

Potential Design Etiological Factors of Simulator Sickness and a Research Simulator Specification

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ABSTRACT

In this paper is addressed the problem of vehicular simulator-induced sickness from the standpoint of simulator design etiological factors. A brief discussion of engineering design characteristics that exhibit potential for contributing to simulator sickness is presented. This discussion draws from studies performed on simulators to date along with other pertinent perceptual distortion literature and documentation of specific simulator problems. Potential etiological factors that are discussed include control loop lags and delays, control loading and damping, dynamic inaccuracies, fixed-base versus motion-base issues, illusory motion techniques, anomalous motion cues, motion enhancement devices, visual generation systems, field-of-view, scene detail and visual motion, dynamic imaging problems, display distortions, and cockpit environment factors. It is clear that many of these factors may interact in their influence on simulator sickness in a manner that is difficult to predict. On the basis of these potential etiological factors, basic requirements needed in a generic simulator research facility to investigate simulator engineering design influences on sickness are suggested.

The tendency of many vehicular simulators, including both driving and flight devices, to induce acute, residual, and sometimes aftereffect symptoms of discomfort in operators and passengers is well documented (1,2). In some devices the incidence of average symptomatology may be quite high, such as the 88 percent reported (3) in the Air Force simulator for air-to-air combat (SAAC), or it may be negligible or nonexistent, such as the 13 percent reported for the 2F106 and 2F64C Navy helicopter devices (4). Symptomatology characteristic of the simulator sickness syndrome varies widely among individuals who experience it and among simulators that induce it. Effects may range from mild disorientation and queasiness to severe ataxia and full emesis. Prolonged postsimulator effects may include gastric disturbances, disequilibrium problems, and illusory aftereffects. In certain military flight training simulators, the problem has been recognized as severe enough to warrant the recommendation of guidelines limiting the use of actual aircraft for a predetermined postsimulator period (5).

These adverse implications of simulator sickness become even more prominent when the increased dependence on simulators in research and training is considered. It has become increasingly critical that the simulator sickness problem be reckoned with in research efforts and subsequently eliminated through refinements in simulator design and usage practices. At least 60 simulator-specific characteristics have been mentioned as potential etiological factors (6 and paper by Casali and Frank in this Record), but few of these have been treated as independent variables and subjected to controlled study using known metrics of simulator discomfort and performance indicants to determine their influence.

The focus of this paper is on the theme that

simulator sickness is provoked by a stimulus array emanating from certain design and usage characteristics of simulators. Therefore a fundamental purpose of this paper is to provide a framework and facility requirements for a laboratory research approach aimed at defining the simulator-based etiology of sickness. A number of potential etiological factors of an engineering design nature are discussed briefly along with associated reference accounts.

Limited precedence for a research approach (but not an associated facility) of the type discussed herein exists for the study of simulator sickness (1,7-9) and a complete listing of simulator sickness studies appears in the paper by Casali and Frank in this Record.

POTENTIAL SIMULATOR DESIGN ETIOLOGICAL FACTORS

When reviewing the literature on simulator sickness (6,10,11), it becomes quite apparent from an engineering design standpoint that the problem is polygenic and that in some cases its causes may be simulator specific.

Control Loop Lags and Delays

It is well known that inappropriate temporal lags and delays may exist between control input and resultant system output, in either visual feedback or motion-base updating, or both, in a simulator (1,12). These control loop lags are inappropriate in the simulator if they are in excess of the normal control response lags inherent in the actual system dynamics. They are a relatively common problem and are sometimes difficult to overcome because they may emanate from a variety of sources in the simulator, such as serial processing time in digital computers for vehicle dynamics modeling, inertial effects in motion and visual systems, control input sampling rates, iteration rates of motion cuing algorithms and visual

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display generators, and analog-to-digital or digital-to-analog conversion rates.

Furthermore, the temporal problems may be of various types, for example, transport (deadtime) delay, exponential (first-order) lag, and second-order lag, all of which degrade vehicular control and potentially result in discomfort problems (11). The duration and profile of the delay or lag may vary during simulator operation, depending on the instantaneous load on the computational systems and memory storage capabilities. For example, in computer-generated imagery (CGI) displays, relatively impoverished, high-altitude flight scenarios may impose less computational load than does high-speed, low-altitude, terrain-following visual flight rules flight. Furthermore, delays may be differential between visual and motion-based feedback systems, either unintentionally or by design. For example, some devices are known to provide physical movement of the operator's seat, which phase-leads visual scene motion slightly and provides a slightly early cue to the operator's semicircular canals (13). Here, the chance for cue conflict is probably greater for experienced pilots who may be much more sensitive to temporal discrepancies in visual-motion coupling.

Inappropriate control-feedback lags are known to degrade controllability and stability of vehicular systems, as demonstrated by Casali and Wierwille (1), and may also induce symptoms of sickness (1,11). First, the closed-loop delay places the extra burden on the human operator of having to "anticipate" system response and introduce compensation to control the system. With long time delays, humans may eventually learn to anticipate and compensate, but particularly for experienced operators, who have well-developed expectancies about system response, the perceptual conflict created by the lagging feedback cues may be too stressful. Furthermore, the simulator pilot (or driver) may adopt control behaviors that lead to sickness-provoking pilot-induced oscillations (PIOs) when control loop delays are too large.

Other Dynamic Inaccuracies

The mathematical model including the equations of motion for the actual aircraft or automobile must be valid and representative of that vehicle, at least within the intended limits of operation of the simulator. Given an accurate mathematical model, the software simulation of that model must also be correct and computing power must be sufficient to solve the simulation in rapid fashion, to avoid problems of delay and priority of update information. Proper modeling of the full-scale vehicle in the simulator's computational systems is perhaps the most fundamental and critical factor underlying the dynamic fidelity of the device. Furthermore, it appears critical that the envelope of accurate correspondence between the simulator's dynamics and those of the actual vehicle must extend to low-speed maneuvers as well as those involving more complex high-speed kinematics. For instance, the authors have observed that sickness can be induced during slow driving simulator maneuvers and during relatively stationary helicopter maneuvers, such as hovering near ground.

Other dynamic inaccuracies may arise as a result of improper scaling of vehicular responses to control inputs, inadequate sampling of manual control input rates for use in dynamics computations, insufficient update rates for operator feedback systems, and improper amplitude quantization of variables during high-speed digital-to-analog and analog-to-digital conversions. In the latter case, inadequate resolution can cause "jumping" in either input or output

variables, which are continuous in the vehicle itself.

Control Loading Factors

Damping

One design factor that appears to be particularly influential in PIO is control damping (9,11). Underdamped vehicular control systems may be problematic in that the pilot or driver has a tendency to over-control the system in an effort to attain and maintain a stable attitude or heading, causing path overshoot and oscillation.

Other Control Factors

Other control design factors that may influence simulator fidelity and control stability include force breakout (preload) and stiction (frictional resistance to moving the control stick from its null position), both of which require force application to overcome initial control position, elastic resistance (spring loading), sliding friction, viscous friction, excursion limits, velocity limits, control inertia, control dead space, and control backlash. Each of these factors has direct bearing on the level of proprioceptive and somesthetic correspondence between the control feel in the simulator and in the actual system and therefore may be a source of cue conflict if fidelity is low and expected feedback is absent or incorrect.

Motion System Factors

Fixed-Base/Moving-Base

In the context of perceptual conflict theory, it has been suggested by Barrett and Thornton (14) that fixed-base simulators are likely to induce sickness because a cue conflict arises when the operator visually senses the appearance of incident vehicular motion but never receives corresponding physical acceleration or positional cues. However, the question of motion versus no-motion is not clear-cut; the addition (and proper tuning) of motion cuing systems to some simulators has greatly reduced the sickness problem (9) whereas in other devices the motion systems do not appear to alleviate discomfort and may, indeed, contribute to it and distract the operator.

Illusory Motion Techniques

Given the limitations of laboratory excursion envelopes and electrohydraulic positioning systems, it is clear that the best that can be hoped for from a motion system is that it convey the illusion of being moved, accelerated, and so forth as in a real vehicle. Of course, in the actual vehicle, movements are complete and actually experienced as they occur; in the simulator, movements may be attenuated or otherwise modified and the hope is that they are experienced as the real motion that they mimic. The success of the motion cuing system, and to some degree its influence on simulator sickness, is largely dependent on whether the subject is actually fooled, by the vestibular and kinesthetic cues combined with coordinated and sustained visual motion cues, into thinking that he or she has actually completed a full maneuver over hundreds of feet. Basically, this illusion is attempted in a simulator motion system

by providing a scaled onset motion cue that corresponds to a given acceleration cue from the computational dynamics and then tapering this cue off over time, or "washing it out," while sustaining the visual motion on the display.

For the motion platform and its associated drive logic, the proper design of such factors as acceleration cuing onset rates, washout time constants, nulling or resetting rates and logic, magnitude scaling, center of gravity positioning, and so forth is likely quite critical to the avoidance of operator discomfort. For example, research reported by Key et al. (15) demonstrated that with rapid motion washouts, with a break (filter corner) frequency of approximately 1.0 rad/sec, pilots reported nausea and vertigo problems. In other research (9) with an early fixed-base V/STOL simulator it was found that the addition of a pitch, roll, yaw motion base greatly alleviated sickness problems but only when a washout time constant of 2 to 3 sec was used. When short time constants on the order of 1 sec were used, inappropriate PIOs and nausea were reported.

Another illusory motion cuing technique involves the use of oversized tilt (i.e., pitch and roll) cues to simulate linear acceleration (i.e., lateral and longitudinal). Some of these systems rely on the use of tilt exclusively and have no translational capabilities; others use the tilt to augment limited existing translation cues. The former type was once used in several [cited in (16,17)] driving simulators but is no longer common because it has largely been replaced by synergistic (all actuators work together) systems or cascaded (actuators feed into each other in succession, a "building blocks" approach) systems of other forms (1). In many cases, in which the angular rotation does indeed produce a linear component of acceleration to a seated subject, perceptual conflict may occur when the subject senses the salient rotational aspect of the motion. Cue disparity may arise when the subject actually perceives the motion as rotational when the motion the subject expects is translational. In terms of vestibular functioning, the semicircular canals signal rotation of the simulator motion base when the expected sensation is linear acceleration as would be transduced by the otoliths. Therefore an intravestibular modality (canal-otolith) cue conflict may arise as well as an intermodality (visual-vestibular) conflict.

In a moving-base driving simulator study (1), which investigated the tilt concept as an independent variable, it was found that tilt (roll-axis) simulation of lateral acceleration cues was associated with significantly higher pallor and respiration rates in subjects than when normal lateral cues were used and affected vehicle path control by tending to inhibit subjects' steering reversals.

Anomalous Cues

Motion bases may, sometimes out of necessity of design, also provide movement and positional cues that are anomalous with respect to the actual vehicle in addition to their "true" cues. Perceptual disparity may occur when rotational acceleration cues in pitch and roll are washed out and the motion platform returns to horizontal while the rotational cue (e.g., aircraft bank or automobile roll altitude) is sustained in the visuals. Other spurious movements that potentially contribute to simulator sickness may arise as a result of parasitic motion between axes, hydraulic actuator "bump" and shudder, and inertial effects during sudden accelerations and reversals.

Motion-Induced Sickness

The occurrence of simulator motion-base resonant frequencies in the problematic range of 0.2 to 0.4 Hz may induce actual motion sickness (18) as evidenced in the Air Force SAAC simulator (19).

Complementary Motion Cuing Devices

Sometimes g-suits, g-seats, and g-dependent visual scene dimming (simulating a tunnel vision effect) are included in flight simulators to enhance the illusion of motion effects. The role of these devices in sickness provocation is unknown, but the potential does exist.

The g-seat device provides limited kinesthetic and somesthetic g-related cues by hydraulic or pneumatic inflation or deflation of cockpit seat pads. In some simulators these devices may be used in lieu of a vestibular cuing motion base. However, their excursions and response rates (especially those of the pneumatic seats) are quite limited and their intent is not to provide true inertial cuing. Furthermore, inflation or deflation of the seat pads may cause off-axis viewing (and resultant distortion) of cockpit displays because the pilot's head position is changed.

Visual System Factors

A variety of visual display characteristics has been hypothesized as contributors to simulator sickness.

Display Type

Common display systems include point-light source through transparency projection, film-based motion picture projection, model board objective with closed-circuit television, and infinity optics or projected CGI. No systematic study has been performed to determine the effects of each type on simulator sickness, and such a study would be difficult to perform because of the plethora of within-display type variables.

Field-of-View and Scene Detail

The visual scene field-of-view has been mentioned by several authors as being potentially critical to the provocation of simulator sickness (10,11). Wide field-of-view devices, such as the Air Force CGI SAAC simulator, the Navy point-light source 2E6 ACM device, and numerous driving devices, are known to induce discomfort; however, the specific etiology has yet to be experimentally verified (6). Nonetheless, the combination of wide displays with presentation of rapid visual motion is known to elicit motion sickness symptoms in passive observers (20). Perhaps one reason for the field-of-view effect is that the wide-screen presentation provides the opportunity for more stimulation of the peripheral retinal receptors, which have been shown to be more important in determining spatial orientation and movement than the center retinal receptors (21). For similar reasons, it may be that field-of-view interacts with scene detail and complexity in its influence. The higher the scene detail, the greater the vection (visual motion without physical cuing) and the greater the likelihood of a conflict with attenuated (or absent) vestibular cues in the simulator (7). This notion is supported by the high

incidence of sickness in some wide-screen CGI simulators but not others. For instance, in the SAAC, considerable detail, ground growth, and progression cues are available and high resolution of detail is possible, and sickness occurs at a relatively high rate (3). In contrast, a much lower reported incidence of sickness exists in wide-screen point-light source display devices, such as the 2E6 ACM simulator (4) and in night-only devices (11), in which display content is, in comparison, quite simple.

Dynamic Imaging Problems

A number of problems emanating from the process of "writing" video display information across a screen face (e.g., as in a CGI raster-scan system) have been mentioned as having potential impact on simulator sickness. For instance, in some interlaced raster-scan systems, double-imaging of displayed moving objects is common when computer video image information is sampled at rates different (slower) than those of display refresh, which is typically 60 Hz (6). Other temporal problems may include display flicker, image smearing, and image jittering. Some CGI-display simulators exhibit priority (bleed-through of background objects), shadowing (ghosting), image swimming (jerkiness of image during head movements), and image chrominance and displacement discontinuities between adjacent CRTs or projection screens. Because some of the problems result from lack of proper maintenance, their presence is fairly common and must be taken into account.

Display Distortions

Spatial distortions, which are elastic and therefore not easily adapted to, may be particularly sickness provocative. An example is optometric distortions that may be due to off-axis viewing and resultant parallax for crew members not at the display design eye position (7) and near-field cues that give indications that infinity optics displays are only a few feet away.

Cockpit Environment Factors

Several other factors pertinent to design of the cockpit or driver's station of the simulator may influence discomfort.

Auditory Cues

The localization and bearing of aural cues may be used by the simulator operator as indicants of aircraft (or automobile) behavior (e.g., slideslip, stall, velocity, ground effects) and orientation.

Ambient Environment

Temperature regulation and humidity control are other factors that may influence simulator sickness. Extremes in either may compound and accelerate any physiological uneasiness the operator may experience. Proper air flow, exchange, and mixing are critical within an enclosed simulator cab.

Simulator Cab Enclosure

The presence of a cab enclosure over the simulator cockpit has been alluded to as a potential contribu-

tor to operator discomfort and disorientation. A boxlike cab (1) was associated with heightened respiration rate and forehead perspiration in subjects. The basis for such a cab influence, if it indeed exists, is unclear. Subjects have reported a claustrophobic feeling in some simulators (22). Likewise, drivers are used to a "greenhouse" situation in an actual automobile; visual cues are apparent through the side and rear windows not just through the windshield as in the cabbed simulator. Without a definite visual frame of reference, observers may have difficulty in distinguishing the visual field from the "visual world." In that case, an artificial, illusory frame of reference, such as the lower horizontal edge of a roadway CRT display, may be adopted. Gibson (23) stressed that disequilibrium and discomfort may result from such an illusory reference that dominates visual perception.

Interactive Effects

From the preceding brief overview of simulator design characteristics with potential for influencing simulator sickness, it appears that the etiology of the problem is quite likely polygenic. Furthermore, there is evidence that many potential factors interact with each other in their effect, sometimes with one influence compounding the strength of another. For instance, a wide field-of-view in the simulator visual system has long been thought to be a provocative stimulus, but its influence is most certainly dependent on the level of detail inherent throughout the scene, the visually implied movement of display content, optometric and geometric distortion of the scene, and so forth. It can be hypothesized that there exists a range of "threshold" values for certain critical variables, which, if exceeded, may result in a high probability of sickness in operators. When two or more critical variables are combined, such as visual horizontal field-of-view and level of moving scene detail, the threshold values for each may in effect be lowered by the interaction. For example, an impoverished but very wide field-of-view display may not induce discomfort whereas a narrow field-of-view display may be quite provocative given enough scene detail conveying vection. The possibility of second-order and higher interactive effects exists for within-modality variables, such as various visual display factors, as well as for between-modality variables, such as the combination of physical motion cue scaling with visually presented motion scaling.

The examination of main effects alone may not provide a full explanation of the cause of simulator sickness. This dictates that laboratory investigations of design characteristics address factorial combinations of those variables with potential for interaction and strict control of other variables. On the other hand, the potential for interaction among variables can lead to factorial designs of unwieldy size, so the use of efficient experimental data collection strategies, such as central-composite designs, is prudent.

SUGGESTIONS FOR A FACILITY FOR SIMULATOR SICKNESS STUDY

One feasible approach to the study of simulator sickness is to examine it experimentally using a framework of independent variables, dependent variables, and appropriate statistical analyses. For such an approach to bear fruit, an appropriate ex-

perimental simulator facility in which carefully controlled experiments can be conducted is needed.

One possibility is to modify and use one or more existing simulators in which specific sets of independent variables could be examined. A research team would move into an existing facility for a period of time, prepare the facility, conduct a specific group of experiments, and then move on to another simulator facility. Funding, facility availability, time away from home for the researchers, lack of consistency of experimental situations, and lack of familiarity with the operating details (hardware and software) of the facilities are some of the major difficulties that would be encountered in this approach. Furthermore, most current facilities exist solely because of their training mission and may not be adaptable to, or available for, research use.

Another approach to the experimental examination of simulator sickness is the development of a dedicated facility. This facility should be designed so that the largest possible range and number of independent variables can be examined with provision for adaptation for study of additional variables that may surface as simulator technology changes.

The largest drawback to the development of an independent facility to study simulator sickness is probably its cost. It is no secret that a high-quality vehicle simulator to be used for training usually represents an initial seven-figure capital investment. Costs for a research facility could be expected to be comparable. Although cockpit or cab instrumentation might not have to be as complex as in a training facility (because the equipment fidelity is more critical for procedures training than for research), the motion base, visual scene generation system, and computational support system must be at least as complex and probably more so. As stated previously, there is a theory that simulator sickness occurs because the cues that the subjects receive are not the same as those in the corresponding real vehicle. In the simulator the cues are approximations of those experienced in the actual vehicle, and the approximations may constitute the causes of simulator sickness.

This is a simplistic point of view, but it does shed light on the design of a research facility for the study of simulator sickness. It follows from this notion that the best design of a facility is one in which the approximations are as small as possible. For instance, suppose the research simulator is designed such that overall minimum delay in visual presentation due to computational limitations is 150 msec. Under such conditions, the independent variable of visual delay is limited on the low end to 150 msec. Although longer delays can be obtained through software modifications, shorter delays cannot, which greatly limits the ability to study the effects of delay that would be a high research priority. Another example involves display field-of-view. The effects of wide viewing angles compared with narrower ones cannot be studied unless the wide viewing angles are available in the research simulator. Viewing angles can always be made narrower by means of opaque shading devices or other optical means, but they cannot be made wider without the addition of substantial amounts of hardware. The point is that the simulation facility must be carefully designed to allow the greatest possible range of manipulation within important independent variables. As a result the subsystems of the simulator must push the state of the art of simulator design.

The major elements of vehicular simulators that are believed to contribute to simulator sickness have been previously described. These are briefly summarized in the following list:

1. Visual System Factors
 - Display type (CGI, TV-model board, motion-picture projection, point-source projection)
 - Field-of-view
 - Scene detail level
 - Visually implied motion (degree of freedom, phase, gain, texturing, progression, vection)
 - Dynamic imaging (smear, swimming, flicker, aliasing, priority, double-imaging)
 - Optometric distortions (off-axis viewing, appropriate focal length and collimation, infinity cues, spherical aberration)
 - Design parameters (luminance, contrast ratio, modulation transfer function, resolution)
2. Motion System Factors
 - Fixed versus moving base
 - Degrees of freedom
 - Excursion and acceleration envelope
 - Frequency bandwidth capability
 - Phasing and gain factors
 - Washout parameters and illusory techniques
 - Anomalous cues (e.g., tilt to simulate linear acceleration)
 - Spectral characteristics [i.e., true motion sickness may result from problematic resonant frequencies (e.g., 0.2 to 0.4 Hz)]
 - Inappropriate cues (hydraulic reversal bump, shudder, stiction effects)
 - Enhancement cuing (vibration, buffet, g-seat, g-suit, restraint tensioning, helmet loading, display dimming, g-dependent control loading)
3. Dynamic Control Loop Factors
 - System lags and delays (transport, exponential and second-order lag, phasing between visual and motion update)
 - Vehicle modeling and computation (model validity and software fidelity, input and output sampling rates, scaling factors, resolution of variables during D/A, A/D conversions)
4. Manual Control Loading and Design Factors
 - Control damping (e.g., influencing pilot-induced oscillation)
 - Control resistance fidelity (elastic, breakout, stiction, sliding friction, viscous friction, inertia, etc.)
5. Cockpit Environment Factors
 - Auditory cue localization (orientation effect)
 - Enclosure, claustrophobic influences
 - Temperature and humidity regulation
 - Air exchange (avoidance of CO₂ accumulation)
 - External or distracting cues

Most of the factors listed can be grouped under three main hardware systems: the motion base, the visual display system, and the dynamics and computation system. There are other factors listed that affect simulator sickness, but they are more easily changed, controlled, or otherwise taken into account. For example, several cab enclosures for a simulator can be easily fabricated of lightweight material and used to examine the effects of enclosure on simulator sickness. Provided the motion base is designed to handle the incremental load, enclosure can be considered as a subsidiary element in the design process. The preliminary characteristics of the three main systems of the simulator are described in the following sections.

Motion Base

The main characteristics of the motion base are the number of degrees of freedom, the allowable excur-

sions in each degree, small signal frequency response, and large signal slew (excursion) rates. Additional characteristics involve aspects such as inherent delays, resonances, and excursion limit interactions.

It is important for the research simulator to have a full six-degree-of-freedom capability. Anything less than this would severely limit the range of problems that could be studied. It is quite likely that a synergistic system would be able to provide the necessary capabilities. The only other alternative is a cascade system, which is likely to require additional expense and design effort and also has inherent weight disadvantages.

State-of-the-art characteristics of a synergistic system include those in the following list:

1. Main Characteristics

- * Excursion for each angular degree of freedom: ± 35 degrees

- * Acceleration for each angular degree of freedom: 200 degrees/sec²

- * Excursion for each translational degree of freedom: ± 36 in.

- * Acceleration for each translational degree of freedom: 0.8 g incremental

2. Additional Characteristics

- * Frequency response bandwidth (3 db) for each axis for a peak-to-peak input amplitude that is 10 percent of full (peak-to-peak) excursion range: 2.5 Hz

- * Phase response bandwidth (45 degrees) for the input signal: 2.5 Hz

- * Response to a step for each axis [step response to be 5 percent of full (peak-to-peak) excursion range]

- a. Type of response: first order (single time constant in waveshape)

- b. Rise time (0 to 90 percent): 0.2 sec

- * Compensation (first seven characteristics to be met without compensation): first-order pre-filter, matched to compensate for closed-loop time constant

The specifications are similar to those already available (11) and should be adequate for a research facility. The additional specifications in the list would be necessary, however, to ensure that full advantage could be taken of the synergistic motion base. These specifications are probably also within the present state of the art. The closed-loop control of each axis should have a closed-loop frequency response that is similar to a first-order lag. The rise time is specified for small input excursions where "handling" aspects are most important. This rise time is faster than that of most degrees of freedom of most vehicles. In addition, by specifying a first-order lag, inertial effects are indirectly taken into account. Compensation is also specified so that any closed-loop lag is compensated by a pre-filter.

An important associated aspect of the motion base is the mass it must move. The greater the "payload" the more powerful the motion base must be and the higher the cost becomes.

Display System

As is the case with the motion base, there is a major choice that must be made between two competing display configurations. One of these is a real image projection CRT system and the other is a virtual image (standard-viewing) CRT system. The projection system would use a large screen that can be held

stationary or attached to the motion platform. This type of system requires a great deal of maintenance and has a focal distance that is nearly fixed. As a result, focal distance is not adjustable as an independent variable.

There is a common misconception that projection systems produce a larger field-of-view than virtual image systems. This is simply not true. One channel of a projection system with an 8-ft-wide screen located 10 ft away from a viewer produces a 44-degree horizontal field-of-view. For a virtual image system with a 24-in.-wide aperture located 28 in. away from the viewer, the horizontal field of view is 46 degrees. Thus there is really no field-of-view advantage for projection systems. In terms of display luminance and luminance contrast ratios, the projection system is at a distinct disadvantage. Extremely high accelerating potentials must be used to achieve minimally acceptable screen luminance. Under such conditions, projection CRT tube life is likely to be short, and characteristics are likely to change with tube age. Finally, projection optics tend to reduce the image resolution more than virtual image optics. This is because the optics must gather as much light as possible from the object surface of the projection CRT and project it in focus onto the screen. In other words, the light-gathering (aperture) capability competes with the resolution (focus) capability.

Usually, projection systems are used where images must be superimposed, for example, in air combat maneuvering simulators where a target aircraft is superimposed on a surrounding sky and ground background scene. They are also used where multiple crew members must view the same image. These capabilities, however, do not appear to be particularly important for the study of simulator sickness. Therefore it can be concluded that the virtual image CRT system would be the better choice for examination of simulator sickness.

As mentioned earlier, the virtual image display system should have a wide field-of-view so that this variable can be experimentally investigated. Probably the best arrangement would be a four-channel system, with each channel having a 37-degree vertical by 50-degree horizontal field-of-view. To allow for some eye position change, an overlap of 3 degrees on each edge should be used, yielding 44 degrees of horizontal field-of-view per channel for a total of 176 degrees. The major characteristics of each channel are given in the following list:

1. Optics

- * Folded path reflective, with virtual image adjustable from 8 ft to infinity

- * Field-of-view should be adjustable by 10-degree horizontal increments by insertable shades at the aperture

2. CRTs

- * Shadow-mask color type with 750 vertical by 1,000 to 1,200 horizontal addressable pixels

- * Refresh rate: 60 Hz for full picture with 2:1 interlace (120 Hz for half picture)

- * Persistence: matched to 60-Hz refresh rate

- * Luminance: 60 candelas/m² (at aperture)

- * Luminance contrast ratio: 100:1 (at aperture)

In terms of the optics to be used, the probable choice is reflective (spherical mirror) infinity optics in a folded optical path. The disadvantage associated with refractive lenses is that they become bulky (thick) for the set of optical properties required or fresnel lenses, with their attendant diffraction at the edges of the rulings, must be used.

An important aspect of the optics is the apparent

distance of the image from the subject's eyes. As indicated, a projection system would require that the image distance be held fixed. Reflective optics, on the other hand, have the potential advantage of allowing adjustment of the apparent image distance. This can be accomplished by moving the object surface (the CRT in this case) inward or outward a short distance. Although it is true that these position shifts also cause a change in image size, the change is relatively small and can probably be compensated computationally in the scene. Thus reflective optics allow apparent image distance to be treated as an independent variable. The desired range of adjustment would be 8 ft to infinity, as previously indicated.

Because field-of-view is an important independent variable in the study of simulator sickness, it should be made adjustable over a wide range. This could be easily accomplished by using shades that allow decreasing widths of field-of-view in 10-degree increments.

The CRTs to be used in the visual system should be such that they allow a minimum of 1,000 addressable points (pixels) horizontally by 750 vertically. Actually 1,200 points horizontally would be better, if attainable, because of cropping. Each addressable point should have a range of color, as in a high-quality color CRT.

The refresh rate (scan rate) of the CRTs should be 60 Hz, that is, double the rate normally associated with standard CRTs. The normal mode of address should be interlaced to further reduce flicker. Thus a "half" picture would be produced every 120th of a second. The reason for using this higher scan rate is to ensure that the presented image is above the flicker threshold for most individuals. There is a possibility that flicker may affect simulator sickness, and, therefore, for purposes of comparison, a high scan rate must be available. Apparent scan rates can then be lowered in submultiples by software to determine the effects of flicker.

As indicated earlier, one major advantage associated with CRTs viewed through reflective optics is that they can produce relatively high luminance levels. It has been observed that simulators capable of high brightness have a greater tendency to induce uneasiness. Therefore, to study the effect of brightness, the obtainable luminance should be relatively high, perhaps a minimum of 60 candelas/m² at the aperture. This is a relatively high value and would only be used part of the time to study effects of high screen brightness.

Similarly, high contrast may have an effect on simulator uneasiness. To achieve high contrast, say 100:1, it is first necessary to have high luminance. Thus the specified contrast ratio will only be achievable if the brightness specification is met first. Contrast ratio is important in the study of "flashbacks" and other aftereffects of simulator uneasiness. Furthermore, brightness, contrast, and flicker may interact to create uneasiness.

The combination of high luminance and high contrast ratio can be more easily achieved using refractive optics. This is because refractive optics have only a lens loss, whereas reflective optics have losses created by half-silvered mirrors, used first in reflection and then in transmission. Although the recommended design here is reflective, it may become necessary after a detailed design process to specify refractive optics in order to meet the luminance and luminance contrast ratio specification.

Emphasis in this section has been on optics and associated CRTs. Scenes to be presented on the CRTs will be discussed in the next section. However, before leaving the topic of displays, it is important to discuss the drive electronics briefly. In partic-

ular, these electronics must be such that they do not compromise the resolution of the scene; that is, they must allow the pixel elements to be individually addressable in sequence and must perform the digital-to-analog conversions accurately and in such a way that the digital video data received are faithfully transformed to color pixel levels at the CRT face.

Dynamics and Computation System

The problems associated with computation systems, resulting in dynamic inaccuracies, are best viewed from a historical point of view. As simulators first began to be developed, the primary method of computation was by means of electronic analog computers. Because they were parallel devices, these computers had the advantage of providing dynamically accurate representations of the vehicle equations of motion. They could solve differential equations accurately, without any problems with delays or unwanted lags. However, these computers were temperamental, required point-to-point wiring, and had to be carefully amplitude scaled to avoid unacceptable inaccuracies. Furthermore, they were limited in versatility because they had very limited storage capability and because accuracy was fixed at about 0.5 percent of full scale. Because of these limitations, simulator manufacturers were anxious to move toward digital computer technology as soon as it was feasible to do so.

Digital computation from the outset has been performed serially. Although there is fundamentally no reason why parallel digital computation could not have been developed, the tradition of digital computers has been and remains to perform computations serially.

Because digital computers are serial devices, they introduce delays of some magnitude in every type of computation performed. High-speed machines can perform simple computations rapidly but not instantaneously. The more complex the computation and the slower the speed of the machine, the longer the computation time. In simulation work the basic computational process involves sampling inputs, performing computations on the inputs, and then providing outputs or commands for the simulator hardware. In display generation the process also includes mass retrieval of information from storage, operations on the information, and mass transfer to display buffers. Regardless of the specific tasks involved, delays occur that must be considered in simulator design. Insofar as a simulator to study motion sickness is concerned, the delays must be sufficiently short that they can be considered negligible. Otherwise, the effects of delays cannot be studied.

The following table gives a proposed delay "budget" for the dynamics and computation system of the simulator.

<u>Process</u>	<u>Allowable Delay (msec)</u>
Input vector sampling and computation of vehicle state	2
Retrieval of scene information from storage	4
Processing of scene information	6
Outputting of scene information to display buffer	3
Update of display visual output	10
Total	25

This budget was developed using the idea that total computational delay must not exceed 25 msec from control input to system response. This delay is the additional delay encountered as a result of serial

computation in digital systems and does not of course include the lags that are normally associated with vehicle dynamics (as a result of the equations of motion).

Most researchers involved in manual control system design would agree that a total loop delay of 25 msec would not appreciably affect system performance or handling. However, they would also indicate that delays greater than 25 msec would probably affect performance. Therefore maximum allowable delay should not be greater than 25 msec.

In examining the table, it should be noted that the motion base has already been specified as compensated so that it does not introduce delays or lags. In any case, when the vehicle state has been computed, it can be outputted to a subsidiary processor that can handle coordinate transformation and washout. In other words, major delays are not expected to occur in the motion-generating system. Instead, they are expected to occur in the visual display system.

The most difficult problem is the retrieval, processing, outputting, and displaying of the visual information. To give some idea of the magnitude of the problem, it need only be recognized that, for color, 2.7 megabytes of data are necessary to complete one full picture for 1/60 sec (750 x 1,200 x 3 data points). Manipulating these data quickly and displaying them with only small delays represent a state-of-the-art design problem that is only now becoming possible. Most visual systems already in existence have delays that approach 100 msec, which are too long for research involving simulator sickness. In any case, regardless of the computational techniques used, total delays must not exceed 25 msec. If necessary, parallel processing can be used to bring delay times down to acceptable levels.

Other important aspects of the dynamics and computation system include the accuracy of computations and software versatility. There is a tendency to think of these machines as absolutely accurate; but, indeed, they are not. Input sampling and quantization introduce small errors, as does word size within the machine. Computational algorithms can also introduce errors, particularly when truncated. Therefore every effort should be made to maintain accuracy throughout the computational process.

The versatility of the software is as important in a simulator designed for study of simulator sickness as it is in any other system. In particular, the range of manipulation of variables should be substantial. For example, scene clutter or density must be specifiable so that it can be studied as an independent variable. However, because of the range of the independent variables, particular care must be taken to ensure that the software is user friendly and that programming time can be held within reasonable limits for new research problems.

CONCLUDING REMARKS

It appears that the motion base proposed for such a research simulator is within the present state of the art and that the major considerations involve getting the system specified correctly while holding payload mass to a reasonable level.

The use of folded reflective optics for the display system appears relatively straightforward and versatile, but the CRTs may be at the edge of the state of the art. In particular, doubling the usual 60-Hz scan rate while maintaining a full 750 by 1,200 pixel color picture in each of four channels may cause technical difficulty. By using four channels in the display system, a field-of-view approaching 180 degrees would be obtainable.

The dynamics and computation system represents a design problem that is again at the edge of the state of the art. In particular, total throughput delays from control inputs to visual scene update must not exceed 25 msec. Current scene generation equipment usually has delays of from 100 to 150 msec. It is likely that parallel computation techniques will be necessary to meet the necessary specification on throughput delays.

There is no question that many important aspects of simulator design have not been covered. However, these other aspects are probably not as critical as the ones presented and in general do not require pushing the state of the art. For example, sound generation can be handled without any particular problem. Furthermore, if found unsatisfactory, modifications or retrofits could probably easily be made. The systems emphasized in the preceding section, on the other hand, could not be easily retrofitted.

Finally, the authors wish to emphasize that simulator sickness is a problem that can be studied scientifically by the usual tools of behavioral research. In particular, it can be studied in a properly designed simulator with well-defined independent variables, dependent variables, and the usual accepted experimental design methods.

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