 0.1672 + 1.0931V + 0.5333M - 0.555VxV + 0.3047MxM + 0.0356VxM

** $p < 0.001$

Table 32

Second-Order Coded Regression* Analysis of Variance Summary Table for Principal Component 2 (Degraded Performance)

Source	df	SS	MS	*F*
Regression	(5)	24.740	4.948	2.900**
Visual delay (V)	1	14.755	14.755	8.649***
Motion delay (M)	1	7.572	7.572	4.438**
VxV	1	2.219	2.219	1.301
MxM	1	0.164	0.164	0.0967
VxM	1	0.030	0.030	0.0189
Residual	(48)	81.498		
Lack of fit	3	4.720		2.767
Error	45	76.778	1.706	
Total	53	106.238		

* Degraded Performance = 0.2271 + 0.6402V + 0.4586M - 0.4299VxV + 0.1171MxM + 0.0354VxM

** $p < 0.05$
*** $p < 0.01$

models. Thus, it is recommended that the first-order models be used for purposes of prediction. These models, in their uncoded form, are:

$$\text{vestibular disruption} = -1.6264 + 0.00643V + 0.00314M,$$

$$\text{degraded performance} = -1.0803 + 0.00377V + 0.00269M.$$

To better visualize how little the inclusion of quadratic and crossproduct terms contributed towards prediction in the second-order models, Figures 13 through 16 are presented. Figures 13 and 14 depict the response surfaces for the first-order and second-order models of vestibular disruption, respectively. Figures 15 and 16 present the response surfaces for the first-order and second-order models of degraded performance, respectively. As can be seen from these figures, the first-order and second-order models are almost identical.

Secondary Analyses

Multivariate analyses of variance.

As will be recalled, each of the nine treatment conditions had an equal number of males and females (three each). In addition, a blocking variable of perceptual style was employed wherein scores on the Rod-and-Frame. Test were separately rank-ordered for each gender and blocked into thirds. A male and a female were then randomly assigned from the lower, middle, and upper third to each treatment condition.

Ideally, to assess the effects of sex and perceptual style, a multivariate analysis of variance (MANOVA) would be performed on the 3 x 3 x 3 x 2 (visual delay x motion delay x perceptual style x sex) factorial design. This analysis could not be performed, however, since

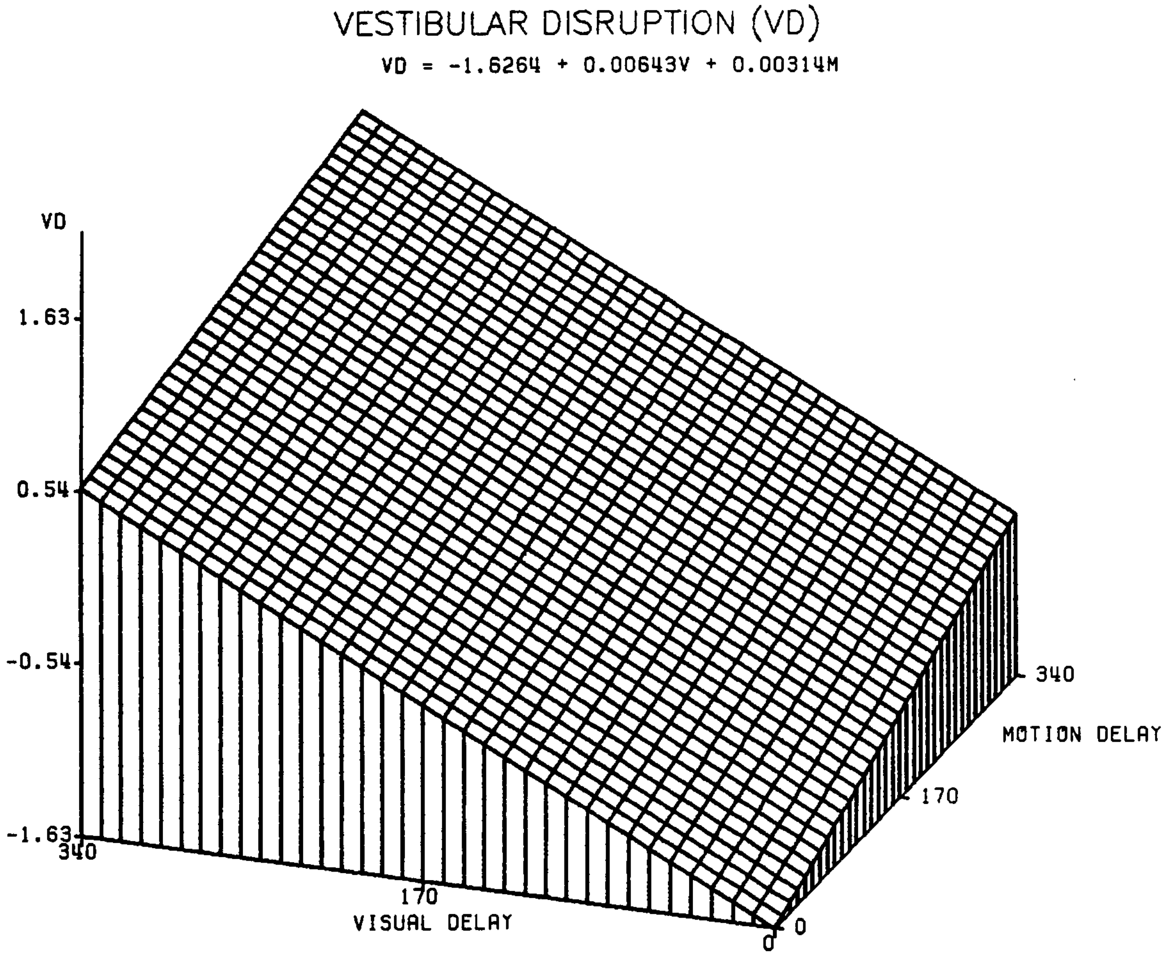

Figure 13. First-order response surface for principal component 1 (vestibular disruption).

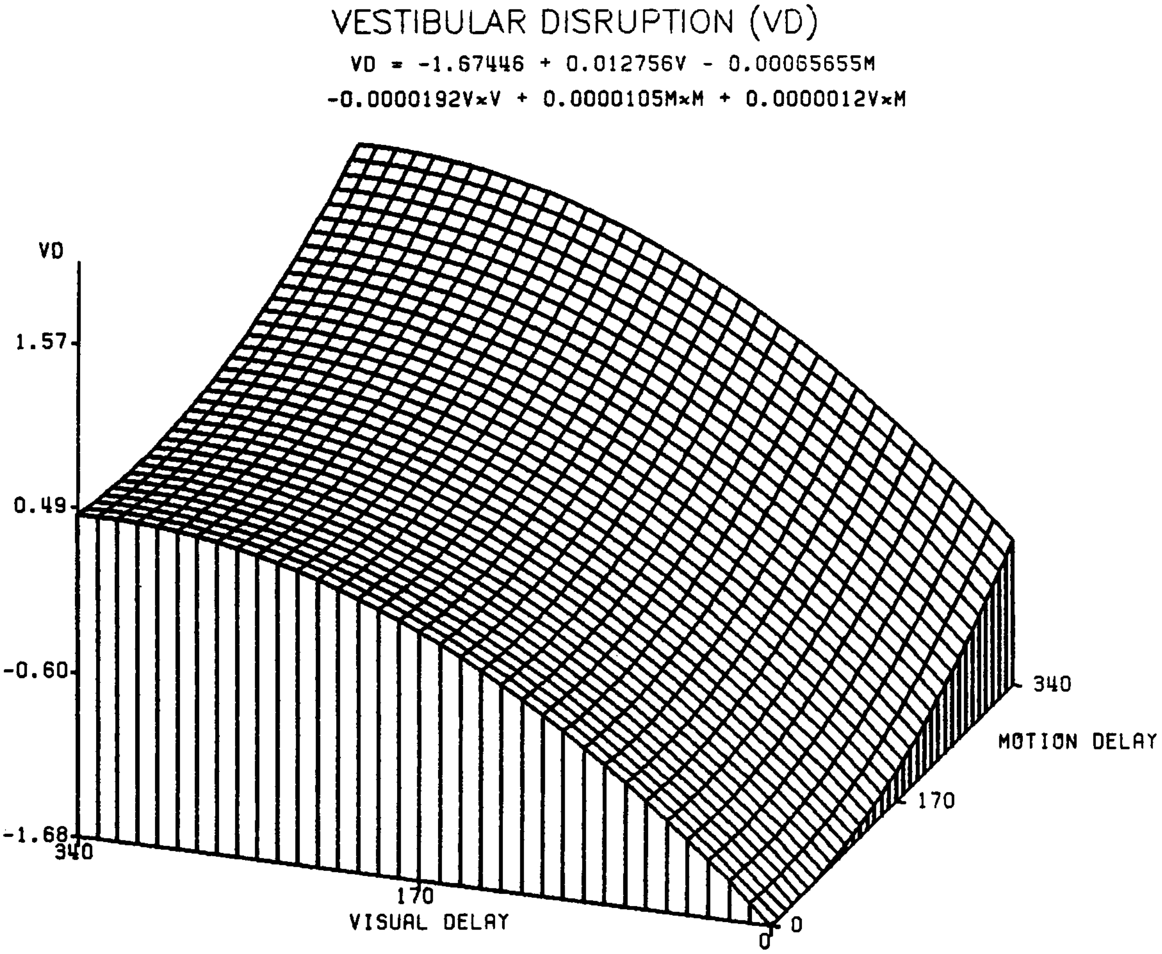

Figure 14. Second-order response surface for principal component 1 (vestibular disruption).

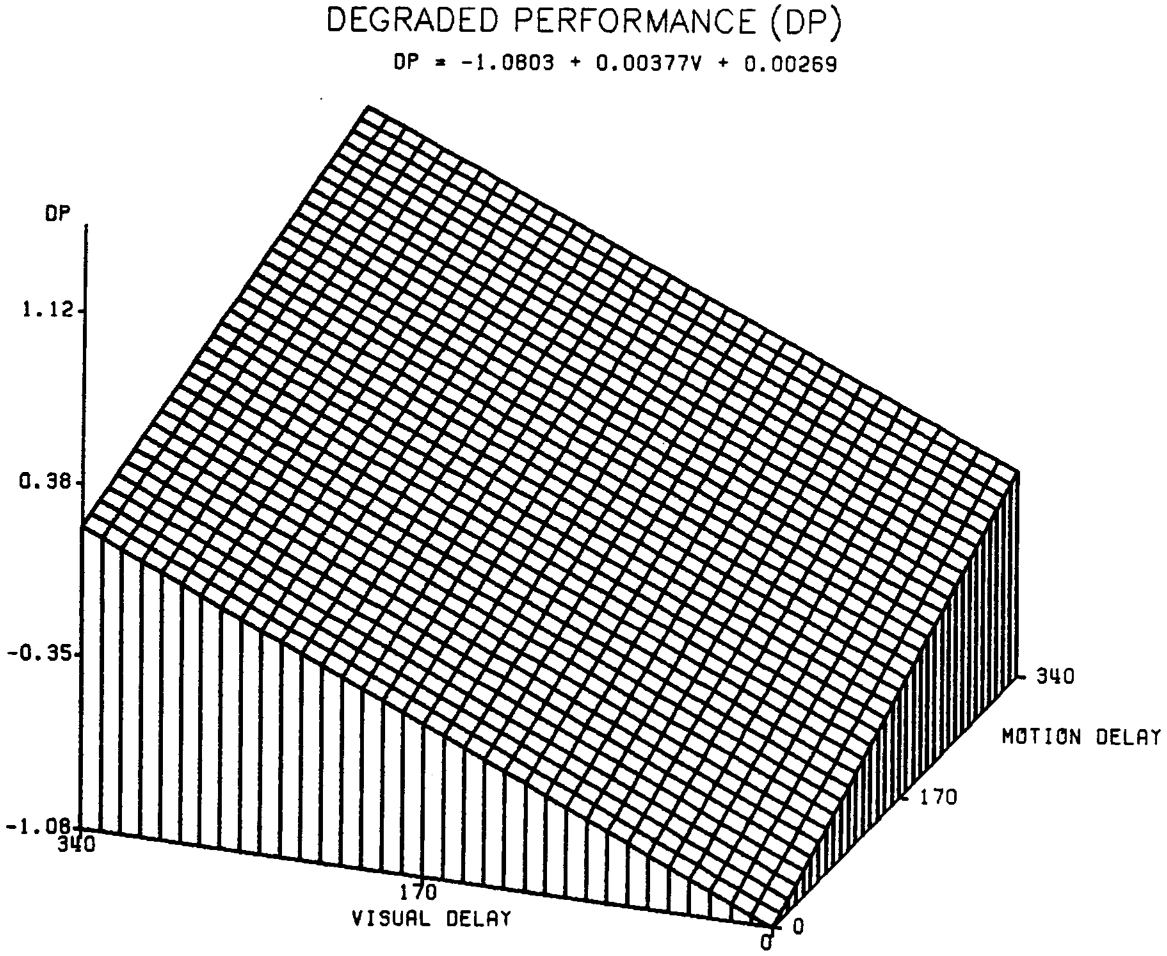

Figure 15. First-order response surface for principal component 2 (degraded performance).

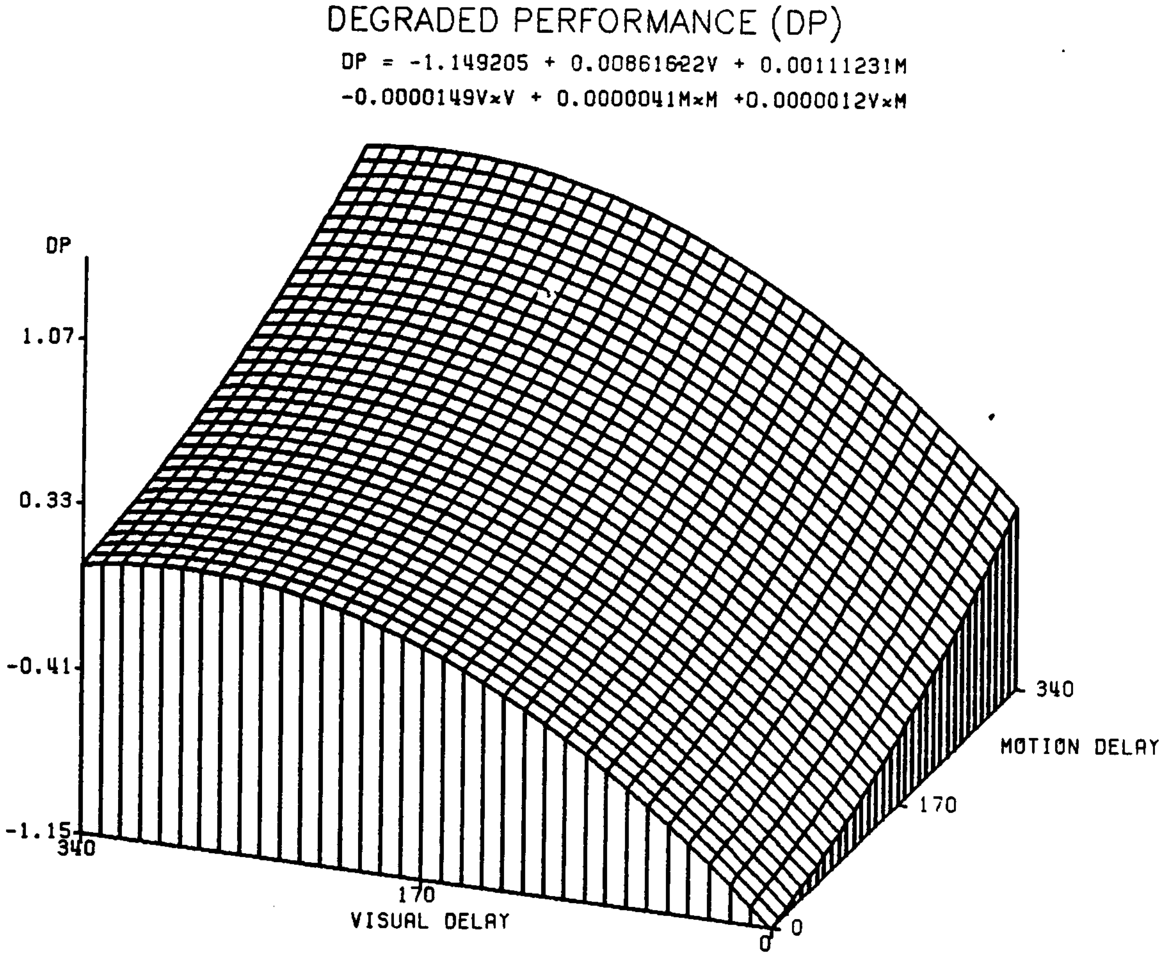

Figure 16. Second-order response surface for principal component 2 (degraded performance).

the above design results in 54 treatment conditions, which is the same as the total number of subjects in the experiment. With only one subject per cell, there is no variance estimate. Since perceptual style and sex were not expected to be significant sources of variance, the inability to estimate the fourth-order interaction was not viewed as representing interpretive problems. By collapsing the data across one of the four dimensions and performing a series of four three-way MANOVAs, all first-, second-, and third-order effects could be estimated. These four MANOVAs are as follows:

(a) Visual Delay x Motion Delay x Perceptual Style,

(b) Visual Delay x Motion Delay x Sex,

(c) Visual Delay x Sex x Perceptual Style,

(d) Motion Delay x Sex x Perceptual Style.

For all MANOVAs, conversion of Wilk's $\underline{U}$ criterion to exact $\underline{F}$ values was used (SAS, 1982). As with the response surface analysis, a criterion of $\underline{p} \leq 0.05$ was used for testing significance.

As expected, the main effects of sex and perceptual style were nonsignificant in each of the MANOVAs in which they appeared. Sex and perceptual style were also not significantly involved in any interactive effects. Table 33 presents the MANOVA summary table for visual delay, motion delay, and perceptual style. Appendix J presents the summary tables for the other three nonsignificant MANOVA tests.

It could be argued that since there were only two subjects per treatment in the Visual Delay x Motion Delay x Perceptual Style MANOVA and only three subjects per treatment in the Visual Delay x Motion

Table 33

Multivariate Analysis of Variance Summary Table for Visual Delay x Motion Delay x Perceptual Style

Source	df	_F_*	_p_
Visual delay (V)	2	1.87	0.0543
Motion delay (M)	2	1.20	0.3186
Perceptual Style (PS)	2	0.56	0.9378
V x M	4	0.66	0.9425
V x PS	4	0.85	0.7292
M x PS	4	1.08	0.3953
V x M x PS	8	1.07	0.3557
Subjects/V M PS	27		
Total	53		

* Approximation of _F_ obtained by conversion using Wilk's criterion (SAS, 1982).

Delay x Sex, Visual Delay x Sex x Perceptual Style, and Motion Delay x Sex x Perceptual style MANOVAs, the sensitivity (i.e., power) of each test would be reduced due to small sample size (Bray and Maxwell, 1985). It should be recalled that the main purpose of the secondary analysis was to determine if a subject's perceptual style or sex was a significant source of variance for any of the dependent measures. Therefore, to explore the possibility that small sample size reduced the MANOVA's ability to detect "real" differences, a two-way MANOVA was performed with perceptual style and sex as the between-subjects factors. The six treatment conditions in this design had nine subjects each. Table 34 presents the results of the MANOVA. As can be observed, no significant effects were found.

As noted earlier, it was surprising that no effect of motion delay was found. The review of the literature on delays indicated that motion delay is detrimental to operator control performance and, in some cases, can cause operator discomfort. Again, using the argument that the small sample sizes inherent in the three-way MANOVAs contributed to a lack of sensitivity, a two-way MANOVA with motion delay and visual delay as the between-subjects factors was performed. (The data in this MANOVA were, of course, collapsed across perceptual style and sex.) The results of this analysis are shown in Table 35 and reveal significant main effects of visual delay and motion delay.

Subsequent univariate analyses of variance were performed to assess which dependent measures were most affected by the visual delay treatment. Table 36 summarizes the results of these analyses for each

Table 34

Multivariate Analysis of Variance Summary Table for Perceptual Style x Sex

Source	df	_F_*	_p_
Perceptual style (PS)	2	0.46	0.9900
Sex (S)	1	0.92	0.5533
PS x S	2	0.67	0.8892
Subjects/PS S	48		
Total	53		

* Approximation of _F_ obtained by conversion using Wilk's criterion (SAS, 1982).

Table 35

Multivariate Analysis of Variance Summary Table for Visual Delay x Motion Delay

Source	df	_F_*	_p_
Visual Delay (V)	2	1.74	0.0333
Motion Delay (M)	2	1.66	0.0473
V x M	4	0.66	0.9616
Subjects/V M	45		
Total			

* Approximation of _F_ obtained by conversion using Wilk's criterion (SAS, 1982).

Table 36

Summary of the Effect of Visual Delay on Each Dependent Measure

Dependent variable	SS	F*	p
Pallor	0.192	0.10	0.9075
Skin Resistance	237.865	0.61	0.5465
Breath Cycles/Second	0.0018	0.18	0.8337
Yaw Standard Deviation	65.353	6.53	0.0032**
Small Steering Reversals	20776.333	5.88	0.0054**
Large Steering Reversals	13398.259	5.52	0.0072**
SEAT Movements	0.2592	0.01	0.9898
Total Seat Movements	2.777	0.21	0.8080
Simulator Sickness Severity Index	8.037	3.82	0.0293**
Total Symptoms	40.111	1.48	0.2380
Stand-on-Preferred-Leg	244.808	4.34	0.0189**
Stand-on-Non-preferred-Leg	10.904	0.27	0.766
Combined Stand-on-Leg	59.657	2.05	0.1406
Percent Stand-on-Preferred-Leg	17528.858	5.61	0.0067**
Percent Stand-on-Non-preferred-Leg	5944.045	2.13	0.1313
Percent Combined Stand-on-Leg	6224.646	4.37	0.0184**

* df = 2,45
** $p < 0.05$

dependent measure. Seven of the dependent variables (YAW, SREV, LREV, SSSI, SOPL, PSOPL, and PCOMB) were sensitive to changes in visual delay. Note that none of the instrumented physiological metrics demonstrated any significance with respect to visual delay. Multiple comparisons across the means for each of the seven significant dependent variables were performed by the Newman-Keuls multiple range test. These results are shown in Tables 37 through 43. It is evident from these tables that operator control performance is significantly disrupted at delays of 170 ms or greater, whereas postural stability and the self assessment of sickness are disrupted at delays less than 170 ms. A better understanding for how visual delay affects these seven dependent measures can be gained by referring to the visual delay axis of the appropriate response surface plots.

Subsequent univariate analyses performed on the motion delay variable revealed that only BCS was sensitive to changes in motion delay. The results of the motion delay univariate test for each dependent measure are presented in Table 44. Table 45 summarizes the results of the Newman-Keuls test on the motion delay means for BCS.

Correlation analyses. The literature on perceptual style has reported that there is a relationship between a subject's gender and his or her score on the Rod-and-Frame Test (RFT). In general, females score higher than males (i.e., greater mean error). To determine whether this finding was replicated in this study, a point-biserial correlation between the dichotomous variable male/female and the subject's score on the RFT was computed (Bruning and Kintz, 1968).

Table 37

Results of the Newman-Keuls Analysis Using Yaw Standard Deviation as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	7.036	8.96	9.63

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 38

Results of the Newman-Keuls Analysis Using Small Steering Reversals as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	222.56	248.39	270.56

* Any two means underlined by the same line are not significantly different (_p_ > 0.05).

Table 39

Results of the Newman-Keuls Analysis Using Large Steering Reversals as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	40.167	41.111	64.778

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 40

Results of the Newman-Keuls Analysis Using Simulator Sickness Severity Index as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	2.94	3.83	3.67

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 41

Results of the Newman-Keuls Analysis Using Stand-on-Preferred-Leg as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	-0.72	-5.09	-5.36

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 42

Results of the Newman-Keuls Analysis Using Percent Stand-on-Preferred-leg as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	0.23	32.51	42.44

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 43

Results of the Newman-Keuls Analysis Using Percent Combined Stand-on-Leg as the Dependent Measure

Visual Delay Treatment	0	170	340
Treatment Mean*	19.01	36.41	44.78

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

Table 44

Summary of the Effect of Motion Delay on Each Dependent Measure

Dependent variable	SS	F*	p
Pallor	0.259	1.31	0.2798
Skin Resistance	75.315	0.19	0.8244
Breath Cycles/Second	0.042	4.24	0.0206**
Yaw Standard Deviation	12.875	1.29	0.2863
Small Steering Reversals	2653.778	0.75	0.4778
Large Steering Reversals	7000.259	2.88	0.0664
SEAT Movements	17.370	0.69	0.5073
Total Seat Movements	4.111	0.32	0.7300
Simulator Sickness Severity Index	3.815	1.81	0.1748
Total Symptoms	8.333	0.31	0.7365
Stand-on-Preferred-Leg	62.618	1.11	0.3385
Stand-on-Non-preferred-Leg	130.364	3.20	0.0504
Combined Stand-on-Leg	82.769	2.84	0.0687
Percent Stand-on-Preferred-Leg	65.774	0.02	0.9792
Percent Stand-on-Non-preferred-Leg	3064.027	1.10	0.3432
Percent Combined Stand-on-Leg	642.416	0.45	0.6398

* df = 2,45
** $p < 0.05$

Table 45

Results of the Newman-Keuls Analysis Using Breath Cycles Per Second as the Dependent Measure

Motion Delay Treatment	0	170	340
Treatment Mean*	0.0177	0.0240	0.0811

* Any two means underlined by the same line are not significantly different ($p > 0.05$).

This value was 0.059, and of course nonsignificant, $t(52) = 0.438$, $p > 0.05$ indicating that a subject's gender had no influence on his or her ability to disembed the rod from the tilted frame.

Also of interest were the correlations among past motion sickness history, perceptual style, and each of the dependent measures, as well as the correlations among the dependent measures themselves. Table 44 presents these correlations. As would be expected, those dependent variables which represent transformations of each other were significantly correlated; for example, BCS and SBC were significantly correlated as were the stand-on-leg tests. Also of note was the significant correlation between BCS and LREV. Of particular saliency was the finding that MSQ and PS failed to correlate significantly or with any of the dependent variables.

Insight into the general lack of sensitivity of the MANOVA analyses is provided by scrutinizing the intercorrelations among the dependent variables. As can be seen, these values are relatively small. Stevens (1980) has shown that the power of the MANOVA test is related to the size of the intercorrelations. Generally, the lower the intercorrelations, the lower the power for the same effect sizes.

Table 46

Correlations Among Motion Sickness History, Perceptual Style, and the Dependent Measures*

	MSQ	PS	PAL	SR	SBC	BCS	YAW
MSQ	1	-0.066	-0.069	0.016	0.088	0.168	-0.068
PS		1	-0.233	0.0137	-0.093	0.075	0.030
PAL			1	0.129	0.0315	-0.106	-0.0143
SR				1	0.083	0.154	0.009
SBC					1	$\underline{0.369}$	-0.190
BCS						1	0.086
YAW							1
SREV							
LREV							
SEAT							
TSEAT							
SSSI							
TSYM							
SOPL							
SONPL							
COMB							
PSOPL							
PSONPL							
PCOMB							

* values underlined are significant ($\underline{p} \leq 0.05$).

Table 46 (Continued)

Correlations Among Motion Sickness History, Perceptual Style, and the Dependent Measures*

	SREV	LREV	SEAT	TSEAT	SSSI	TSYMP
MSQ	-0.005	-0.080	-0.096	-0.037	0.087	0.184
PS	0.050	0.016	0.219	0.161	-0.142	-0.012
PAL	0.077	-0.074	0.189	0.161	0.049	-0.095
SR	0.179	0.122	0.104	0.214	0.100	0.206
SBC	0.091	-0.019	-0.008	-0.116	-0.111	-0.044
BCS	0.173	0.304	-0.222	-0.120	0.209	0.077
YAW	0.116	0.719	0.039	0.157	0.235	-0.141
SREV	1	0.501	0.092	0.170	0.181	0.126
LREV		1	0.022	0.212	0.286	0.042
SEAT			1	0.557	-0.216	-0.131
TSEAT				1	.078	0.003
SSSI					1	.544
TSYM						1
SOPL						
SONPL						
COMB						
PSOPL						
PSONPL						
PCOMB						

* values underlined are significant ($p \leq 0.05$).

Table 46 (Continued)

Correlations Among Motion Sickness History, Perceptual Style, and the Dependent Measures*

	SOPL	SONPL	COMB	PSOPL	PSONPL	PCOMB
MSQ	-0.534	-0.156	-0.099	0.077	0.117	0.096
PS	0.160	0.119	0.106	-0.207	0.038	-0.199
PAL	0.159	0.176	0.191	-0.142	-0.209	-0.190
SR	-0.197	0.013	-0.134	0.176	0.123	0.131
SBC	0.162	-0.072	0.010	-0.426	0.112	-0.014
BCS	0.183	0.196	0.164	-0.226	-0.039	-0.215
YAW	-0.219	-0.193	-0.234	0.212	0.225	0.230
SREV	0.006	0.013	0.039	0.112	0.089	0.189
LREV	-0.213	-0.126	-0.195	0.236	0.131	0.258
SEAT	-0.015	-0.062	-0.062	0.043	0.121	0.156
TSEAT	-0.071	-0.113	-0.091	0.170	0.193	0.207
SSSI	-0.005	0.004	0.003	0.304	0.047	0.183
TSYM	0.062	-0.159	-0.032	0.154	0.125	0.096
SOPL	1	0.347	0.804	-0.707	-0.166	-0.689
SONPL		1	0.808	-0.169	-0.664	-0.595
COMB				-0.475	-0.521	-0.759
PSOPL				1	0.152	0.706
PSONPL					1	0.561
PCOMB						1

* values underlined are significant ($p \leq 0.05$).

DISCUSSION

Model Application

The results of the experiment clearly demonstrate that visual and motion systems delays are detrimental to both an individual's control performance and well-being. Ten significant empirical models were found which predict a subject's simulator driving performance (YAW, SREV, LREV), vestibular disturbance (SOPL, SONPL, COMB, PSOPL, PCOMB), and well-being (BCS, SSSI) as a function of visual-motion coupling delays. Obviously, there is a danger in applying the derived models to other simulators. However, it is expected that the general relationship between the dependent variables and the regressors will be substantially the same, although the coefficient weightings would, no doubt, change. It should also be emphasized that the detrimental results of visual-motion coupling delays found in this experiment are most probably underestimates of the effects that would be produced in other simulators. The driving simulator used in this study had a motion system which is accurately modeled from a mid-size American automobile. As departures from expected vehicle dynamics occur, such as in flight simulators, the effect of motion delay is anticipated to increase. Also in the present study, the subjects were presented with a relatively narrow field of view (48 deg horizontal by 39 deg vertical). Anecdotal and theoretical evidence (Frank, Kennedy, and McCauley, 1983; Leibowitz and Post, 1982b) strongly indicates that wider field of view will be more provocative. Similarly, the visual display in this particular experiment, though geometrically accurate, was relatively uncluttered in terms of scene content as compared, say, to some flight simulators especially those presenting low-level terrain following flight, landing scenarios, and hover. Again, both anecdotal and theoretical evidence indicate that greater scene detail will make the effects of visual-motion coupling delays more detrimental. Moreover, the driving scenario in this study was benign compared to other scenarios where much more rapid movement is introduced. For these reasons, it is believed that the empirical models provided herein can provide some simulator design guidance relative to visual-motion coupling delays.

It should also be noted that, although the driving simulator used in this study accurately incorporates the basic equations of motion for normal highway driving (Wierwille, 1975), it is essentially representative of a "generic" automobile; it was not designed to mimic the driving characteristics of a specific commercial automobile. Thus, all of the subjects were experienced in driving automobiles different from that mimicked by the simulator. It might be expected, then, that the responses exhibited by the subjects in this experiment would be different from those exhibited by individuals exposed to a simulator specifically designed to replicate a vehicle which they were experienced in operating. For example, McGuinness, Bouwman, and Forbes (1981) found that the more experienced F-14 aircraft pilots exhibited greater simulator sickness symptomatology when exposed to the F-14 aircraft simulator.

Motion Cueing Order

One purpose of this study was to determine whether the current design philosophy of having the motion system lead the visual system was satisfactory. Insight into the relationship between visual lead versus visual lag can be gained by examining the visual and motion delay regressor coefficients in each empirical model. In the discussion to follow, recall that the larger the value predicted by a model, the poorer the performance or well-being. The coefficients represent weightings of how "important" that regressor is to the prediction of the dependent measure. In a first-order model, for example, if visual delay has the larger coefficient, then it contributes more to the prediction. This relationship would indicate that a smaller delay in the visual system is required to produce the same outcome that a larger delay in motion would. Such a relationship would also indicate that, if the visual system leads the motion system, better performance will occur. The converse holds if the motion delay coefficient is higher.

This is easily demonstrated by considering the following hypothetical model:

$$\text{Discomfort} = 10 + 2V + M. \qquad (1)$$

In the 3 x 3 design used in this study, there are three situations in which the visual system leads and three in which the motion system leads. These are depicted in Table 47 along with the predicted discomfort based upon the hypothetical model given above. As can be seen from this table, visual system lead produced the more desirable outcomes ($\underline{p} < .03$ by a binomial test).

Table 47

Hypothetically Predicted Discomfort for Six Treatment Conditions Having Asynchronous Delays

Visual Delay (ms)	Motion Delay (ms)	Discomfort
0	170	180
0	340	350
170	340	690
170	0	350
340	0	690
340	170	860

Examination of the 10 models presented in Table 24 indicates that, depending upon the dependent measure of interest, sometimes it would be desirable to have motion leading visual while, at other times, it would be more desirable to have visual leading motion. Of course, the most desirable condition is that having no delays.

Summary Models

For general design recommendations, perhaps the most useful models are the two derived from the principal components analysis. These models represent a composite of the 10 significant models with each predicting one specific outcome. For ease of reference, these two models, in uncoded form, are repeated here:

$$\text{Vestibular Disturbance} = -1.6264 + 0.00643V + 0.00314M, \text{ and} \quad (2)$$

$$\text{Degraded Performance} = -1.0803 + 0.00377V + 0.00269M. \quad (3)$$

As can be observed, these models clearly indicate that when asynchronous delays occur in a simulator, visual system movement should begin before motion system movement to produce the best performance. This finding is in direct conflict with the Federal Aviation Administration's design guidance for Phase II and Phase III simulators (Draft FAA Advisory Circular 120-40A, 1985) and general simulator design philosophy.

Delay Type

This experiment certainly does not represent the definitive study on simulator visual-motion coupling delay. As previously noted, many other variables interact with delay. However, the results of this study strongly suggest that visual delay is far more disruptive to a simulator operator's control performance and physical comfort than is motion delay. The results also suggests that, when asynchronous delays occur in a simulator, visual scene movement should begin before movement of the inertial system. The first-order models produced by the principal components decomposition demonstrate a linear relationship between increased vestibular disturbance, degraded performance, and increases in delay. This relationship is graphically illustrated in Figures 13 and 15. Perusal of these two figures reveals that any delay in either system decreases performance. These figures can also be quite helpful in estimating the effects of different visual-motion coupling delays. It is difficult, however, to make recommendations on what represents an acceptable delay. Clearly, less is better, but less delay is also far more costly to implement. The question of how much delay can be tolerated in a system before transfer of training or experimental results are compromised is not answered by this study. However, the empirical models provided in this study can provide estimates when the model user has a definite criterion level in mind.

Again, it must be emphasized that the models are not definitive, but they can at least provide a relative rank ordering among various design alternatives. It is in this manner that their use is recommended.

Of theoretical interest is the question of why visual delay appears to be more disruptive than motion. It is hypothesized that, as an individual learns to drive, he or she develops selective filtering mechanisms for visual and motion inputs. For example, the individual learns to disregard many spurious motions, such as road vibration or shock-absorber damping, which most often have little effect upon operator control ability. Similarly, the individual learns to filter out "nonsignificant" visual information and to attend to the geometrically reliable cues needed to control the automobile. It is further hypothesized that, under normal everyday driving conditions, visual cues provide the primary information for vehicle control and motion cues provide the secondary information. Assuming these two hypotheses to be accurate, it follows that degradation of the visual cues would be more disruptive than degradation of the motion cues.

The above speculation also coincides with the perceptual decorrelation model of motion/simulator sickness. Visual delay represents a conflict between what is being experienced in the simulator and the correlations that have built up in an individual's lifetime. Moreover, the literature reviewed on perceptual simultaneity and temporal order suggests that the faster sensory system may have to lead the slower for simultaneity to be perceived (Rutschmann and Link, 1964). Using visual lead may reduce conflict, since it causes the human's perceptual system to perceive less of a delay between the onset of the visual and motion systems. In other words, there is less of a decorrelation.

Perceptual Style

Ancillary to the main purpose of this study was an attempt to provide a clearer understanding of the relationship between perceptual style and simulator sickness. As evidenced in both the MANOVA and correlational analyses, no significant relationship was found. Based upon the critical review of former studies on perceptual style and simulator sickness given in the Literature Review section and the results of this study, it is concluded that a subject's perceptual style is unrelated to simulator sickness susceptibility. This conclusion is given credence when it is recalled that the dependent measures of simulator sickness, namely SSSI, and the postural stability tests were sensitive to changes in delay.

Motion Sickness History

Also of note is the finding that motion sickness history was not significantly correlated with any of the dependent measures. Past research has indicated that scores on the MSQ can be mildly predictive of motion sickness susceptibility (Reason and Diaz, 1971). Similarly, respiration rate and pallor have been reported to be reliable indicators of simulator sickness (Casali and Wierwille, 1980; Testa, 1969). In the present study, they were unreliable. However, direct comparisons among these studies is difficult since different independent variables were investigated. Due to building air conditioning problems, the experimental room temperature varied between 18°C to 20°C. It is possible that the low ambient room temperature affected these measures, due to vasoconstriction, although the author feels it is unlikely.

Ataxia Tests

In general, both types of ataxia tests, absolute time and percent time, were sensitive. However, because subjects varied so much initially in their ability to stand on one leg with their eyes closed before simulator exposure, it is believed that the percentage measure may be a more meaningful and sensitive measure. The regression and MANOVA analyses seem to bear this out.

Seat Movement

The author's speculation that the number of seat movements may indicate simulator sickness was unsupported in this study. Very few seat movements were recorded and, for many subjects, no seat movements occurred. It could be that the threshold set on the linear potentiometers used to measure movement was too high. However, Dingus et al. (1986) used exactly the same apparatus and threshold and found seat movements to be a reliable measure of alcohol consumption and drowsiness.

CONCLUSIONS

1. The results of this study strongly indicate that visual delay is more detrimental to operator control performance and sensations of uneasiness than is motion delay. Moreover, the data indicate that when asynchronous delays exist, better operator performance and well-being occur if visual system movement leads motion system movement.

2. The empirical models derived in this study are specific to the simulator and delay type/duration used herein. Nevertheless, the models may have some benefit in determining relative tradeoffs among competing design alternatives for other simulators through application of a rank-ordering method.

3. The results of this study also indicate that neither subject gender nor perceptual style influenced susceptibility to simulator sickness, driving performance, nor postural stability.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Further work is required on visual-motion cueing order. Young (1978) reports that, at low-level frequencies, visual cues dominate, while at higher frequencies, vestibular cues dominate. It may well be that systems which respond quickly to a control input--such as a fighter aircraft simulator--may benefit from intertial lead, whereas a relatively "sluggish" system--such as a ship simulator--may benefit from visual lead.

2. In the present study, all delays were constant. In many operational simulators, delays are variable. For example, visual delay is, in part, due to visual scene calculation time. The more complex the scene to be generated, the greater the delay. A similar relationship holds for motion delay. Thus, the simulator operator is more or less exposed to "random" delays within some bandwidth. These random delays would probably be more disruptive, since the human operator could not predict the "randomness." Therefore, it is recommended that variable delays also be studied.

3. Past research indicates that the greater the visual delay, the poorer the performance and the greater the task difficulty, the smaller the acceptable time delay (Ricard and Puig, 1977). Consequently, it is recommended that operator workload be assessed in conjunction with visual-motion cueing delays.

4. Many other factors, such as field of view, exposure duration, visual and motion system degrees of freedom, display refresh rate, and dominant simulator frequency are all expected to influence operator control performance and feelings of comfort. What is required is a sequential approach to model building (such as Simon's, 1977). By use of a sequential approach, the large set of possible contributory variables can be screened to identify the critical variables that affect performance. Application of response surface methodology central composite design techniques would permit a more economical approach than that afforded by the classical analysis of variance approach. In addition, the resultant models would provide insights into the interrelations among the variables studied.

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APPENDIX A

SUBJECT'S SELF-EVALUATION FORM

Subject's Self Evaluation

Directions: Please check any of the following symptoms you experienced while driving the simulator or that you are experiencing now. If you experienced any of these symptoms before entering the simulator, inform the experimenter. Please respond to each numbered item.

1. General discomfort None___ Slight___ Moderate___ Severe___

2. Fatigue None___ Slight___ Moderate___ Severe___

3. Boredom None___ Slight___ Moderate___ Severe___

4. Mental depression No_______ Yes________

5. Drowsiness None___ Slight___ Moderate___ Severe___

6. Headache None___ Slight___ Moderate___ Severe___

7. Fullness of head No_______ Yes________

8. Blurred vision No_______ Yes________

9. a. Dizziness with eyes open No_______ Yes________

   b. Dizziness with eyes closed No_______ Yes________

10. Difficulty focusing No_______ Yes________

11. Eye strain No_______ Yes________

12. Visual flashbacks No_______ Yes________

13. Vertigo No_______ Yes________

14. a. Salivation increased None___ Slight___ Moderate___ Severe___

    b. Salivation usual No_______ Yes________

    c. Salivation decreased None___ Slight___ Moderate___ Severe___

15. Sweating None___ Slight___ Moderate___ Severe___
16. Faintness No_______ Yes________
17. Aware of breathing No_______ Yes________
18. Stomach Awareness * No_______ Yes________
19. Nausea None___ Slight___ Moderate___ Severe___
20. Burping No_______ Yes_______ No. of times_______
21. Confusion No_______ Yes________
22. Loss of appetite No_______ Yes________
23. Increased appetite No_______ Yes________
24. Desire to move bowels No_______ Yes________
25. Vomiting No_______ Yes________
26. Other ____

* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

APPENDIX B

DIAGNOSTIC CATEGORIZATION SCORE SHEET

Diagnostic categorization score sheet.

PATHOGNOMIC SYMPTOM

Vomit

MAJOR SYMPTOMS

Increased salivation	moderate and severe
Nausea	moderate and severe
General discomfort	severe
Fatigue	severe
Boredom	severe
Sweating	severe
Pallor	severe
Retch	severe
Drowsiness	severe

MINOR SYMPTOMS

Increased salivation	slight
Nausea	slight
General discomfort	moderate and slight
Pallor	moderate and slight
Sweating	moderate and slight
Drowsiness	moderate and slight
Fatigue	moderate
Boredom	moderate

MENTAL SYMPTOMS ("minor" and "other" symptoms)

Difficulty concentrating	minor
Confusion	minor
Fullness of head	other
Depression	other
Apathy	other

VISUAL SYMPTOMS ("minor" and "other" symptoms)

Difficulty focusing	minor
Visual flashbacks	minor
Blurred vision	other
Eye strain	other

OTHER SYMPTOMS

- Character facies
- Increase yawning
- Stomach awareness
- Loss/increased appetite
- Anorexia
- Burping
- Bowel movements
- Headache
- Dizziness
- Aerophagia
- Vertigo
- General fatigue
- Faintness
- General boredom

APPENDIX C

PENSACOLA MOTION SICKNESS HISTORY QUESTIONNAIRE

Subject: ______________ Treatment: _______________ Date: ______________

This questionnaire is designed to find out: (a) how susceptible to motion you are; and (b) what sorts of motion are most effective in causing that sickness.

Section A is concerned with your childhood experience of motion sickness, that is, prior to the age of 12. Section B is concerned with your experience of motion sickness since the age of 12.

The correct way to answer each question is explained in the body of the questionnaire. Please read these instructions carefully as you go along. It is important that you should answer <u>every</u> question.

Your replies to these questions will be treated in the strictest confidence. Thank you for your help.

SECTION A

All questions in this section refer ONLY to your childhood experiences of motion sickness (if any) where childhood is defined as the period prior to 12 years of age. It is quite possible that you will have difficulty recalling childhood motion sickness; nevertheless, please try to answer the questions to the best of your ability.

1. Indicate approximately how often you traveled on each type (before age 12) by using one of the following numbers:

0 - no experience
1 - less than 5 trips
2 - between 5 and 10 trips
3 - more than 10 trips

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

Considering ONLY those types of transportation that you have marked 1, 2, or 3 (i.e., those that you have traveled on), go on to answer the two questions below. Use the following letters to indicate the appropriate categories of responses:

N - never
R - rarely
S - sometimes
F - frequently
A - always

2. How often did you feel sick while traveling, i.e., queasy or nauseated?

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

3. How often were you actually sick while traveling, i.e., vomiting?

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

SECTION B

This section is concerned solely with your experience of motion sickness (and travel) SINCE the age of 12. Please answer the questions in exactly the same way as in Section A.

1. Indicate approximately how often you traveled on each type (since age 12) by using one of the following numbers:

0 - no experience
1 - less than 5 trips
2 - between 5 and 10 trips
3 - more than 10 trips

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

Considering ONLY those types of transportation that you have marked 1, 2, or 3 (i.e., those that you have traveled on), go on to answer the two questions below. Use the following letters to indicate the appropriate categories of responses:

N - never
R - rarely
S - sometimes
F - frequently
A - always

2. How often did you feel sick while traveling, i.e., queasy or nauseated?

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

3. How often were you actually sick while traveling, i.e., vomiting?

Cars	Buses or Coaches	Trains	Airplane	Small Boats	Ocean Liners	Swings	Merry Go Round	Roller Coasters

APPENDIX D

SUBJECT'S INFORMED CONSENT-TO-PARTICIPATE DOCUMENT

RESEARCH SUBJECT'S INFORMED CONSENT-TO-PARTICIPATE DOCUMENT

The purpose of this study is to investigate the effects of driving simulator visual scene and motion cue synchronization on simulated driving performance and driver comfort. In this study you will be asked to drive the Virginia Polytechnic Institute and State University's (VPI&SU) driving simulator in a simulated highway driving scenario. This simulator is a safe method of conducting driving research which has been used by over 1000 persons like yourself.

You will also be requested to wear special physiological sensors during the experiment. These sensors may be slightly uncomfortable to wear but they will not harm you in any way. Some of them emit only a minute electrical current which you will not be able to feel. The sensors sit on the surface of the body. The purpose of the sensors is to monitor your body's reaction during the experiment.

You will also be asked to take some short perceptual, and postural stability tests before and following the driving scenario. These include simple tests such as standing on one leg for a few minutes to test balance. In addition, you will be asked to fill out two questionnaires regarding your perceptions of the simulator and motions in general at the conclusion of the experiment.

If you decide to participate, you will be paid $4.00 per hour for the time you spend in the study plus a $1.00 per hour bonus if you complete the study. The entire experiment is expected to last less than two hours.

In the experiment you will be asked to drive the simulator in a typical highway driving task much as you would drive your own car. No high-speed driving, violent maneuvering, or long driving periods will be required of you.

The risks involved in this experiment include the following:

1) If you should attempt to leave the moving simulator before the motion system is stopped you could be injured. Therefore, you will be required to wear a lap belt at all times. Also, if you wish to stop driving you should inform the experimenter who will shut-off the simulator and allow you to exit. Furthermore, there is an "emergency shut-off" button on the simulator dashboard which you can press if you feel you must stop immediately. (It should not be necessary to press this button but it is included on the simulator as an extra safeguard.)
2) The simulator may respond to your driving inputs differently than the cars you are used to driving. In some cases, the simulator may be difficult to control. If so, simply do your best, driving the simulator as you would a car on a highway. If you have difficulty in maintaining control, don't be alarmed, as there is no danger of "crashing" in the simulator. Though the experimenters want you to drive normally, the study is not aimed at testing your driving skill per se.

3) Because the simulator may not feel or react like your car, you may experience some discomfort or mild uneasiness as a result of driving it. Such uneasiness might be likened to that resulting from a mild amusement ride and it should not harm you. However, if you do experience discomfort (for example, dizziness) after exiting the simulator, the experimenter will ask you to remain in the lab for a few minutes to insure your well-being.

Similar studies to this one have been conducted in the simulator without harm to any subject. The research team greatly appreciates your interest in participation and wants you to be aware of all aspects of the study before consenting to participate.

As a participant in this experiment, you have certain rights, as stated below. The purpose of this sheet is to describe these rights to you and to obtain your written consent to participate.

1) You have the right to discontinue participating in the study at any time for any reason. If you decide to terminate the experiment, inform a member of the research team and he will pay you only for the portion of time you have spent, at a rate of $4.00 per hour.

2) You have the right to inspect your data and to withdraw it from the experiment if you feel that you should. In general, data are processed and analyzed after all subjects have completed the experiment. Subsequently, all the data are treated anonymously and confidentially. Therefore, if you wish to withdraw your data, you must do so immediately after your participation is completed, otherwise your name cannot be associated with your data.

3) You have the right to be informed as to the general results of the experiment. If you wish to receive a summary of the results, include your address (three months hence) with your signature on the last page of this form. If after receiving the summary, you would then like further information, please then contact the Vehicle Simulation Laboratory and a full report will be made available to you. To avoid biasing other potential subjects, you are requested not to discuss the study with anyone until after November 31, 1986.

4) You may ask questions of the research team at any time prior to data collection. All questions will be answered to your satisfaction subject only to the constraint that an answer will not prebias the outcome of the study. If bias would occur, with your permission, an answer will be delayed until after data collection at which time a full answer will be given.

The research team includes Mr. Larry Frank (Ph.D. candidate in IEOR), Dr. J. G. Casali (faculty member in IEOR), and Dr. W. W. Wierwille (faculty member in IEOR). Their lab address and phone number are as follows:

Vehicle Simulator Lab
Room 526 Whittemore Hall
VPI&SU
Blacksburg, VA 24061

(703) 961-7962

If you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Charles Waring
Chairman, University Human Subjects Committee
301 Burruss Hall
VPI&SU
Blacksburg, VA 24061

(703) 961-5283

(Please tear off and keep this page for future reference.)

Before you sign this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask them of the experimenter at this time. Then if you decide to participate, please sign your name below and provide your phone number so that you may be contacted if necessary.

I have read a description of this study and understand the nature of the research and rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid only for the portion of time that I spend in the study.

Signature ______________________________

Printed Name ______________________________

Date ______________________________

Phone ________________________

Witness to above signature:

Signature ______________________________

Printed Name ______________________________

Date ______________________________

If you would like a summary of the results from this study, please print the address where you will reside three months from now:

Name ____________________________________

Address __________________________________

APPENDIX E

ROD-AND-FRAME TEST SUBJECT INSTRUCTIONS

RFT INSTRUCTIONS

The purpose of this test is to determine how well you can establish the upright (that is vertical) under various conditions. Vertical or upright is defined as parallel to the outside walls of this building and perpendicular to the floor of this room. In a few moments I will ask you to remove your goggles. Upon doing so, you will see a square frame and within it a rod. I can tilt the frame or the rod to the left or right, either independently or together. On each trial you are to describe the initial positions of the rod and of the frame and then direct me in adjusting the rod to the true vertical position. If you perceive that the rod is not vertical, tell me which direction to move the rod to make it vertical. I will turn the rod a little at a time. After each turn if you still perceive the rod as tilted, say more. When you perceive the rod to be vertical, say stop.

If you have any questions feel free to ask them now or during the experiment.

APPENDIX F

SUBJECT'S DRIVING INSTRUCTIONS

DRIVING INSTRUCTIONS

Because of the simulator's active motion system, you will be required to wear the lap seat belt at all times during the experiment. During the experiment you can communicate with the experimenter via the dash-mounted speaker and microphone located to your upper right.

In front of you is a visual display consisting of a moving geometrical roadway simulation. During operation of the simulator, you will experience simulated vehicle motions corresponding to the driving conditions and to your control maneuvers. Your control of the simulator's speed and road position will be by means of a standard steering wheel, accelerator pedal, brake pedal, and speedometer as in a normal automobile with an automatic transmission.

The complete driving task will take about 25 minutes. While driving, you are to perform two tasks:

1. Maintain a constant speed of 55 mph at all times, and
2. Maintain a normal right-lane highway driving position at all times.

Please keep in mind that you are at all times to drive in the same manner as you normally would on a superhighway. During the run you will experience road curvature and simulated cross-wind gust which tend to push your vehicle off the roadway. When these changes occur, your job will be to maintain the vehicle's right-lane position and speed as well as possible. We again want to remind you that in some cases it may be very difficult to control the vehicle. Remember, the experiment is not designed to test your driving skill per se, but to collect data on simulator motion cueing synchronization.

If during the driving task you feel that you must discontinue for any reason, you have the right to do so. For your safety, the motion platform must be stopped before you leave the simulator. This can be accomplished in either of two ways.

1. Inform the experimenter of your wish to stop, and the experimenter will stop the motion from the control console.

2. Inform the experimenter of your wish to stop and then press the emergency stop button on the dash.

The experimenter will aid you in leaving the simulator. Obviously, the research team would like for you to complete the experiment if you can.

If you have any questions please ask the experimenter.

APPENDIX G

SIMULATED ROAD-CURVATURE PROFILE

Road Type*	Time in ms	Cumulative time in ms
C	30	30
S	15	45
C	60	105
S	30	135
C	25	160
S	30	190
C	35	225
S	230	455
C	70	525
S	20	545
C	45	590
S	25	615
C	60	675
S	235	910
C	80	990
S	25	1015
C	50	1065
S	25	1090
C	40	1130
S	130	1260

* C = curved
S = straight

APPENDIX H

DIAGNOSTIC CRITERIA FOR LEVELS OF SIMULATOR SICKNESS SEVERITY

Diagnostic Category	Criteria
0	No symptoms reported
1	Any symptom related to motion sickness reported
2	More than TWO OTHER symptoms reported
3	ONE MINOR plus OTHER symptoms reported
4	ONE MAJOR symptom alone -- or -- TWO MINOR symptoms -- or -- ONE MAJOR and ONE MINOR symptom -- or -- ONE MINOR plus FOUR OTHER symptoms, of which two or more are: stomach awareness, sweating, drowsiness or pallor
5	ONE MAJOR and TWO MINOR symptoms
6	TWO MAJOR symptoms (including retch and subject's report of emesis)
7	Experimenter's report of emesis

APPENDIX I

MOTION SICKNESS HISTORY QUESTIONNAIRE SCORING PROCEDURE

(FROM MOORE, LENTZ, AND GUEDRY, 1977, P. D-1)

SCORING THE MSQ

Each section is scored separately and yields two subscores, which are summed for a section score. The two section scores are then summed to yield a total score, the MSQ.

Scoring is done with the aid of the following conversion table:

Experience Level	Frequency of Report R	S	F	A
1	2	4	6	8
2	3	5	7	9
3	4	6	8	10

Example: A subject has reported Section A as follows:

Question	Cars	Buses or Coaches	Trains	Airplanes	Small Boats
A1	3	2	2	3	3
A2	S	R	R	R	N
A3	R	R	N	R	N
Score					
A1&A2	6	3	3	4	0
A1&A3	4	3	0	4	0

Question	Ocean Liners	Swings	Merry Go Round	Roller Coasters
A1	0	3	3	3
A2	0	N	N	N
A3	0	N	N	N
Score				
A1&A2	0	0	0	0
A1&A3	0	0	0	0

Determine the cell score for "nausea in cars" by determining the experience level from A1. This is 3. The frequency is S. Enter the table and read the weight 6 at the intersection of Row 3 and Column S. Repeat for the remaining cells in Lines A1 and A2. Determine the cell score for "vomiting in cars." The experience level is 3. The frequency is R. Read the weighted score 4 at the intersection of Line 3 and Column R. Enter the weight on the "Vomiting" line under "Cars" as indicated. Note that 0 experience level and/or N frequency always lead to a zero cell score.

Sum the nausea weights to obtain the "corrected frequency score" for nausea: $6 + 3 + 3 + 4 = 16$. Sum the vomiting weights to obtain the "corrected frequency score" for vomiting: $4 + 3 + 4 = 11$. Determine the number of types of motion experienced: $9 - 1 = 8$.

The total section score is obtained as follows:

$$\text{Section Score} = \frac{\text{Sum of the corrected frequency scores}}{\text{No. of types of experience}} \times 9$$

$$= \frac{16 + 11}{8} \times 9 = 30.4 \text{ (to the nearest tenth).}$$

The procedure is then repeated for Section B. Let us assume the section score for B is 12. The Motion Sickness Quotient is then obtained by summing the section scores:

$$\text{MSQ} = \text{Section A score} + \text{Section B score}$$

$$= 30.4 + 12 = 42.4$$

APPENDIX J

MANOVA SUMMARY TABLES FOR:

VISUAL DELAY X MOTION DELAY X SEX
VISUAL DELAY X SEX X PERCEPTUAL STYLE
MOTION DELAY X SEX X PERCEPTUAL STYLE

Table J1

Multivariate Analysis of Variance Summary Table for Visual Delay x Motion Delay x Sex

Source	df	_F_*	_p_
Visual Delay (V)	2	1.52	0.1004
Motion Delay (M)	2	1.51	0.1038
Sex (S)	1	0.94	0.5433
V x M	4	0.64	0.9650
V x S	2	0.69	0.8603
M x S	2	0.71	0.8334
V x M x S	4	1.02	0.4639
Subjects/V M S	36		
Total	53		

* Approximation of _F_ obtained by conversion using Wilk's criterion (SAS, 1982).

Table J2

Multivariate Analysis of Variance Summary Table for Visual Delay x Sex x Perceptual Style

Source	df	*F**	*p*
Visual Delay (V)	2	1.62	0.0707
Sex (S)	1	1.19	0.3478
Perceptual Style (PS)	2	0.39	0.9952
V x S	2	0.84	0.6806
V x PS	4	0.88	0.6924
S x PS	2	0.65	0.8864
V x S x PS	4	1.07	0.3807
Subjects/V S PS	36		
Total	53		

* Approximation of *F* obtained by conversion using Wilk's criterion (SAS, 1982).

Table J3

Multivariate Analysis of Variance Summary Table for Motion Delay x Sex x Perceptual Style

Source	df	*F**	*p*
Motion Delay (M)	2	1.30	0.2131
Sex (S)	1	0.82	0.6509
Perceptual Style (PS)	2	0.48	0.9821
M x S	2	0.69	0.8548
M x PS	4	0.92	0.5327
S x PS	2	0.65	0.9135
M x S x PS	4	1.01	0.5541
Subjects/M S PS	36		
Total	53		

* Approximation of *F* obtained by conversion using Wilk's criterion (SAS, 1982).

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