SIMULATOR SYSTEMS INTEGRATION

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INTEGRATION AND SYNCHRONIZATION AS PERCEPTUAL ISSUES

These notes address the issues of cue integration and synchronization in terms of their effects on human sensation, perception and performance. Before exploring these issues, let us define a few terms. Sensation is usually defined as the process of converting or transducing physical energy into neural impulses. The energies being transformed may arise externally (e.g., light quanta) or from within the person (e.g., feedback from joint motion). Perception is typically defined as the organization of these stimuli into meaningful patterns. In the vast majority of cases the resulting percept is stable and in direct correspondence with the state of the observer and the environment. Perceptual theorists have argued that stability is maintained because the critical sensory elements do not vary from situation to situation.

This leads to the integration and synchronization problem. What happens when all of the critical elements are not present? What happens when the critical sensory elements are not presented in the correct temporal sequence? As suggested above, the stability of the perceptual process will be affected. The observed effects may range from a complete absence of the desired percept, to a delayed or weak percept, or in extreme cases to severe psychological and physical discomfort. This is not meant to imply that successful simulation requires reproduction of all the physical energies produced by actual flight. Rather, most perceptual theorists maintain that the critical sensory events are some subset of the real-world stimuli, or are some higher-order pattern or relationship among the stimuli. Regardless, the key elements must be included (integration) and the critical spatial and temporal relationships must be maintained (synchronization).

The term cue is more troublesome to define, because of its wide variety of uses. Some use the term to mean a stimulus or stimuli which elicit(s) a percept. Others use the term to mean a stimulus or stimuli which elicit(s) a specific action, or provides specific information. However, all of these uses are an attempt to name the critical stimulus elements or patterns that must be included in the simulation. While the precise definitions of the terms are not critical, the sensory and perceptual processes the terms describe are. Human perception is a highly tuned and integrated process that has evolved and developed to respond to specific patterns when certain events occur in the environment. When these relationships are violated, perception is degraded.

The remainder of this paper provides an overview of the integration and synchronization issues in flight simulation. Sources of integration and synchronization errors are identified. Typical effects of these errors on pilot training and performance are discussed. Finally, means available to minimize the errors are reviewed.

SIMULATOR CUE INTEGRATION

Errors of Inclusion and Omission

There are basically two types of errors that may be made in integrating the cues in a simulator. Spurious cues may be included, or necessary cues may be omitted (Boff and Martin, 1980). Examples of errors of inclusion are:

(1) Highly saturated colors in computer generated images (CGI).
(2) Level of detail switching, i.e. the lack of smooth movement of objects in and out of view.
(3) Overly sharp surface definition and delimitation, i.e. highly visible edges and polygon components in complex scene elements.
(4) Visible raster patterns in cathode ray tube (CRT) displays.
(5) Hydraulic bump in six-post motion bases.
(6) Spurious rate cues during motion washout.

Examples of errors of omission are:

(1) Textureless CGI surfaces.
(2) Limited scene content, i.e. current image generators are capable of producing only a fraction of the edges that would appear in a real-world scene.
(3) Limited peripheral coverage in visual displays.
(4) Limited visual display resolution.
(5) Minimal simulation of aerial perspective effects, i.e. changes in the contrast and hue of objects, produced by the atmosphere.
(6) Minimal simulation of directional illumination effects, i.e. shadowing.
(7) Absence of g-forces and sustained motion.

The above lists are not exhaustive, nor are the examples of equal importance in terms of their effects on pilot performance. Many are being eliminated by current technological developments. In some cases the examples would not constitute integration errors. Limited peripheral visual coverage, for instance, would only constitute an error if information in the periphery was necessary to perform a specific flight task, or if there was insufficient peripheral imagery to maintain spatial orientation.

Augmentation

Display augmentation may be defined as any addition to a simulator, which would not occur in actual flight, designed to facilitate the acquisition of information. Augmentation includes the addition of artificial features and the enhancement of representational features. Lintern and Roscoe (1980) provide a review of the research in this area. They show that appropriate application of augmentation, while formally producing errors of inclusion and omission, can enhance performance and training.

One study, which evaluated the training of landing approach skills, used the display shown in Figure 1. Student pilots learned to make landing approaches with one of three simulator conditions: (1) A runway outline display, (2) A runway outline plus the inverted L symbols, shown in Figure 1, which indicate the correct glide slope, and (3) A runway outline with the glide slope markers tuned on only when the student's glide slope error exceeded some criterion value. Condition (3) was termed the adaptive condition and was designed to provide the augmenting cues without allowing the trainee to become dependent on them. After training, all groups were transferred to the runway outline condition. The augmenting cue significantly improved transfer of training, but only under the adaptive condition.

More recent experiments (Lintern et al., 1987; Lintern et al., 1990a, 1990b) continue to show that augmentation can be a potent instructional aid. The studies also suggest that the effective use of augmentation requires an in-depth analysis of the actual flight task and the information or relationships the augmentation is designed to enhance. No simple rules can be provided concerning optimum designs, expected benefits, or the importance of selecting adaptive versus constant augmentation (Lintern and Koonce, 1992).

Simulator Fidelity Research Summary

The literature on simulator cue integration includes all of the simulator training effectiveness and fidelity research. Training effectiveness research generally evaluates a simulator's capability to train specific tasks. The fidelity research evaluates the impact of various simulator features (e.g. motion, field of view) on pilot performance and training. Detailed reviews of this literature have been conducted by others (Hays and Singer, 1988; Semple et al., 1981) and are summarized here by addressing three questions: (1) What does the training effectiveness research tell us about cue integration requirements? (2) What cueing features are known to improve pilot performance in simulators? (3) What features are known to enhance transfer of training?

Training Effectiveness Research

Orlansky and String (1977) reviewed 33 studies conducted between 1939 and 1977, which showed that flight simulators are effective training devices. These experiments typically involved two groups of subjects; one group was trained on some specific task(s) in a simulator and the other group was given no simulator training. Then both groups were "transferred" to the aircraft to determine if there was any difference in their ability to learn or perform the tasks in the actual flight environment. One of the measures used to compare results across studies was the transfer effectiveness ratio. This metric indicates whether or not simulator hours save training time in the aircraft. Across the 33 studies, the median value observed for this measure was 0.45, which indicates that almost one-half hour of flight time was saved for each hour in the simulator. Given the much lower cost of simulator hours, this value represents a significant cost and training benefit. The authors noted that simulators appear to be most effective for training tasks that involve precise procedures. Unfortunately, Orlansky and String were not able to identify any differences in training effectiveness due to specific simulator features.

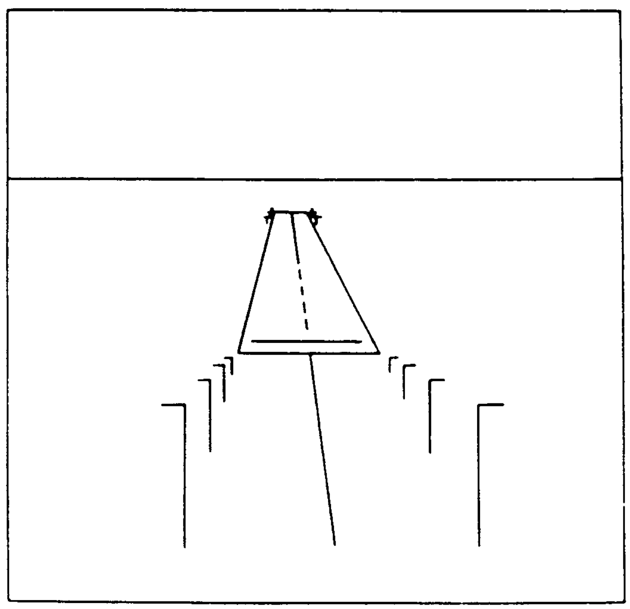


FIGURE 1. LANDING APPROACH DISPLAY WITH GLIDE SLOPE CUE.
(From Lintern and Roscoe, 1980)

In 1981, Semple et al. reviewed the available training effectiveness research from the standpoint of simulator design. They reviewed 21 studies with visually equipped simulators and concluded that training in such devices will almost certainly transfer to the aircraft for approach and landing, and contact flight tasks. They also concluded that transfer is likely to be observed for stall recovery, air refueling, formation flight, and air-to-ground weapon delivery. Semple et al. reached the following conclusions concerning simulator design features

(1) Visually-equipped simulators are effective training devices, but the transfer-of-training research offers little guidance on how to design visual systems to maximize training effectiveness. No improvement in transfer of training has been demonstrated for high fidelity in the following areas: color in the visual scene, virtual- versus real-image displays, high resolution displays, large numbers of CIG edges, wide field of view, specific scene content, and scene texture. This does not mean that these features are not required, just that their use cannot be justified on the basis of training effectiveness data.

(2) Flight control system fidelity (aircraft dynamics, control loading, etc.) is highly important for user acceptance, but there is no evidence that high fidelity enhances transfer of training.

(3) No training benefit has been demonstrated for the inclusion of motion and force cueing devices.

These conclusions are supported by a recent meta-analytic review of the training literature by Jacobs et al. (1990). Meta-analysis is a statistical procedure for determining whether experimental manipulations (simulator characteristics in this case) have consistent effects across multiple studies. While the analysis showed reliable training benefits for fixed-wing simulators, no specific simulator features were found to enhance transfer. No conclusion could be reached for rotary-wing simulators since there were so few applicable studies. For fixed-wing simulators, transfer was stronger for tasks such as takeoff, approach and landing, and for training, which used proficiency-based methods, as opposed to procedures which allocated fixed amounts of time to each pilot.

The training effectiveness reviews point out trends that have been stable across a number of research studies. One can also turn to specific studies (often not replicated) which suggest that positive transfer will be observed for air combat maneuvers (Jenkins, 1982), helicopter maneuvers (Holman, 1979; Bickley 1980; McDaniel, 1983), for approach and landing (Lintern et al., 1990a), and for air-to-ground weapon delivery (Lintern et al., 1989). The results of the transfer-of-training studies are summarized graphically in Figure 2. Clearly, simulators have been shown to be effective training devices for a large number of flight tasks. However, with the exception of Lintern et al. (1989) and McDaniel et al. (1983), these studies did not systematically manipulate simulator visual or motion cueing features. As a result, they offer little guidance to the simulator designer on the cue integration issue.

Performance Research

More insight is provided by research, which has evaluated the effects of various design features on pilot performance in simulators. The results of these studies are summarized in Figure 3. A number of simulator display characteristics have been shown to enhance pilot performance in the simulator. This does not guarantee that the benefit will transfer to actual flight. Nevertheless, if one is using a simulator for engineering design, or for experimentation, this research provides a basis for selecting specific simulator features. Gray (1982) demonstrated that a wide field-of-view (FOV) visual display improved pilot control of the A-10 aircraft in a simulated manual reversion mode, a degraded flight control condition. Wide FOV displays have also been shown to enhance performance of basic flight maneuvers (Irish et al., 1977; Irish and Buckland, 1978), of carrier landings (Westra et al., 1982), and of helicopter shipboard landings (Westra et al., 1987). The increasing interest in helmet-mounted displays is also generating research on the effects of FOV in this environment. Wells and Osgood (1991) investigated FOV size and the performance of a simulated air-to-ground night attack. Circular FOV of 20, 30, 40, 60, and 80 degrees were evaluated. The helmet display provided a field of regard limited only by the cockpit structure. While increasing the FOV did not improve bombing accuracy, pilots did acquire targets in a significantly shorter period of time with the 40, 60 and 80 degree FOV, than with the 20 and 30 degree conditions.

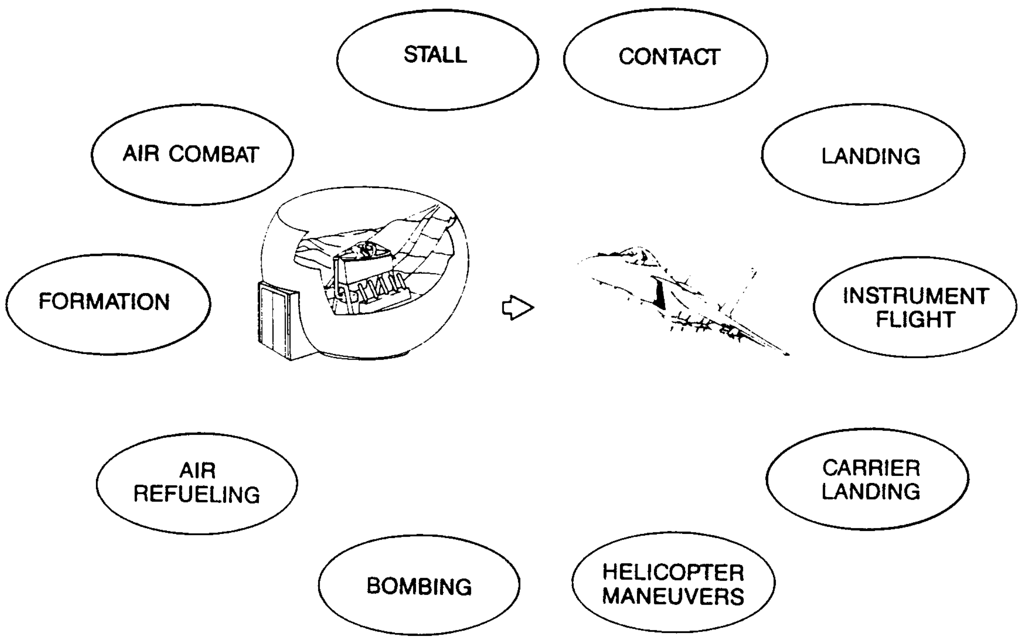


FIGURE 2. FLIGHT TASKS WHICH HAVE SHOWN POSITIVE TRANSFER OF TRAINING FROM THE SIMULATOR TO THE AIRCRAFT.

Buckland, Monroe, and Mehrer (1980) demonstrated improved control of landing vertical velocity, and Buckland (1980) observed improved terrain following accuracy when higher resolution texture patterns were included in the visual scene. In the same study of terrain following performance, Buckland also found that the presence of 3-D objects allowed pilots to significantly decrease aircraft altitude when cresting hills. In a related study Kleiss, Curry, and

Hubbard (1988) found that the density of 3-D objects was much more important than the type of object in detecting changes in altitude.

The higher scene detail provided in day versus dusk/night CIG scenes has been shown to improve both ground and carrier landing performance (Buckland, Monroe, and Mehrer, 1980; Westra et al., 1982) and bombing accuracy (Lintern et al., 1989). Increased scene detail has also been shown to improve helicopter shipboard landings (Westra et al., 1987) and air-to-ground weapon delivery (Lintern et al., 1987).

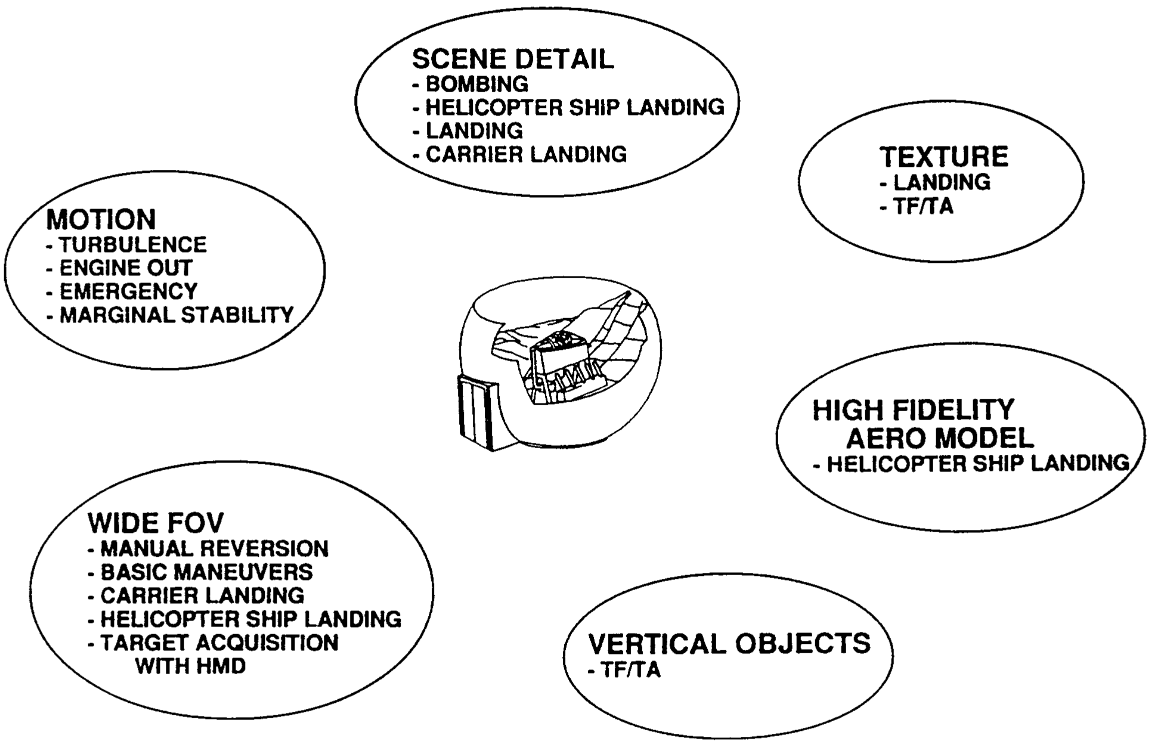


FIGURE 3. DESIGN FEATURES WHICH HAVE IMPROVED PILOT PERFORMANCE IN THE SIMULATOR.

Platform motion typically improves pilot performance in cases where unexpected external forces (disturbances) are acting on the aircraft. Caro (1979) provides numerous examples of improved aircraft control in turbulence when motion cues are provided. Hosman and van der Vaart (1981) also demonstrated that peripheral visual cues do not produce the same benefits as motion cueing for turbulence regulation. Platform motion has been shown to improve pilot response to engine-out conditions in multi-engine aircraft (DeBerg, McFarland, and Showalter, 1976) and for the execution of other emergency procedures (Semple et al., 1981). Finally, motion cues improve the control of marginally stable vehicles such a VTOL aircraft, or helicopters in certain maneuver conditions (Caro, 1979).

One recent experiment demonstrated a performance benefit for improving the fidelity of aerodynamic models. Westra et al. (1987) found that an updated model, designed to produce a more accurate simulation of helicopter vertical responses to collective inputs, improved vertical control performance in a shipboard-landing task.

The in-simulator performance studies offer some guidance to the simulator designer and user. The results suggest, for example, that surface texture is primarily important for precision operations at low altitude. Vertical objects appear to be very useful altitude cues and their density is an important factor. Simulation of pilot induced aircraft motion is unlikely to enhance performance; the primary benefit of motion cueing is alerting the pilot to unexpected disturbances. A careful review of these studies can lead to other useful conclusions. However, the fact that performance is improved in the simulator is no guarantee that improved transfer will be observed in the aircraft. A clear demonstration of this fact is the series of air-to-ground weapon delivery studies (Lintern et al., 1987 and Lintern et al., 1989) and the carrier landing experiments (Westra et al., 1982; Westra, 1982; and Westra et al., 1986) conducted at the Naval Training Systems Center. In both cases simulator features such as wide field of view and scene detail enhanced in-simulator performance, improved quasi-transfer of training from one simulator condition to another, but did not enhance transfer of training to the aircraft. Because of this discontinuity between performance and training, the user interested primarily in training benefits must use the above results with caution.

Transfer-of-Training Research

Figure 4 summarizes the very limited number of cases in which specific simulator features have been shown to improve transfer of training. Two potential transfer tests are shown there. The first is termed quasi-transfer and involves a within-simulator test. Two groups of subjects are trained under different fidelity levels of some feature, for example low versus high scene detail. After training, both groups are "transferred" to the high scene detail condition within the simulator, to determine if there is any differential benefit to the two training conditions. The second type of transfer is termed true transfer. The training procedure is identical to the quasi-transfer paradigm. The difference is that the subjects are transferred to the actual aircraft for testing.

The results shown in Figure 4 are meager, to say the least. Higher scene detail has improved quasi-transfer in one study of air-to-ground weapon delivery (Lintern et al., 1987). Lintern et al. (1990b) found better quasi-transfer with a pictorial display than a symbolic one on a landing task. Lintern and Koonce (1992) found better quasi-transfer with a moderate detail pictorial scene than a low detail pictorial scene on a landing task. Both of these studies also observed better quasi-transfer following training with aircraft roll dynamics that exactly matched, or were more sluggish than, those in the transfer condition. Training with dynamics that were more responsive than those in the transfer condition led to degraded transfer of training. Finally, Westra (1982) observed a very short duration effect of field of view and scene detail on carrier landing quasi-transfer.

To date, I am aware of only one study, which demonstrated a true transfer advantage for any simulator feature. This is the work of McDaniel et al. (1983) which showed improved transfer with platform motion for three helicopter tasks: aircraft stabilization equipment off, free-stream recovery, and coupled hover. For all other tasks, motion actually degraded transfer. In contrast to this single study showing positive and negative motion effects, there are a host of experiments showing no effect of simulator motion on transfer of training (Lintern and McMillan, 1993).

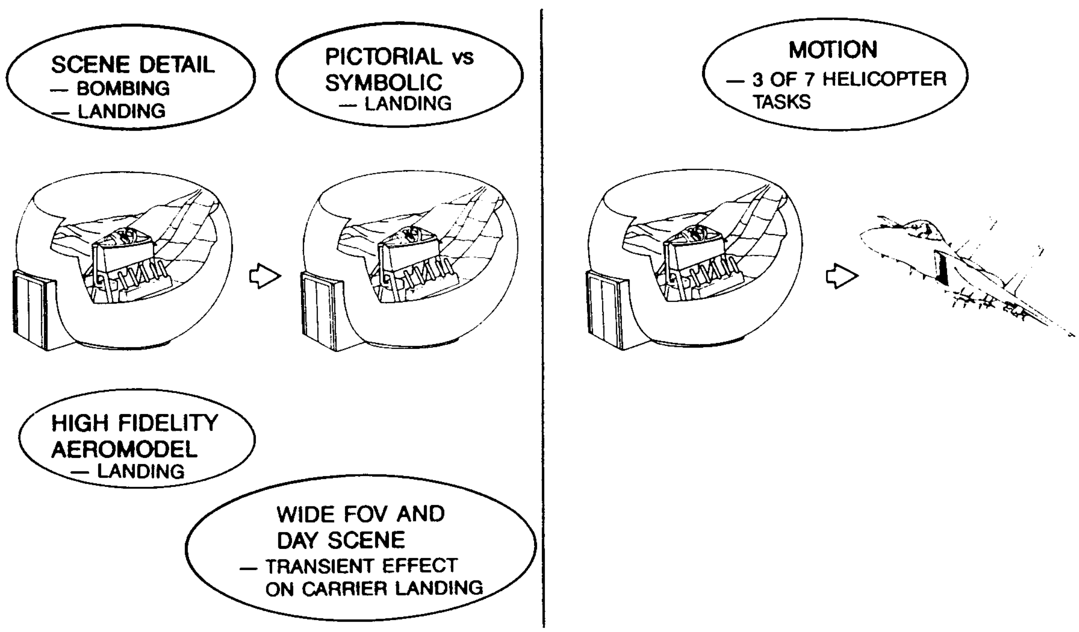


FIGURE 4. SIMULATOR DESIGN FEATURES WHICH HAVE ENHANCED TRANSFER OF TRAINING.

Clearly, the simulator cue integration research does not provide the guidance needed by simulator designers and users. The research does provide insights, trends, and suggestions, but not the solid evidence one needs for multi-million dollar design decisions. Until empirical answers are available, the designer must utilize task and cue analysis techniques, pilot opinion, and training specialists' judgments to guide the choice of simulator features. This issue is discussed in more detail at the end of this section.

Simulator Sickness

The most extreme effects of cue integration errors are probably seen in the phenomenon known as simulator sickness. Simulator sickness is that condition where pilots suffer physiological discomfort in the simulator, but not while flying the same maneuvers in the aircraft. Gower and Fowlkes (1989), in a study of sickness in the AH-1S helicopter simulator, found evidence supporting this definition. The pilots who experienced the most severe discomfort usually rated their symptoms as being worse than those they experience in the actual aircraft. Some pilots commented that the simulator was their first experience of motion sickness. In a comparison of pilot head movements in flight versus in a simulator, Hennessy et al. (1992) observed sickness in the simulator, but not in flight for the same maneuvers.

Typical symptoms include nausea, dizziness, spinning sensations, eyestrain, visual flashbacks, motor dyskinesia, confusion and drowsiness (Frank et al., 1983). Observable signs of simulator sickness may include pallor, cold sweating, and vomiting. Thus, simulator sickness is akin to motion sickness in flight, space, automobiles, and ships. Simulator sickness has been observed in pilots, co-pilots, and other crewmembers **in** flight simulators. In addition, it has been reported for drivers and passengers in automobile simulators (Casali and Wierwille, 1980). Early studies of flight simulator sickness are summarized in Table 1. As can be seen there, symptoms have occurred in helicopter, fighter, and patrol aircraft. Fixed- and moving-base simulators have been implicated with about equal frequency. In addition, all types of visual display systems have been involved, although the phenomenon seems to be more characteristic of wide field-of-view (FOV) displays. Percentages of aircrew members reporting symptoms have ranged from a low of about 10% (Frank, 1981), to a high of 88% in an air combat maneuvering trainer in which high accelerations were simulated (Kellogg, Castore, and Coward, 1980).

TABLE 1. SIMULATOR SICKNESS SUMMARY.

REPORT	DEVICE	INCIDENCE (%)	BASE	VISUAL TYPE	FOV(H × V)
HAVRON & BUTLER (1957)	2-FH-2 (H)	77	FIXED	PS	260 × 75
MILLER & GOODSON (1958, 1960)	2-FH-2 (H)	60 (I) 12 (S)	FIXED	PS	260 × 75
HARTMAN & HATSELL (1976)	SAAC (F)	52	MOVING	CIG	296 × 180
KELLOGG, CASTORE & COWARD (1980)	SAAC (F)	88	FIXED*	CIG	296 × 180
MONEY (1980)	CFF140FDS (P)	43	MOVING	T/N/CIG	48 × 36(?)***
MCGUINNESS, BOUWMAN, & FORBES (1981)	2E6 (F)	27	FIXED	T/PS CAM MOD	360 × 150
FRANK (1981)	2F112 (F)	10	FIXED	T/PS CAM MOD	360 × 150
FRANK (1981)	2F110 (P)	48	MOVING	T/N/CIG	120 × 36
CROSBY & KENNEDY (1982)	2F87 (P)	50	MOVING**	T/N/CIG	48 × 36***
FRANK & CROSBY (1982)	2F117 (H)	?	MOVING	CIG	175 × 50

* MOTION NOT USED IN STUDY
** MOTION OR LACK OF MOTION HAD NO EFFECT
*** ONE WINDOW
PS = POINT SOURCE
T = TWILIGHT
N = NIGHT
CIG = COMPUTER IMAGE GENERATION
CAM MOD = TARGET CAMERA MODEL
I = INSTRUCTORS
S = STUDENTS
H = HELICOPTER
F = FIGHTER
P = PATROL

Theory

Flight simulators present the trainee with new relationships among visual, vestibular and somatosensory stimuli. In a fixed-base simulator, for example, the visual cues may indicate that the aircraft is accelerating while the vestibular and somatosensory cues indicate constant velocity or no motion. The most popular theory argues that this constitutes a sensor-y conflict and that this conflict produces a range of perceptual problems. In severe cases, the sensory systems respond to this conflict with nausea and vomiting, similar to poisoning. In addition to conflict between sensory systems, there can be conflicting cues within a sensory system, or conflict between what one experiences in a simulator and what one expects to experience based on actual flight.

Some recent research provides support for the sensory conflict model. Conflict theory predicts that visually specified motion, in the absence of corroborating vestibular and somatosensory inputs, will produce illness. Hettinger et al. (1990) found a strong correlation between the occurrence of vection (the illusory sensation of self-motion) and the occurrence of simulator sickness. In their study, subjects passively viewed simulated flight through mountainous terrain. The flights involved maneuvers designed to be nauseogenic, and nonvisual motion cues were not provided. These results suggest that a problematic simulator will only produce sickness if the visual displays are compelling enough to produce illusory self-motion.

While sensory conflict is the most commonly accepted theory, it has many shortcomings. Foremost is the fact that the measurement of conflict -nay be impossible (Stoffregen and Riccio, 1991). For example, how does one measure the difference between the sensations of self-motion produced by the visual and nonvisual components of a simulator when both are active? Or how does one measure the difference between a pilot's expected sensations and those that he or she experiences in the simulator? Because of these measurement difficulties, there are apparent high-conflict situations, which produce little sickness, and low-conflict situations, which produce significant sickness.

A recent alternative to the sensory conflict theory addresses many of its shortcomings (Stoffregen and Riccio, 1991; Riccio and Stoffregen, 1991). In these articles, the authors develop a new theory of motion sickness, which also applies to the specific case of simulator sickness. Riccio and Stoffregen (1991) argue that pilots become sick in simulators "when they do not possess (or have not yet learned) strategies that are effective for the maintenance of postural stability." (Pg. 195) For example, pilots may make postural adjustments to the simulated aircraft motions. These adjustments will, however, be inappropriate for the actual motion and force environment of the simulator and may be destabilizing.

At first glance, this may seem like a restatement of the sensory conflict theory. There are, however, fundamental and important differences. First, postural instability can be quantified, unlike sensory conflict. Second, the new theory explicitly considers both pilot perception and action in making its predictions. For example, the theory suggests that passive restraints, or other techniques which minimize postural changes, will reduce simulator sickness. Conflict theory, which is based on sensory and perceptual mismatches, would not make this prediction. This theory may also account for findings such as the Hettinger et al. study (1990) discussed above. In that study, inappropriate postural adjustments would be much more likely when the subjects were experiencing strong vection.

Measurement of Simulator Sickness

Lane and Kennedy (1988) have developed and standardized a scale for the measurement of simulator sickness termed the "Simulator Sickness Questionnaire". (In some papers it is referred to as the "Simulator Side Effects Questionnaire".) This scale is based on previous motion sickness questionnaires and is the recommended instrument for use in quantifying simulator sickness problems. The work of Lane, Kennedy and their colleagues suggests that simulator sickness symptoms can be divided into three broad categories, which represent pilot responses to different simulator characteristics. The first category is termed Visuomotor and reflects eyestrain-related problems. The second is termed Nausea and reflects gastrointestinal stress. The third category is Disorientation and is related to vestibular disturbances such as dizziness and vertigo. The latter two symptom categories probably represent sickness of the type being addressed by the conflict and postural instability theories. The Visuomotor category may reflect problems with simulator visual displays, such as poor resolution and contrast, and may not be symptomatic of motion sickness.

Users interested in monitoring their simulators and/or in identifying pilots who are having significant problems should consider using the automated version of the "Simulator Sickness Questionnaire" (SSQ) developed by Kennedy et al. (1991) and implemented on a laptop computer. This software can be used for rapid evaluation of symptoms as pilots complete their simulator sessions. By tracking simulator sickness symptoms over time, the need for recalibration, syllabus changes, etc. may be identified. The authors show how the SSQ subscales may be used to suggest which simulator subsystems are likely to be causing the problems. The computerized version of the SSQ is termed BESS (Biomedical Evaluation and Systems-Engineering for Simulators; Fowlkes et al., 1990).

Contributing Factors

Pilot Variables. Individual differences are the largest factor in simulator sickness and account for about 20-40% of the variance. As is the case with true motion sickness, some individuals are simply more susceptible than others are. Kennedy et al. (1989) and Gower and Fowlkes (1989) found correlation between a previous history of motion sickness and the occurrence of sickness in the simulator. Experienced aviators seem to be much more susceptible to sickness than less experienced trainees (Crowley, 1987; McGuinness et al., 1981;

Miller and Goodson, 1960; Money, 1980). This may be due to the fact that experienced crew members have better established expectancies concerning the sensory patterns that should occur in flight, and are therefore more prone to a violation of these expectancies. Finally, it is believed that illness, hangover, and poor physical condition can potentiate the occurrence of simulator sickness.

Simulator Usage. How a simulator is used can play an important role in controlling simulator sickness. Initial simulator flights tend to be the most provocative, and significant adaptation is observed in later sessions (Crowley, 1987; Kennedy et al., 1987; Money, 1980). In addition, sickness is more likely with long simulator sessions, since the effects tend to build up over time (Sharkey and McCauley, 1991). It is also believed that increased scene content, particularly in the visual periphery, can contribute to simulator sickness. Finally, inappropriate use of simulator freeze and reset functions can increase symptoms. Suggestions to help manage these factors are summarized in a later section.

Simulator Equipment. A recent survey of ten US Navy flight simulators (Kennedy et al., 1989) sheds some light on simulator design factors that may contribute to sickness. The results of this survey are summarized in Tables 2 and 3. Table 2 provides a ranking of the simulators in terms of the incidence of Nausea symptoms such as stomach awareness, sweating, vomiting, and dizziness. Table 3 ranks the same simulators in terms of Visuomotor symptoms such as eyestrain, blurred vision, difficulty focusing, and headache. The motion sickness symptoms show the highest incidence for helicopter simulators with motion bases and wide field-of-view, multiple-CRT display systems. Eyestrain symptoms also seem to be associated with motion bases and multiple-CRT displays, but are about as common in fixed-wing simulators. In general, the lowest incidence of both symptom types seems to be associated with fixed-wing, fixed-base, dome simulators.

Based upon observations such as these, a number of visual display design factors are believed to contribute to the occurrence of simulator sickness. We have already mentioned the FOV of the visual display. This is reasonable, given the importance of peripheral vision in spatial orientation. Increased scene detail may also be a significant factor. In addition, it has been suggested that the multiple video raster orientations in mosaic or area-of-interest displays may be important. Multiple rasters may create apparent simultaneous motion in different directions on adjacent displays. Finally, factors such as poor resolution, flicker, optical distortions, and off-axis viewing have been implicated (McCauley, 1984). Unfortunately, there are no precise data with regard to any of these factors. They are only reasonable, suggested elements.

TABLE 2. CHARACTERISTICS OF SIMULATORS* THAT ELICIT MOTION SICKNESS-LIKE SYMPTOMS. (From Kennedy et al., 1989)

Aircraft	Simulator	Nausea	6 DOF Motion Base	FOV H/V (Degrees)	CRT/ Dome	Helo/ Fixed Wing	Image Generation/ Display Character
High Incidence							
SH-3H	2F64C	15.4%	Yes	130/30	CRT	Helo	Digital CGI/ calligraphic CRT
CH-53E	2F120	11.1%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
CH-46E	2F117	8.9%	Yes	175/50	CRT	Helo	Full raster scanned CGI/6500 color edges 6-window segmented virtual
Moderate Incidence							
CH-53D	2F121	7.8%	Yes	200/50	CRT	Helo	Digital CGI/ raster CRT
E-2C	2F110	5.5%	Yes	139/35	CRT	Fixed	Digital CGI/ Hybrid calligraphic-raster scan CRT
F/A-18	2E7	6.0%	No	360/145	Dome	Fixed	Digital CGI/ TV projectors
Low Incidence							
F/A-18	2F132	0.0%	No	48/32	Dome	Fixed	Calligraphic CGI/ dome projection
P3-C	2F87F	0.0%	Yes	48/36	CRT	Fixed	TV camera-model board Calligraphic D/N CGI
F-14A	2F112	0.0%	No	350/150	Dome	Fixed	TV camera-carrier model. Pt. Lt. Background 4 AOI Projectors
Total N = 1111							

* The 2E6 simulator was excluded because of the insufficient number of cases (N = 8).

Research with helmet-mounted displays does not suggest that they produce a higher incidence of simulator sickness than other wide FOV systems (Kruk, 1992; Barrette et al., 1990). While deliberate degradation of parameters such as scene update rate, head tracker update rate, and head position prediction was very provocative, operation within specifications produced only about 10% sickness incidence in studies at the Air Force Human Resources Laboratory.

Motion base design and performance characteristics are believed to play a role. Limited excursion, velocity, and acceleration envelopes dictate that inappropriate cueing must occur, at least at the level of sensation. In addition, washout and other drive algorithm characteristics can produce a wide range of amplitude and phase distortions. Nevertheless, many of the simulator sickness surveys and anecdotal reports show no clear motion/no-motion effect (Casali, 1986). In a recent experimental evaluation, Sharkey and McCauley (1992) found no difference in the occurrence of simulator sickness in the NASA Vertical Motion Simulator when the motion base was tuned on or off. The study used Army helicopter pilots flying saw-tooth and s-turn maneuvers that had generated a high incidence of sickness in previous studies. In this study the pilots showed sickness symptoms in both the motion and no-motion conditions.

TABLE 3. CHARACTERISTICS OF SIMULATORS* THAT ELICIT EYESTRAIN RELATED SYMPTOMS. (From Kennedy et al., 1989)

Aircraft	Simulator	Headache	6 DOF Motion Base	FOV H/V	CRT/ Dome	Helo/ Fixed Wing	Image Generation/ Display Character
High Incidence							
SH-3	2F64C	30.5%	Yes	130/30	CRT	Helo	Digital CGI/ Calligraphic CRT
E-2C	2F110	20.4%	Yes	130/35	CRT	Fixed	Digital CGI/ Hybrid calligraphic-raster scan CRT
P-3C	2F87F	20.3%	Yes	48/36	CRT	Fixed	TV camera-model board calligraphic D/N CGI
CH-53E	2F120	16.8%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
Moderate Incidence							
CH-46E	2F117	12.0%	Yes	175/50	CRT	Helo	Full raster scanned CGI 6500 Color edges 6-window segmented virtual
CH-53D	2F121	9.1%	Yes	200/50	CRT	Helo	Digital CGI/raster CRT
Low Incidence							
F/A-18	2E7	7.1%	No	360/145	Dome	Fixed	Digital CGI/TV projectors
F/A-18	2F132	4.2%	No	48/32	Dome	Fixed	Calligraphic CGI/ dome projection
F-14A	2F112	0.0%	No	350/150	Dome	Fixed	TV camera-carrier model Pt. Lt. Background 4 AOI Projectors
Total N = 1111							

* The 2E6 simulator was excluded because of the insufficient number of cases (N = 8).

Despite the fact that no one has demonstrated an overall effect of simulator motion on sickness, two systematic studies suggest that specific motion conditions can be important. Casali and Wierwille (1980) compared two means of simulating lateral forces in a driving simulator. One produced direct lateral movement of the platform and the other produced a platform roll angle proportional to the lateral acceleration. This is known as the residual tilt technique, and is based upon the fact that the otolith organs cannot discriminate tilt and lateral acceleration. The results showed a higher incidence of symptoms with the residual tilt technique, possibly due to the inappropriate rotational cues being produced. Of significance is the fact that residual tilt is sometimes used in flight simulators to simulate sustained acceleration.

Sinacori (Casali, 1986, pg. 18-19; McCauley, 1984, pg. 16-19) reported some personal experience with a wide FOV, fixed-base V/STOL simulator. The test pilot conducting initial evaluations reported significant symptoms during certain maneuvers. As a result, a roll, pitch, yaw motion base was added. In tuning the motion base, Sinacori found that the selection of washout time constant was critical. With acceleration time constants in the 2-3 second range, sickness symptoms were alleviated in the test pilot. With time constants less than 2 seconds, nausea was reported much as in the fixed-base mode. For other pilots who flew the simulator, about 75% experienced problems in the fixed-base mode while only about 10% experienced symptoms with the motion base active.

Finally, cue synchronization errors within and among displays are believed to be important factors. The two experimental studies, which investigated delay effects, have yielded somewhat conflicting results. Frank, Casali, and Wierwille (1988) found that both visual and motion system delays were detrimental to operator performance, postural equilibrium, and a simulator sickness severity index in a driving simulator. Uliano, Kennedy, and Lambert (1986) investigated variable visual delay effects on two helicopter flight control tasks. Although simulator sickness was observed, visual delay had no significant effect on the sickness measures. Interpretation of the latter results is difficult since the range of delays was from 125 ±17 ms to 215 ±70 ms**,** and the tasks were selected to be provocative. In my opinion, this range of delays is not large enough to show a differential effect. Also, the delay effects may have been masked by other simulator distortions, or by the fact that the tasks tended to cause sickness under all conditions.

Potential Compromise of Simulator Effectiveness

Many experts are concerned that simulator sickness may compromise simulator effectiveness in several ways (Frank, et al., 1983):

(1) Compromised training - Learning in the simulator may be retarded as a result of the symptomatology. In addition, if the trainee develops flight control strategies to minimize sickness effects, these strategies may be inappropriate for flight.

(2) Decreased simulator usage - Use of and confidence in the simulators may decrease because of the unpleasant side effects.

(3) Simulator aftereffects - The continuation of symptoms after the simulator session may constitute a safety hazard for activities such as driving or flight. Gower et al. (1987) showed that as symptoms decreased over flights in a helicopter simulator, postflight ataxia increased. In other words, as the pilots were adapting to the simulator, they were having increasing difficulty readapting to the normal environment. In a recent survey of over 700 Army and Navy aviators concerning their simulator sickness experiences, Baltzley et al. (1989) found worrisome results. Eleven percent of the aviators reported symptoms lasting over one hour and four percent reported problems lasting over six hours. Finally, some pilots have reported the onset of symptoms eight to ten hours following the simulator session (Kellogg, Castore, and Coward, 1980).

Procedures to Reduce Simulator Sickness

While firm data are rather limited, several suggestions have been made which may reduce the 'incidence of simulator sickness (Casali, 1986; McCauley, 1984). The US Navy has prepared a field manual (Naval Training Systems Center) which is available to simulator users and elaborates many of the following guidelines:

Simulator Usage Guidelines:

(1) Become knowledgeable of the symptoms of simulator sickness.

(2) Brief trainees on the likelihood of symptoms.

(3) Use simulation freeze judiciously. Avoid freezing in off-horizon aircraft positions.

(4) Use the slew function judiciously. The high rates of motion in the visual display can be very disconcerting. Blank the display or have trainees close their eyes during slew.

(5) Avoid lengthy sessions, particularly if they involve high acceleration maneuvers. Use within-session breaks if problems are expected or experienced. Sharkey and McCauley (1991) found a positive correlation between simulator session length and sickness.

(6) Turn off the visual display during simulator entry and exit. If this is not possible, recover to straight and level flight before exiting.

(7) Decrease the field of view during initial simulator sessions or if discomfort occurs.

(8) Minimize close ground interaction, e.g. turning, taxiing, low-level flight where possible. Sharkey and McCauley (1991) found increased sickness during simulated helicopter flights at 100 ft compared to identical flights at 400 ft above ground level.

(9) Have trainees go on instruments if discomfort occurs.

(10) Plan the training syllabus for incremental exposure to provocative maneuvers and scenarios. The results in Figure 5 show that sickness symptoms are significantly reduced after four or five training sessions (hops), and that training sessions should be separated by two to five days. On the other hand, no strong day of week or hour of day effects were observed (Kennedy et al., 1991).

(11) Avoid high levels of scenario turbulence when sickness problems are anticipated. Turning off the motion base may help also.

(12) Avoid simulator use if a trainee is suffering from other illnesses that produce nausea. The symptoms may sum.

(13) Instruct trainees to avoid excessive head movement and stay within the design eye location of displays.

(14) Motion sickness medications may be effective for simulator sickness.

Engineering and Maintenance Guidelines:

(1) Minimize lags and timing mismatches where possible. Calibrate routinely.

(2) Minimize spurious simulator motion in the frequency range of 0.2 Hz. This range is highly related to motion sickness and appears to be correlated with simulator sickness (Van Hoy et al., 1987).

(3) Align CIG projectors, screens or displays, especially with respect to virtual image distances. Align horizon and structures between displays. Discrepancies in these areas could be the principal causes of eyestrain type symptoms.

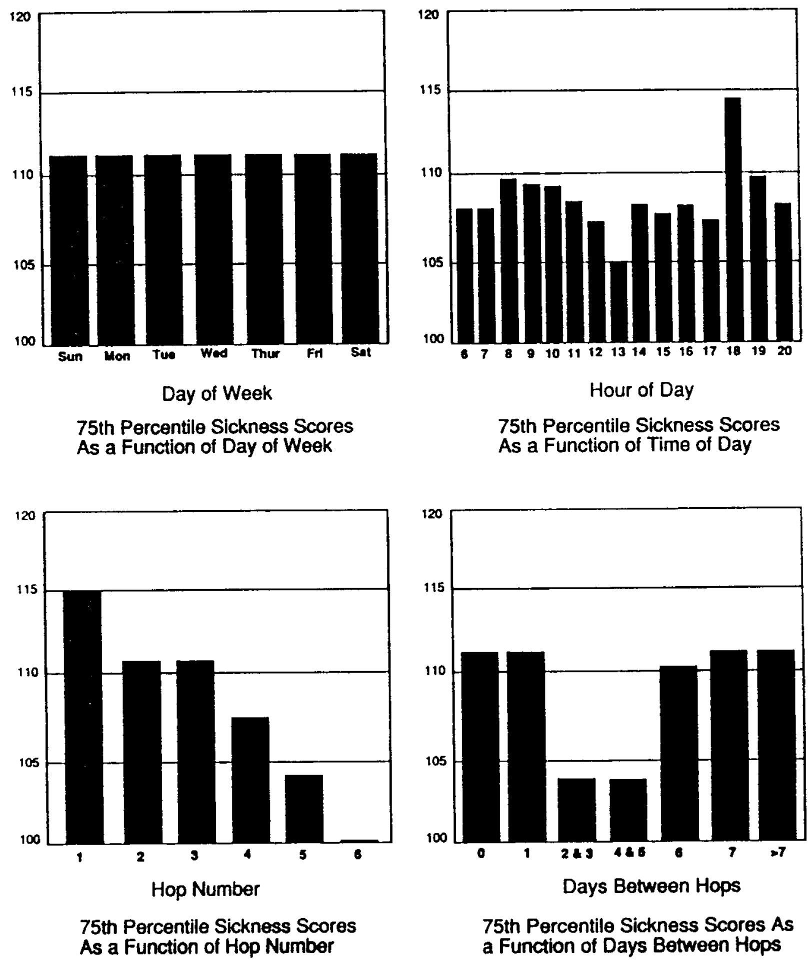


FIGURE 5. EFFECTS OF DAY OF WEEK, TIME OF DAY, HOP NUMBER, AND HOP SPACING ON SIMULATOR SICKNESS. (From Kennedy et al., 1991)

Minimizing Integration Errors - Task and Cueing Analysis

The primary methodology available to minimize integration errors is task and cue analysis. This should be accomplished during the Instructional System Design process in which training objectives are outlined, the specific tasks to be trained are identified, and the cue-response relationships are specified. A good example of how task and cueing analysis can solve design problems is given by McCormick (1983). The design issue was CGI requirements for glideslope control in an aircraft carrier landing simulation. A cueing analysis showed that to perform this task a pilot requires information concerning aircraft position, velocity, (and perhaps acceleration) with respect to the desired glideslope. Over the years the Navy has evolved a visual aid, the Fresnel Lens Optical Landing System (FLOLS), to provide this information. However, McCormick observed that if one attempts to replicate the physical dimensions of the FLOLS display with a CIG system, the resolution limitations will cause the simulated display elements to overlap and merge together, rendering it useless. This is where the cueing analysis offered a solution. It suggested that the critical information is provided not by the physical size of the FLOLS display, but by the relationships among the FLOLS elements. Thus the designer was able to increase the simulated size of the FLOLS display, to overcome the resolution limitations, while maintaining the correct relationships among the elements. By determining the pilot's information requirements the designer was able to violate one aspect of physical fidelity and maintain informational fidelity.

Although the above example is instructive and clearly shows the potential of task and cue analysis, the process is usually much less straightforward. This is especially true when the designer is dealing with complex flight tasks that are performed with natural imagery rather than with instruments or visual aids. In such cases the analysis generally produces a list of pilot information requirements for specific tasks. As discussed by Semple et al. (1981, p. 66), previous studies which have produced such lists have arrived at essentially the same conclusion: "...there is no logical, systematic way of proceeding from visual information requirements to the nature of the picture scene required to provide the information to the pilot."

This conclusion is not limited to visual display questions. In all cases a creative leap on the part of the designer is required to overcome gaps in our knowledge of human information requirements for real-world tasks and in our knowledge of the information available in simulator displays. Despite these difficulties, task analysis should be carefully conducted since it at least bounds the creative activities required by the designer. In addition, the analysis may guide the designer to the perceptual and simulation literature most relevant to his problem. A-n excellent discussion of this issue is provided by Semple et al. (1981). A-n important source of human perception and performance information applicable to simulator design is provided in the Engineering Data Compendium by Boff and Lincoln (1988).

FAA Standards For Cue Integration

In 1980 the Federal Aviation Administration (FAA) published, in effect, a cue integration and synchronization standard for commercial airline simulators. In Appendix H to Part 121 of the Federal Aviation Regulations (FAR) required simulator components are established and the general functional characteristics of these components are specified for Phase I, II, and III simulators. Associated with each of these simulator "Phases" are specific types of pilot qualification that can be accomplished. The specifications include: (1) the aerodynamic effects that must be included, (2) the type of motion base required, (3) the type of visual system required (e.g. night, dusk, day, and field of view), (4) weather and other external scene characteristics that must be included, (5) the digital computer resolution required for aerodynamic calculations, (6) auditory cues that must be provided, (7) the control feel characteristics that must be included, (8) and certain calibration procedures that are required. The details are beyond the scope of these notes, but are rather extensive.

FAA Advisory Circular 120-40B (1991) (120-40C has been in review for several years) specifies a set of procedures for insuring compliance with the FAR standards for "Airplane Simulators". In this document Phase 1, II, and HI simulators are renamed Level B, C, and D, respectively. A similar advisory circular for "Helicopter Simulator Qualification" is in the approval process, if not already approved.

Cue Integration Issues in Simulator Networks

Perhaps the most revolutionary developments in simulation technology are ongoing efforts to link together large numbers of simulators for the purpose of training teams. While simulator networking provides many new capabilities, it also generates a host of new cue integration issues. The research reviewed above provides some guidance for the design of individual simulators on a network. However, it does not answer questions such as the following:

(1) What are the visual, motion, and aerodynamic fidelity requirements for the cognitive and teamwork skills trained in simulator networks? Are they different from the requirements for the visual-motor skills previous research has addressed?

(2) Can abstract or symbolic depiction of the environment be used effectively?

(3) If the stations on a network do not have approximately equal levels of fidelity, will this provide a tactical advantage for some players?

(4) What performance characteristics should any computer-generated players have?

Current work addressing these issues is largely focused on solving the engineering problems - developing standard hardware, protocols, and procedures that will allow different simulators to work together. Little human factors work has been done to address these questions. Interested readers should review the proceedings of recent AIAA Flight Simulation Technologies Conferences and Interservice/Industry Training Systems and Education Conferences to keep abreast of current developments in this area.

Measurement of Delay

To begin the discussion of simulator temporal distortions, (changes in the timing of events), it will be useful to define a few terms. Transport delay, or pure time delay, is simply dead time in a system. Transport delay does not change the shape of a waveform. It simply shifts it in time, regardless of the frequency content. If the system includes dynamic elements (e.g. filters), these elements will produce phase lag or lead when the input is a periodic waveform. Because their filtering action depends on the frequency of the input, such elements will typically change the shape of a complex waveform. That is, the different frequency components will be shifted by different amounts of time. One can use phase lag measures to quantify transport delays. Such a measurement process will show that although the various frequencies in the input are being shifted by different fractions of their period, they are all being shifted by the same amount of time.

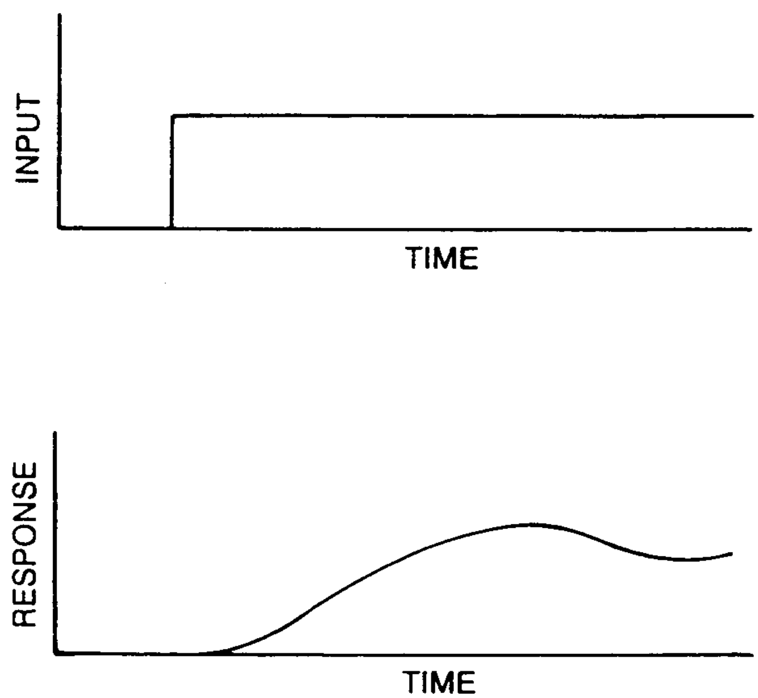


FIGURE 6. TIME DOMAIN MEASUREMENT.

23

Two domains in which synchronization errors may be characterized are the time domain and the steady-state frequency domain. For other than research simulator applications, time domain techniques arealmost used. A step input is used to excite the selected control-display loop, and the initial system response is measured using accelerometers, voltmeters, photosensitive devices, etc. (Figure 6). The delay is defined as the time difference between the input and some defined output, e.g. a just noticeable change, 63% of the commanded final value, etc.

Most real systems include elements that produce both transport delay and phase lag. Because of this it becomes difficult to measure the precise onset of a system's response, and some other technique may be used to estimate the transport delay component. Figure 7 illustrates two of these estimates. It shows the response to a step input of a system, which includes both transport delay and phase lag. Effective time delay is measured graphically. It is defined as the intercept on the time axis of the maximum slope of the system's response. Implicit in this measurement is the assumption that the system has a first order response. Equivalent time delay is determined by modeling a higher order system as a lower order system (e.g. second order) plus a delay term. One then determines the value of the delay term, e^{-TS}, required for a good match to the actual system's behavior over some range of interest. This approach lumps all the system's transport delay and higher order phase characteristics into this equivalent delay term. The term equivalent delay is sometimes used when the measured phase lag of a system is mathematically converted to a time delay. Although this case does not involve an explicit modeling step, it constitutes a similar use of the term.

The FAA specifies the use of time domain techniques for demonstrating that a simulator meets the response specification for its Level C and D ratings. Typically, time domain techniques produce a range of values depending on the time of occurrence of the step input and the next sampling event of the digital system. Browder and Butrimas (1981) report a procedure in which the step input is generated at a different rate from the digital sampling rate. This causes the step input to move with respect to the simulation computer's time frame. With this procedure the full range of maximum to minimum delays is produced. A copy of a later paper (Butrimas and Browder, 1987) is attached to these course notes.

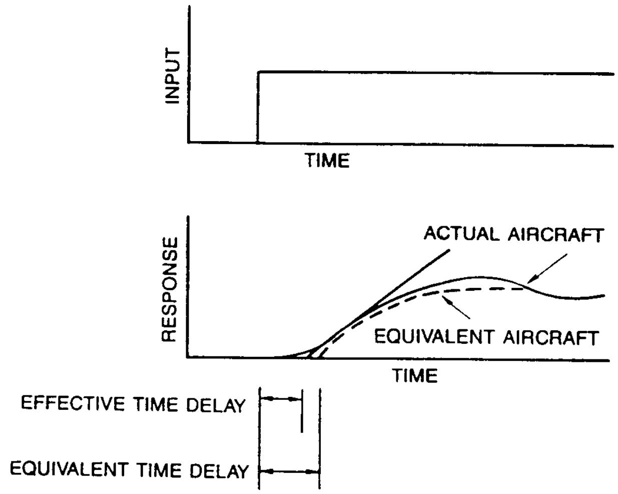


FIGURE 7. GRAPHIC ILLUSTRATION OF EFFECTIVE TIME DELAY AND EQUIVALENT TIME DELAY. (From Horowitz, 1987)

To enable convenient characterization of their frequency dependent gain and phase effects, dynamic elements are sometimes measured using frequency domain techniques. The particular control-display loop is excited with sinusoidal signals of different frequencies, and the system's response is recorded. The phase characteristics may be shown in detail in a Bode plot (Figure 8), or approximated by calculating an equivalent delay for specific frequencies or frequency regions. The latter approach is only appropriate for regions in which the gain is constant and the phase response is proportional to input frequency. In this case the various frequencies are being shifted by approximately the same amount of time, and their relative amplitudes are not being changed.

There are several advantages to using frequency domain techniques for measuring the response of systems containing any combination of phase lags and transport delays. With this approach one does not generate a range of delay values which depend on the timing of the discrete input. In addition, one does not have to define when the system output has reached a large enough value to say that a response has occurred. Finally, this approach can characterize the system's response over the entire perceptual-motor bandwidth of the pilot. If the system is composed of pure delay elements, the phase lags measured by this technique can be easily converted to a constant delay value.

In the paper attached to these notes, Gum and Martin (1987) show that these two approaches measure somewhat different aspects of a simulator's behavior and can yield quite different numbers. The choice of numerical integration technique, the effects of asynchronous operation of simulator subsystems, and other details of simulator implementation will be manifested differently in the two measurement domains. For example, use of a second-order Adams integrator will introduce a 1-2

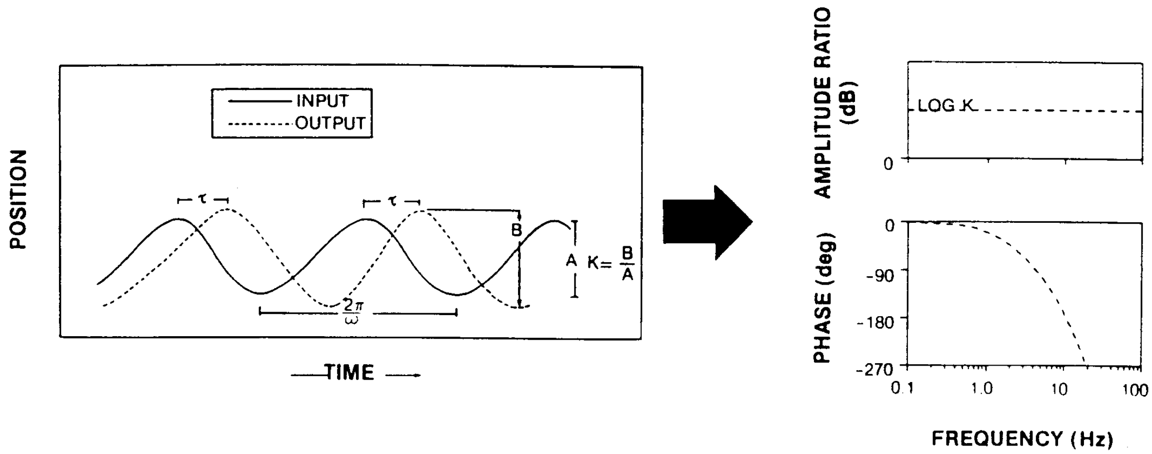


FIGURE 8. FREQUENCY DOMAIN MEASUREMENT OF A SYSTEM WITH GREATER THAN UNITY GAIN AND A TRANSPORT DELAY.

frame transport delay if the response to a step input is measured. It will introduce no transport delay if the input is a steady-state sinusoid. This is due to the predictor incorporated in this algorithm. The Tustin method, on the other hand, will introduce a one-frame delay with either "e of input.

Capitalizing on these differences, simulator designs can be optimized with respect to one or the other measurement technique. It 's not clear which measurement domain is more relevant from the perspective of a pilot controlling the simulator, since pilots produce both abrupt and relatively smooth inputs. The measurement of delay would benefit from standardization, and any such standard will most likely involve the use of both time and frequency domain techniques.

Sources of Delay

There are numerous sources of temporal distortion in flight simulators. One source is the digital computations involved in state-of-the-art systems. Simulation of aircraft aerodynamic responses requires the use of some digital integration technique to calculate aircraft position in 3-D space given the forces acting on the vehicle. A typical approach uses numerical integration methods such as Euler, Adams, or Tustin to provide the desired approximations. However, numerical integration usually produces gain and phase response errors that increase with input frequency (See Figure 9). More critically, these errors increase as the iteration rate for calculation of aerodynamic responses decreases. This problem can be minimized by employing sufficient iteration rates, e.g. 20-30 Hz or above.

A more important source of temporal distortion is the image generation system typical of current flight simulators. These distortions are transport delays, i.e. independent of input

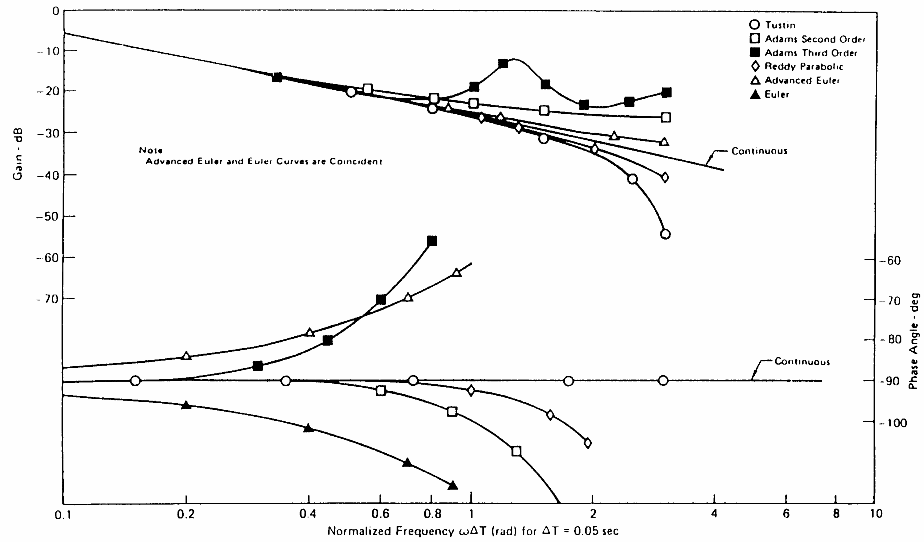


FIGURE 9. FREQUENCY RESPONSES FOR SEVERAL DIGITAL APPROXIMATIONS OF A SINGLE INTEGRATOR. The "Continuous" line represents the response of an analog integrator. The abscissa has been normalized to the sample period of the integrator. The phase response shown for the Tustin method is only realizable if the inputs are predefined. In real-time applications the Tustin method produces a one sample period delay.

frequency. Once the image generator has received the current aircraft state information from the aerodynamic model, the required display cannot be generated instantaneously. Some finite time period is required. Typically this is one or more time frames of the image processor, and the resulting delay will be in the range of 50-100 milliseconds (ms or msec). Again, this problem can be minimized by increasing the iteration rate of the image generator, subject to limitations of the state-of-the-art. If the image generator is a camera-modelboard system, phase lag rather than transport delay will be produced. This is a function of the dynamics of the camera probe that must "fly" over the terrain in response to the aerodynamic commands of the simulator.

Other elements of the flight simulator that produce phase lags or transport delays include physical data holds in the digital to analog conversion (DAC) process, low pass filters to smooth DAC outputs, data holds between subsystems operating at different iteration rates, and any delays or dynamics associated with the actual display devices (CRT frame rates, motion base dynamics, etc.). Specifically, the output of the DAC must hold the most recently computed value until it is updated.

To prevent noticeable stepping in the display devices, the converter outputs may be smoothed with a low-pass analog filter. This filter will produce phase lag as a function of its dynamic characteristics. Finally, the actual display devices may produce phase lags (motion bases, simulated instruments), or transport delays (CRT frame rates) that are not typical of the aircraft being simulated.

The combined effects of these temporal distortions are summarized in Figures 10 and 11. These figures show a highly simplified digital flight simulation operating at a rate of 60 Hz. Figure 10 shows the delay values that would be obtained using time domain measures, while

Figure 11 shows the results with frequency domain techniques. In addition to demonstrating the combined delay effects, they show the mechanism by which timing mismatches are generated, i.e. by differing dynamics or delay elements in the various loops.

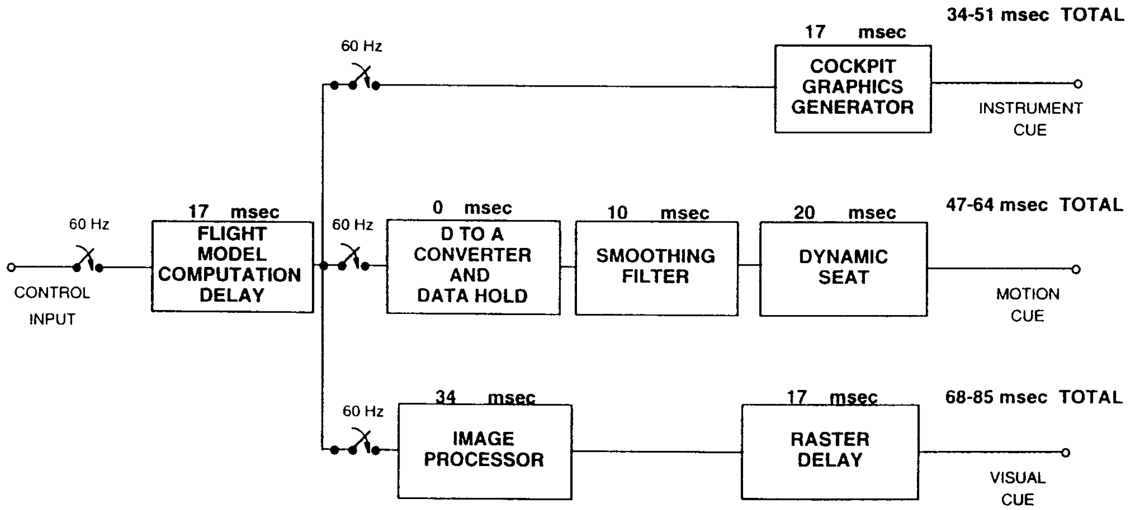


FIGURE 10. EXAMPLE DELAYS IN A SIMPLIFIED FLIGHT SIMULATOR USING TIME DOMAIN MEASURES. Synchronous 60 Hz operation and the use of second-order Adams integration is assumed. The delay shown for any analog element is the time constant to 63% of the commanded value. The 17 msec raster delay in the visual cue path assumes one full video field to update the scene. The range of total delays shown for each display path represents sampling uncertainty, i.e., the step input can occur just before or just after the next sampling instant of the host computer. Some implementations would not require two flight model iterations to calculate aircraft position information.

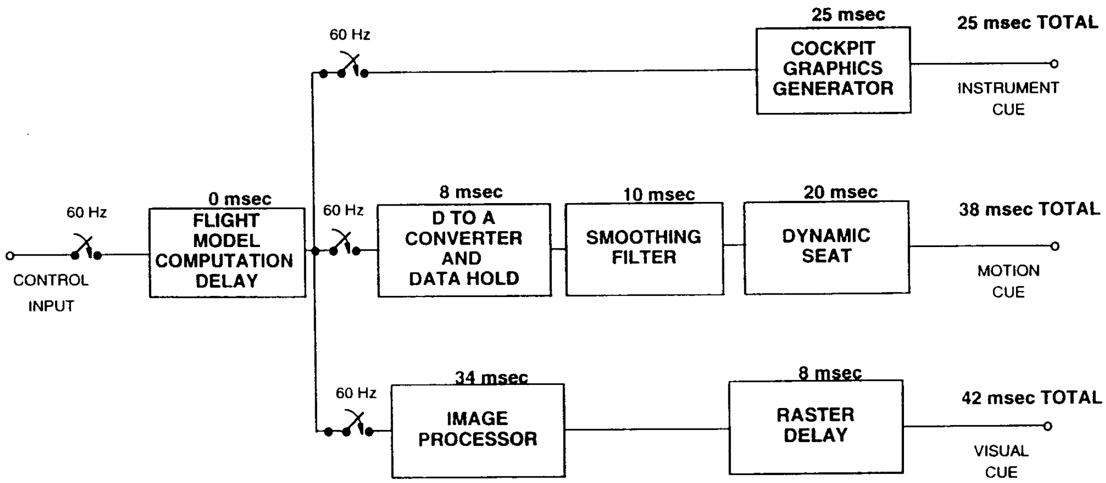


FIGURE 11. EXAMPLE DELAYS IN A SIMPLIFIED FLIGHT SIMULATOR USING FREQUENCY DOMAIN MEASURES. Synchronous 60 Hz operation and the use of second-order Adams integration is assumed. The delay shown for any analog element is the time constant to 63% of the commanded value. The flight model now contributes no delay because of the predictive nature of second-order Adams integration with sinusoidal inputs. The data hold now contributes 8 msec delay since it must hold the most recently sampled value of the sinusoid for an entire time frame and is, on average, one-half of a time frame behind the input. The delay contributed by the cockpit graphics generator has increased by 8 msec because, in addition to the 17 msec graphics generation time, it also represents a data hold operation. The raster delay in the visual cue path represents a data hold of one-half of the 17 msec video time frame.

Effects on Pilot Behavior

Theoretical Background

Studies of transport delays and cue mismatches have concentrated on the effects of these distortions on pilot flight control performance. Before discussing this literature, let us review some of the predictions that models of human manual control performance make concerning delay. One of the best known and validated of these tools is the Crossover Model (McRuer and

Krendel, 1974). This model is a frequency domain representation of human tracking behavior. It models the pilot as a number of simple elements: a gain, an indifference threshold, an information processing (transport) delay, a source of noise, and lead/lag terms that can be adjusted to meet the dynamic requirements of a given tracking task. Numerous experiments have demonstrated that a pilot can adjust his gain over a 20 dB range and that his processing delay will have a minimum value of about 200 ms. Within the structure of the model, it is this delay and the potential lead/lag adjustments that determine how a pilot will control a dynamic system. The Crossover Model has proven to be a powerful tool for predicting the effects of task variable manipulations on measures of human-machine system performance such as the crossover frequency and phase margin.

A large body of research has shown that pilots try to force the system to cross over (pass from greater than unity to less than unity gain) in the frequency range of 3-6 radians per second with a phase margin (the difference between the system phase lag and -180 degrees) of 25 to 45 degrees. If the system has greater than unity gain at frequencies with greater than 180 degrees phase lag, instability will result. Thus the Crossover Model shows that the pilot attempts to produce high response bandwidth (crossover frequency) while maintaining stability (phase margin).

In Figure 12 system phase margin has been related to milliseconds of delay for several crossover frequencies. The abscissa gives the phase margin be' g produced by the pilot. The parameter on each of the four "curves" is the system crossover frequency the pilot is attempting to achieve. The ordinate gives the amount of delay (phase margin converted to milliseconds) that can be added before the phase margin is reduced to zero and the system becomes unstable. Ricard and Puig (1977) give the following example:

> For instance, suppose that a high performance aircraft was being simulated under conditions that forced the turbulence to be relatively wide-band, and the pilot controlled the simulator such that the system crossed over at six radians per second. Now if a 150 millisecond total transport delay were incorporated into the device, it would be unlikely that the pilot could adjust his lead to produce a phase margin in excess of 45 degrees, so he would have to cross over at a lower frequency. If he choose four radians per second he would have to produce better than 33 degrees phase margin in order to remain stable.

Unfortunately, one cannot precisely predict pilot response to complex systems and tasks from this figure. In such cases pilots will continually modify their control characteristics. Nevertheless, this figure is useful in that it does suggest the types of effects delays will have on pilot performance:

(1) The human-machine system's bandwidth will be decreased. Performance will be degraded when the task contains frequency components to which the pilot must respond with reduced gain.

(2) The pilot may be forced to perform with reduced phase margin. Thus, the system will be more prone to instability.

(3) The pilot's ability to generate lead will be taxed. As the handling qualities of the aircraft are degraded, the delay effects will be exacerbated.

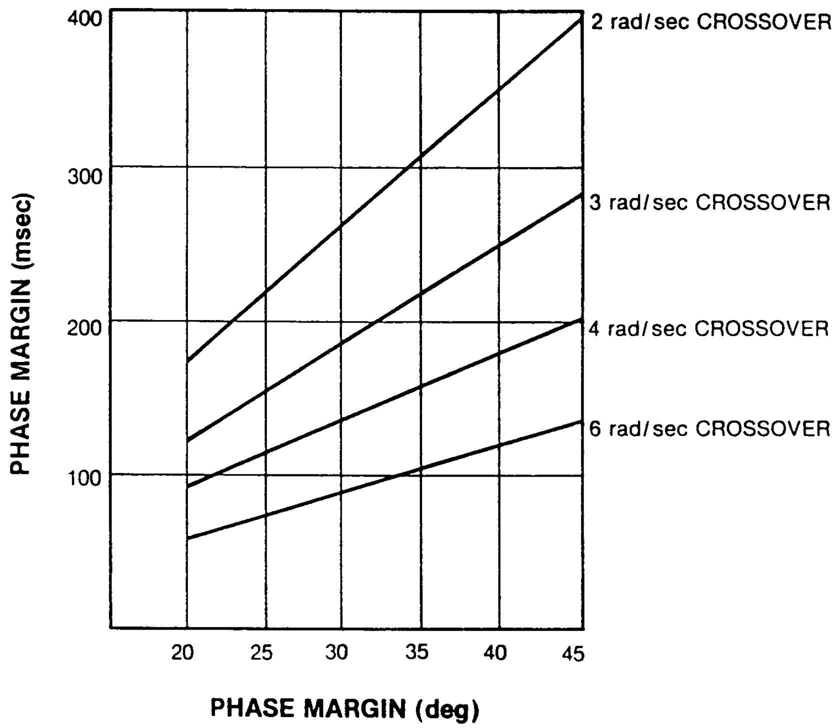


FIGURE 12. THE RELATIONSHIP BETWEEN PHASE MARGIN AND MILLISECONDS OF DELAY FOR SEVERAL CROSSOVER FREQUENCIES. See text for example. (From Ricard and Puig, 1977)

As we shall see, these are the exact trends reported in the research literature. This literature is summarized in the following manner. First, delay effects on well-trained (asymptotic) performance are discussed as a function of several important simulator variables. Second, the impact of transport delay on skill learning is reviewed. Finally, effects on transfer of training are summarized. Although the literature is not always clear on the issue, the reader may assume that the delay values given in these notes are in addition to any phase lag or delay due to aircraft dynamics. That is, they are unwanted simulation artifacts.

Effects on Asymptotic Performance

Axis of Aircraft Control. The initial reports of axis-specific effects were case studies of performance anomalies when CIG systems were added to flight simulators. O'Conner, Shinn, and Bunker (1973) reported pilot-induced roll-axis oscillations during some flying tasks following the addition of a CIG system to Device 2F90, a Navy TA-4j simulator. It was later determined that this simulator had transport delays in excess of 100 ms. Gum and Albery (1977) noted that the Advanced Simulator for Pilot Training (ASPT) at Williams Air Force Base initially displayed similar roll control problems, especially in tasks such as formation flight. Extensive measurements showed that the ASPT had delays of 126-193 ms in the visual system and 249-383 ms in the six-post motion base.

Three research studies have investigated the effects of transport delay on various axes of flight control. Cooper, Harris, and Sharkey (1975) measured the performance of pilots flying simulated carrier approaches with and without an additional 100 ms delay inserted in the CIG display loop. The authors do not give the baseline delay value. The only effects observed on pilot behavior were in lateral-axis control. Ricard, Norman, and Collyer (1976) assessed the performance of straight-and-level flight in the presence of mild turbulence. The baseline delay was 17.5 ms. An artificial horizon display was provided and delays of 0 to 1400 ms were added to the baseline delay condition. While control of pitch angle was hardly affected by delay, roll errors tended to increase when the delay exceeded 100 ms. In more recent work Riccio, Cress and Johnson (1987) found that lateral-axis control was more sensitive to transport delay than altitude control. In this experiment, subjects were attempting to maintain a specified heading and altitude in the presence of strong turbulence.

Aircraft Dynamics and Handling Qualities. Aircraft handling qualities are important variables with respect to delay. judgments of handling qualities are usually based on the Cooper-Harper rating scale shown in Figure 13. This scale requires test pilots to make a series of decisions concerning their ability to control an aircraft with acceptable levels of workload. The reader should note that although handling qualities are a function of aircraft dynamics, they do not reflect a simple dimension such as responsiveness. Both fighter and transport aircraft can have good handling qualities, although their dynamic responses are quite different. A Cooper-Harper scale value of 1 represents excellent handling qualities and 10 represents major deficiencies. Ratings of 1, 2 and 3 are termed Level 1 handling qualities. Level I ratings are required before a new aircraft can be accepted into the military inventory. Ratings of 4, 5 and 6 are termed Level 2, and indicate that significant pilot compensation is required to achieve adequate mission performance.

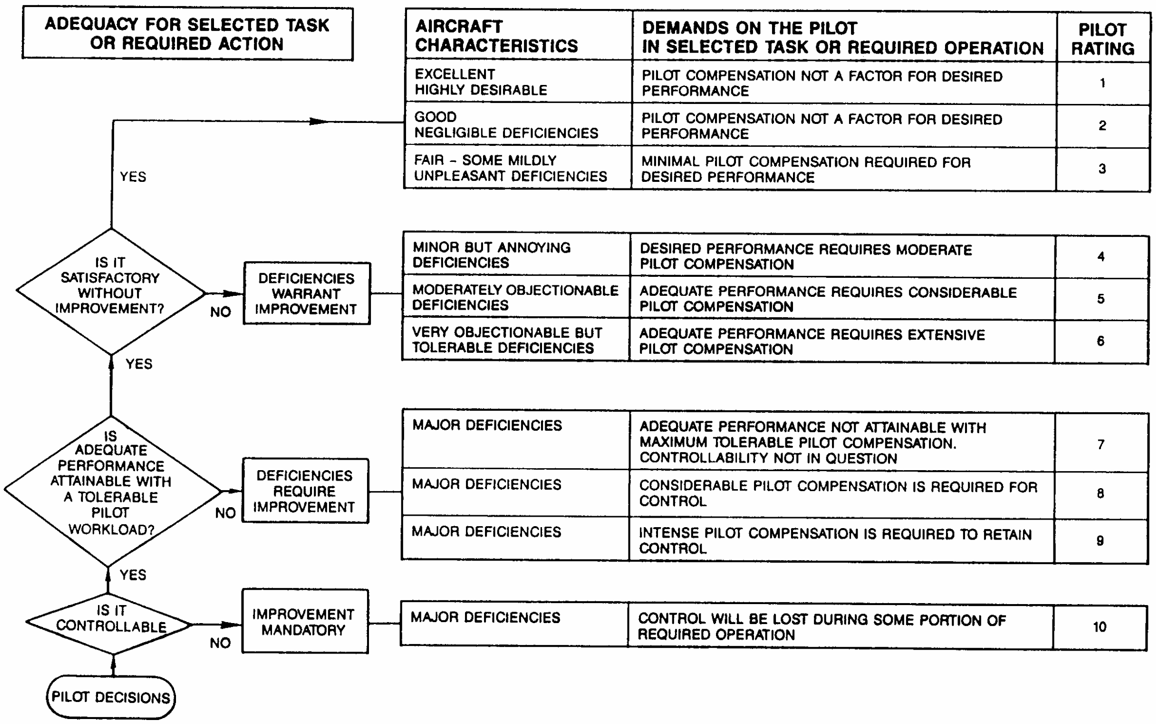


FIGURE 13. COOPER-HARPER RATING SCALE.

Queijo and Riley (1975) investigated total transport delays of 47-297 Ms using the NASA Visual Motion Simulator (VMS). The simulator was used in a fixed-base mode, and pilots tracked a vertically oscillating target driven by a 0.03 Hz sinusoid. This represented a relatively easy tracking task. Seventeen configurations of aircraft dynamics were investigated, covering a range of poor to excellent handling qualities. All configurations included a baseline transport delay of 47 ms. Delays of 0-250 ms were added to this baseline. The authors found that acceptable delay (no measurable performance decrement) was highly dependent on the aircraft handling qualities. As shown in Figure 14, acceptable delay generally decreased as the aircraft handling qualities became less desirable. In this figure the study results are plotted on frequency-damping charts. Cooper-Harper contour lines are shown there also. Ricard and Puig (1977) replotted some of Queijo and Riley's data showing the delay required to produce a 10% increase in tracking error as a function of aircraft responsiveness, not handling qualities. As shown in Figure 15, the tolerable delay was not a monotonic function of aircraft responsiveness.

That is, both sluggish and highly responsive aircraft appeared to be less tolerant of delays. Neither Queijo and Riley nor Ricard and Puig conducted statistical analyses to determine if the differences in "acceptable delay" across aircraft dynamics were statistically significant.

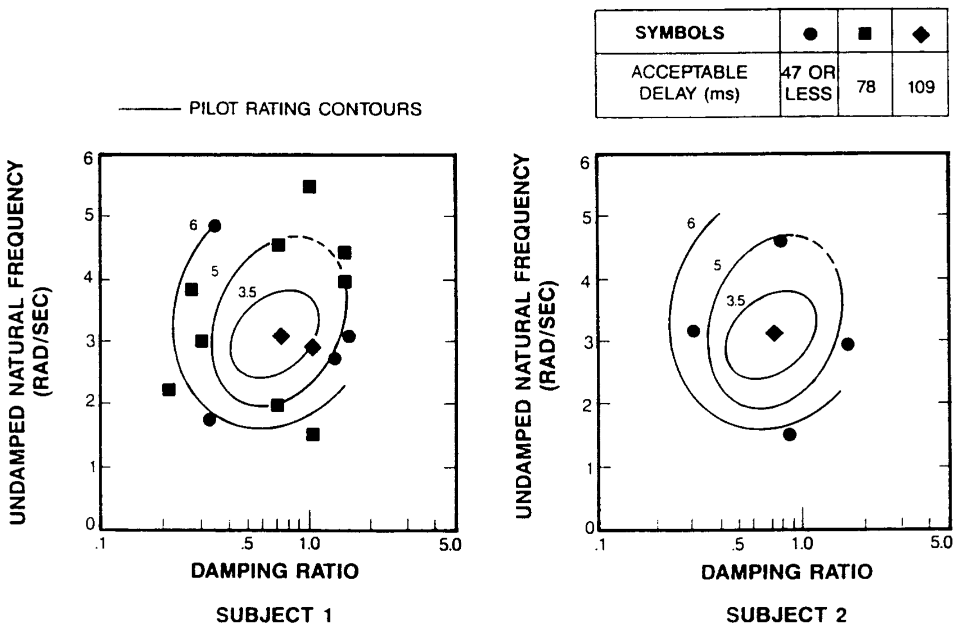


FIGURE 14. ACCEPTABLE TOTAL TRANSPORT DELAY AS A FUNCTION OF HANDLING QUALITIES AND PARAMETERS OF AIRCRAFT LONGITUDINAL RESPONSE. Higher ratings represent poorer handling qualities. (From Queijo and Riley, 1975)

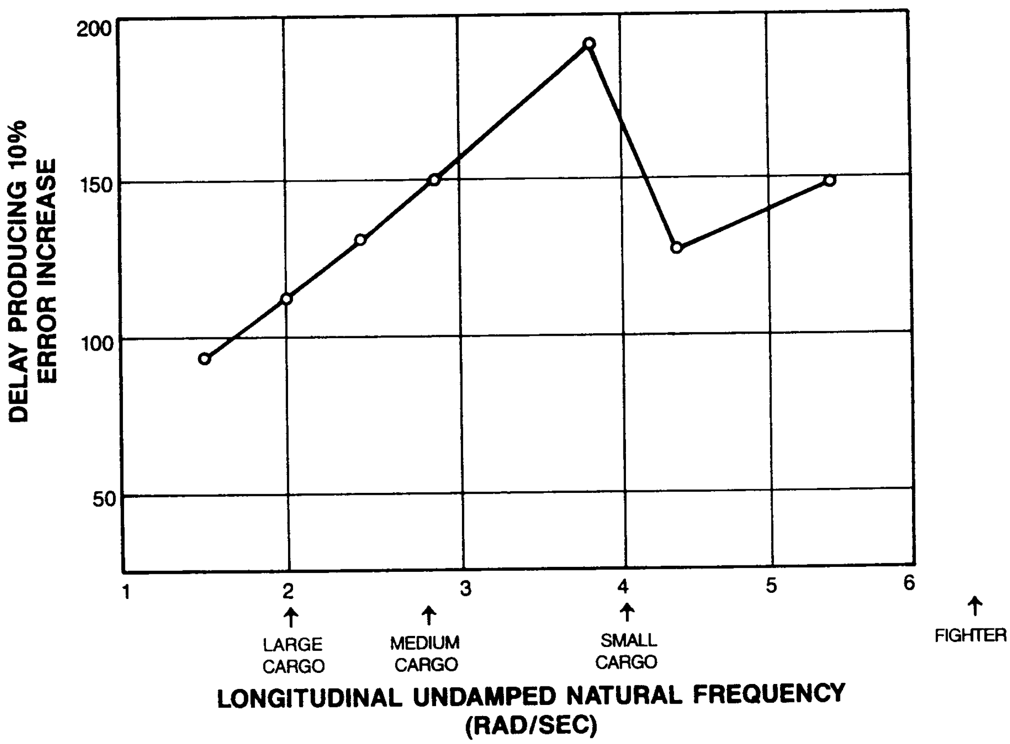


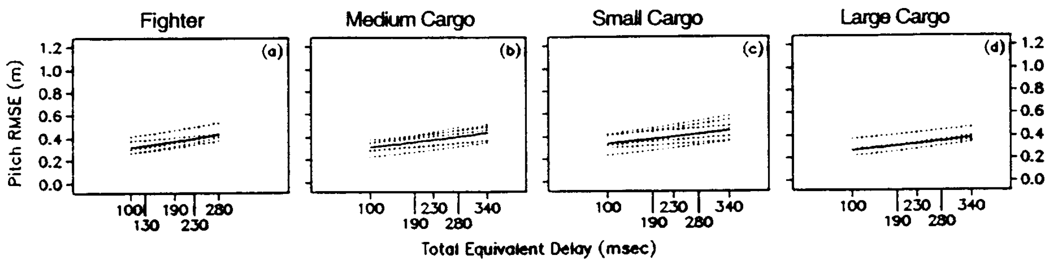
FIGURE 15. TOTAL TRANSPORT DELAY REQUIRED TO PRODUCE A TEN PERCENT INCREASE IN TRACKING ERROR AS A FUNCTION OF SIMULATED AIRCRAFT LONGITUDINAL DYNAMICS. The undamped natural frequency of several aircraft types are noted below. The solid line represents results averaged over several damping ratios, where appropriate. The open circles represent individual data points for the damping ratios shown. (From Ricard and Puig, 1977)

Recent experiments, which used more demanding flight control tasks than Queijo and Riley (1975), included aircraft dynamics as a variable also. Calspan Corp. completed a series of studies for the Air Force addressing the transport delay issue. These studies used the NT-33 variable stability aircraft in both its ground-based and in-flight modes. Data from some of this work (Bailey et al., 1987) are summarized in Figure 16. Four aircraft configurations were chosen to cover a range of aircraft sizes and missions. It should be noted that these studies utilized only low-order approximations to the aircraft dynamics and control feel systems. None of the configurations were high fidelity simulations of the actual vehicle. The pilots flew a variety of demanding tasks selected to permit sensitive flying quality evaluations. All tasks were presented on a head-up-display (HUD) and the pilots wore a special visor that prevented them from seeing outside the cockpit. The ground-based evaluation utilized the actual NT-33 connected to a computer system. The primary difference between the in-flight and ground-based cases was the presence or absence of aircraft motion. Each of the four simulated aircraft included a baseline equivalent delay of 100 ms over and above the aircraft phase lag. Delays of 0-240 ms were added to this basic delay.

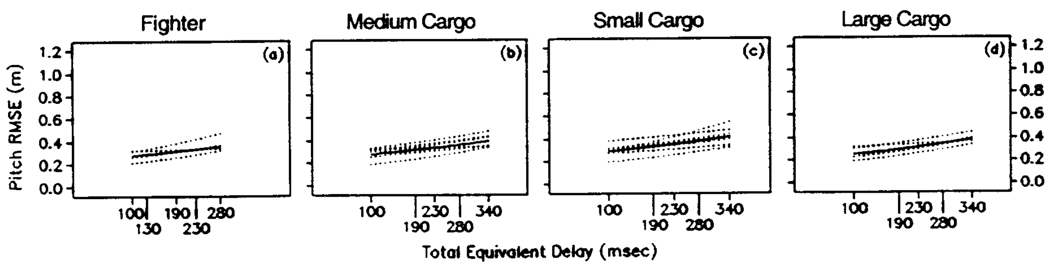
Parts (a) and (b) of Figure 16 show delay effects on pitch axis control in a target following task. In the ground simulation, transport delay significantly degraded performance with all aircraft dynamics. The differences in delay effects (differences in the slopes of the lines) among the four simulated aircraft were very small. In flight, transport delay significantly degraded performance for all except the fighter. Despite this statistical finding, the differences in delay effects among the four simulated aircraft were of no practical significance.

Parts (c) and (d) of Figure 16 show delay effects on pilot ratings of aircraft handling qualities. The in-flight data are the easiest to interpret. For all simulated aircraft, the pilots rated the baseline case (100 ms equivalent delay) as having Level 1 handling qualities. Handling qualities ratings were significantly degraded by delay for all aircraft, and the regressions fitted to the pilot ratings cross the Level I to Level 2 boundary at 110-180 ms total delay. As will be corroborated below, the lack of motion cues in the ground-based cases made the pilots more sensitive to delay. In fact, even the baseline delay condition was rated as Level 2 for all aircraft.

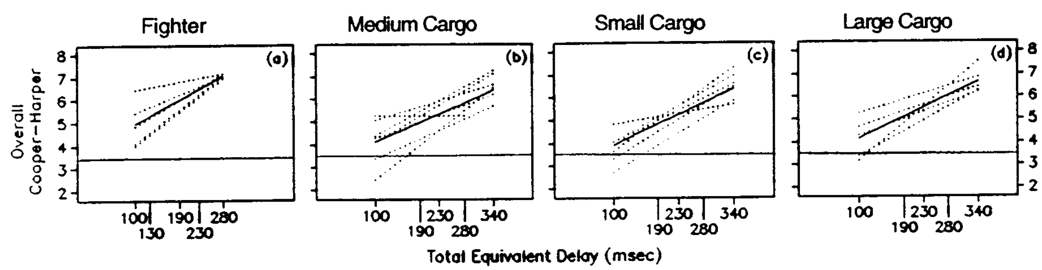
Studies at the USAF Armstrong Laboratory (Riccio, Cress and Johnson, 1987) evaluated the effects of transport delay on performance with simulated fighter and large cargo aircraft dynamics. Both simulated aircraft included baseline transport delays of 50 ms in addition to aircraft phase lags. Delays of 0-350 ms were added to this baseline. The flight task required the subjects to maintain a constant heading and 100 ft altitude over flat terrain. Wide-bandwidth turbulence continually perturbed the aircraft's flight path. This task, although idealized, was quite demanding. The effects of delay on root-mean-square error are shown in Figure 17. Although the delay effects were larger for the cargo aircraft, the differences between the fighter and cargo were not statistically significant. In both cases delay significantly degraded heading and altitude control.



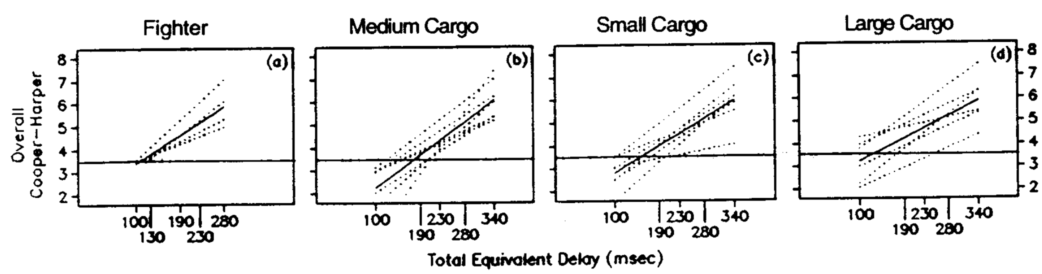
(a) Ground-based pitch-axis control results.



(b) In-flight pitch-axis control results



(c) Ground-based handling quality results



(d) In-flight handling quality results

FIGURE 16. EFFECTS OF DELAY ON PERFORMANCE AND HANDLING QUALITIES FOR FOUR SIMULATED AIRCRAFT. Dotted lines represent data for individual subjects and solid lines represent regression models for the data. (From Bailey et al., 1987)

It is clear that aircraft dynamics and handling qualities are important variables when considering the effects of transport delay. Nevertheless, the recent studies do not suggest that one can set different delay criteria for different aircraft. This conclusion is actually fairly consistent with the earlier results shown in Figure 15. In that figure, the three cargo aircraft only show about 50 ms difference in their delay sensitivity.

Motion Effects. By essentially repeating the Queijo and Riley study with the VMS motion base active, Miller and Riley (1976) demonstrated that providing motion cues can significantly reduce the effects of delay. Both the visual and motion cues were delayed equally. For their "basic" airplane, which had a handling qualities rating of 5, the acceptable total delay in a fixed-base mode was 172 ms. Statistically significant degradations in performance were observed for longer delays. When the motion base was active, the acceptable delay increased to 297 ms. Since motion cues are known to allow a pilot to generate additional lead compensation (Shirachi and Shirley, 1977), this result is quite reasonable.

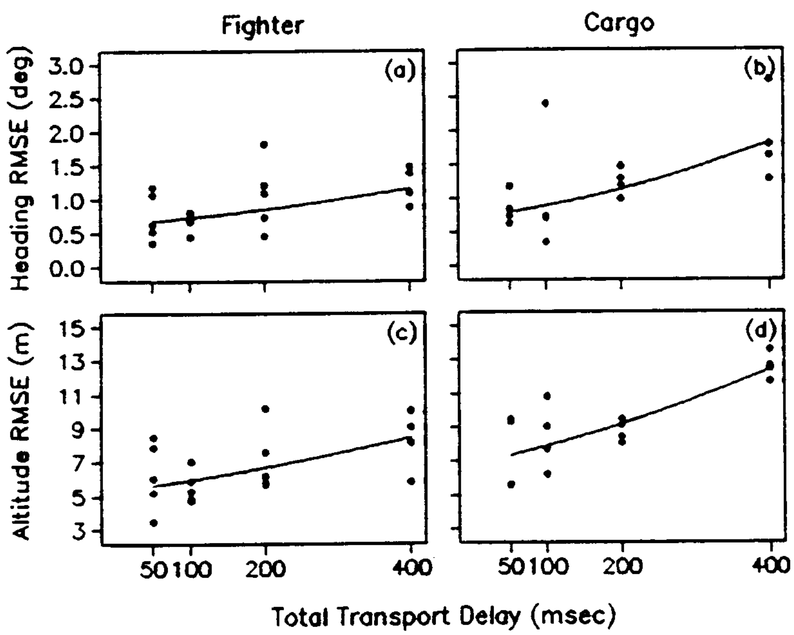


FIGURE 17. EFFECTS OF TRANSPORT DELAY ON HEADING AND ALTITUDE CONTROL WITH SIMULATED FIGHTER AND CARGO AIRCRAFT. The points represent data for individual subjects and the lines represent regression models for the data. (From Riccio, Cress and Johnson, 1987)

Task Type/Difficulty. Task characteristics are an important determinant of delay effects. For example, Queijo and Riley (1975) and Miller and Riley (1976) manipulated the frequency content of their tracking task. When the target frequency was doubled, the acceptable delay decreased by a factor of two to three. Sevier, et al. (1984) investigated the effects of 110 vs. 160 ms visual system delays on the performance of two tasks: (1) tracking a target which was oscillating vertically, or (2) maintaining a constant 45 degree bank angle using a constant-rate turning target as a reference. Effects were only observed for the pitch-tracking task.

On the other hand, simply increasing task difficulty does not always magnify the effects of delay. Cooper, Harris, and Sharkey (1975), in their study of simulated carrier landings with and without an additional 100 ms delay, investigated three levels of task difficulty. (Baseline delay was not given.) These levels were based on the initial offset of the aircraft from the carrier, and on the presence or absence of turbulence. While performance on all tasks was degraded by the added 100 ms delay, the effects were no larger for the more difficult conditions. Queijo and Riley (1975) and Miller and Riley (1976) were clearly manipulating the high frequency control demands of their tasks. It is not clear that the Cooper, Harris, and Sharkey manipulations required the pilots to expand their bandwidth of control.

In the Armstrong Laboratory program, a number of flight control tasks have been investigated. In the most recent work, delay effects on a sidestep landing maneuver (Whiteley and Lusk, 1990) and on a low-level flight task (Middendorf, Fiorita, and McMillan, 1991) were evaluated. In both studies the baseline fighter aircraft simulation included a transport delay of 90 ms, similar to the Calspan study reported above. This baseline delay is actually representative of modern fighter aircraft. Delays of 110 or 210 ms were added to this baseline case. For both tasks, total delays of 300 ms produced statistically significant degradations in performance and were clearly unacceptable. Total delays of 200 ms degraded some aspects of performance in both experiments and probably represent the maximum permissible delays for these tasks. Figure 18 presents some data from the low-level flight experiment.

Multi-variable Effects. To help the reader understand how transport delay affects pilot control behavior, this review has discussed variables such as aircraft dynamics, task type and motion cueing as if they were operating independently. However, in real-world situations, these variables are acting in concert.

A good illustration of this issue is the common opinion that large cargo aircraft simulations can tolerate more delay than fighter simulations. In actual practice, this may be true because of the effects of task type. The reader will recall the research, which showed that, under equivalent task loading, pilots are about equally sensitive to delay in all types of aircraft. In typical simulated missions, however, cargo pilots will be operating at much lower control bandwidth than fighter pilots. Thus the common opinion may be correct, except when cargo pilots must respond to high-bandwidth task demands.

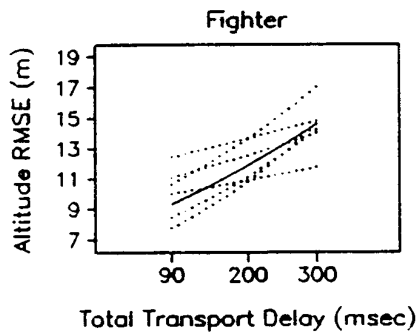


FIGURE 18. EFFECTS OF TRANSPORT DELAY ON ALTITUDE ERROR IN A SIMULATED LOW-LEVEL FLIGHT TASK. Subjects were required to fly at an altitude of 53.3 meters over rolling terrain. The dotted lines represent data for individual subjects and the solid line represents the regression model for the data. (From Middendorf, Fiorita, and McMillan, 1991)

Visual-Motion Cue Mismatches

Although mismatches undoubtedly existed between the visual and motion cues in many of the above studies, their effects have received little systematic investigation. Gum and Albery (1977) reported that when they reduced the visual/motion mismatch in the ASPT by delaying the visual cues to match the motion, the pilots did not like the result. They preferred the more timely visual cues and seemed able to tolerate the mismatch.

Shirachi and Shirley (1977), investigated the effects of four temporal relationships between visual and motion cues on the performance of a roll-axis tracking task (Figure 19). Under normal simulator conditions (Condition A) the motion cues were delayed with respect to the visual cues. This was due to the first order filter characteristics of the motion base (break frequency of 4.8 radians per second). Condition B added a similar lag filter to the visual loop. In Condition C a first-order lead was added to the motion loop. Finally, in Condition D the first-order lag was included in the visual loop, and the lead was included in the motion loop (the reverse of Condition A). As expected, performance was best under Condition C, in which the motion lag was compensated. However, the fact that Condition B (both cues delayed) was not superior to conditions A or D, suggests that mismatch per se had a minor effect on pilot performance. The authors contend that delayed feedback to the pilot in any of the display paths was the critical factor.

Levison, Lancraft, and Junker (1979) also investigated the effect of mismatches between visual and motion cues. In their study, naive subjects performed a roll-axis tracking task with synchronous visual and motion cues, or one of three delayed motion conditions. The results are shown in Figure 20. Roll error was significantly greater for the 80, 200 and 300 ms mismatch conditions than for the synchronous visual-motion case (O ms mismatch). Although this

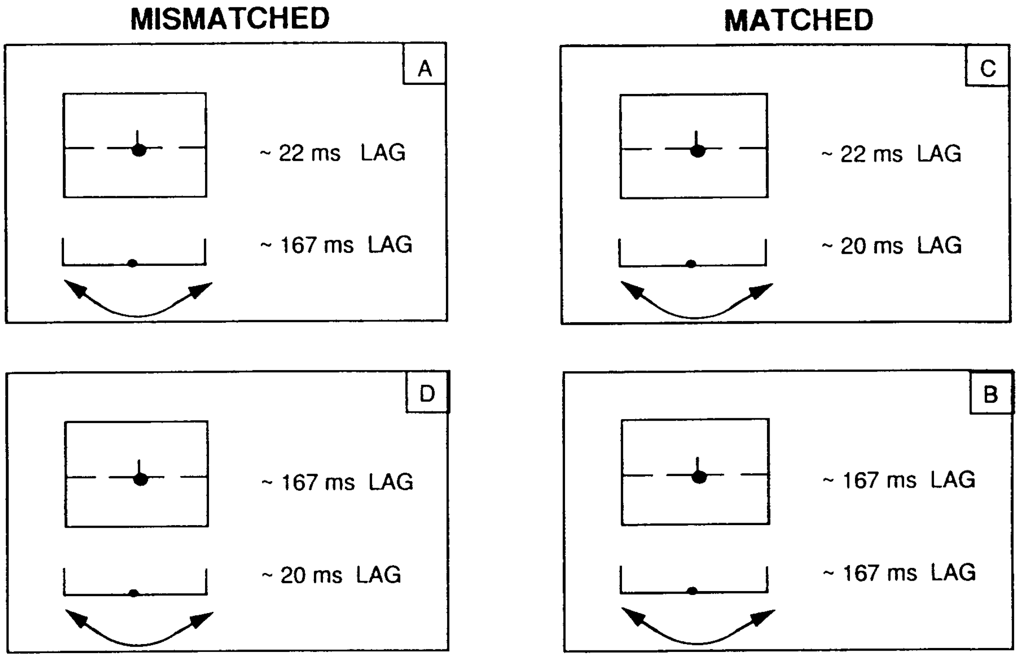


FIGURE 19. EXPERIMENTAL CONDITIONS FOR THE SHIRACHI AND SHIRLEY (1977) MISMATCH EXPERIMENT.

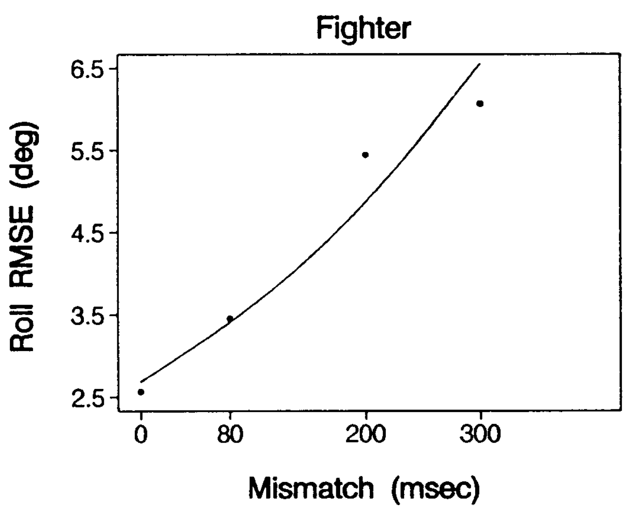


FIGURE 20. EFFECTS OF VISUAL-MOTION CUE MISMATCH ON PERFORMANCE OF A ROLL-AXIS DISTURBANCE REGULATION TASK. The mismatches were produced by delaying the motion cues with respect to the visual cues. (From Levison, Lancraft, and Junker, 1979)

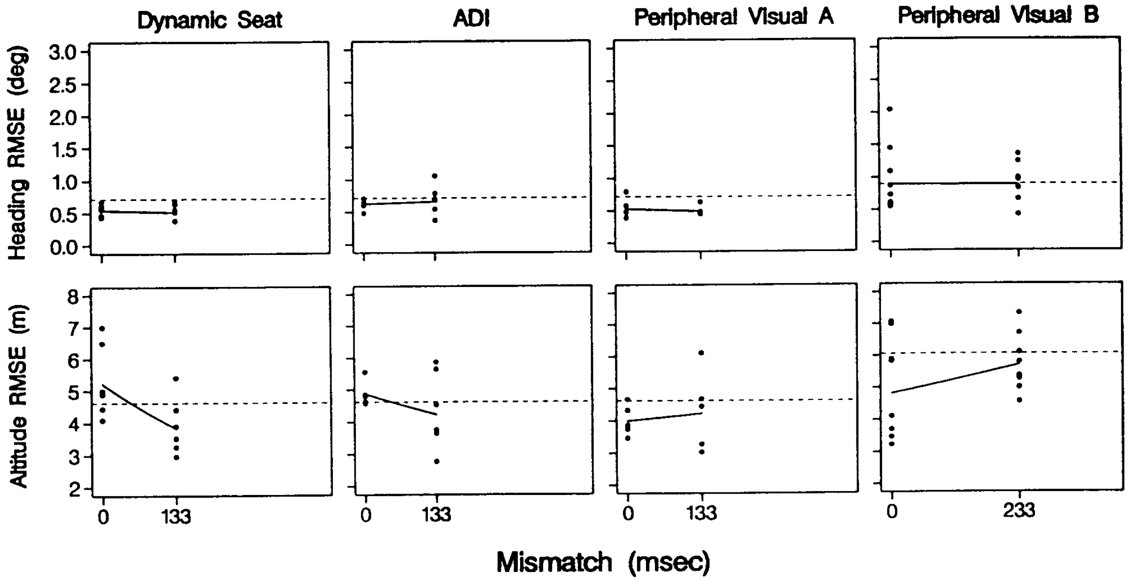


FIGURE 21. EFFECTS OF MISMATCH BETWEEN A CENTRAL VISUAL AND SEVERAL SECONDARY DISPLAYS ON PERFORMANCE OF A HEADING AND ALTITUDE CONTROL TASK. The mismatches were produced by allowing the secondary displays to <u>lead</u> the central visual display. The delay in the central visual display was 300 msec for Peripheral Visual B and 200 msec for all other cases. The dotted lines represents performance with the delayed central visual display alone. The points represent data for individual subjects and the solid lines represent the regression models for the data. (From Merriken, et al., 1988, and Lusk, et al., 1990)

These four studies suggest that delay of information is more critical than mismatch for values likely to be encountered in modern flight simulators. That is, the simulator designer is not likely to achieve any benefit by adding delay to either the visual or motion cues to eliminate a mismatch between the two. Eliminating mismatch by reducing delay in the "slower" display may have performance and simulator sickness benefits, however.

Effects on Training

In the study discussed above, Levison, Lancraft, and Junker (1979) also examined the impact of cue mismatch (or motion delay) on <u>rate of learning</u>. Analysis of the four groups showed no consistent differences in learning rates. In a study of simulator delays and the acquisition of flight control skills (Riccio, Cress, and Johnson, 1987), there were no significant differences in the learning rates of groups trained with total delays of 50, 100, 200, and 400 ms. However, the delays did significantly reduce the performance levels the groups were able to achieve. Thus the learning curves appeared as vertically displaced, parallel functions similar to those in Figure 22.

The pattern of results shown in Figure 22 lead one to expect that delays would affect training measures when a trials to criterion metric is employed. That is, increased training time would be required to reach the same level of performance as delay is increased. In fact, Ricard, Norman, and Collyer (1976) found increases in trials to criterion for learning a roll-axis control task when delays were added. It is somewhat surprising that Cooper, Harris, and Sharkey (1975) did not see a change in this metric for simulated carrier landings, with and without an added delay. The lack of an effect in their study may be due to the fact that all of their subjects were pilots, most of whom had carrier landing experience. All other studies used naive, nonpilot subjects.

Effects. on Quasi-Transfer of Training

Three of the above studies also evaluated delay effects on quasi- (simulator-simulator) transfer of training. In the Levison, Lancraft, and Junker study, the 200 and 300 ms mismatch groups had worse initial performance than the 80 ms group when all groups were transferred to a synchronous visual-motion condition. Statistical analysis showed that the 200 and 300 ms groups experienced less training benefit than the 80 ms group. Nevertheless, the delayed motion conditions had a much larger effect on pre-transition performance than on transfer of training.

Ricard, Norman, and Collyer (1976) found no differences among their delay groups when they were transferred to a zero delay condition with different simulated aircraft dynamics. Recall, however, that all their groups were trained to a common performance criterion before transfer.

Some of the results from the Riccio, Cress, and Johnson study (1987) are shown in Figure 23. The subjects were trained for 50 trials to perform a heading and altitude control task with total transport delays of 50, 100, 200 or 400 ms. Heading control error at the end of training is indicated by the curve labeled Performance. All subjects were then transferred to the 50 ms delay condition. Heading error in the initial transfer trials is indicated by the .curve labeled Transfer. A comparison of the two curves suggests that the delay effects on performance were much larger than the effects on transfer.

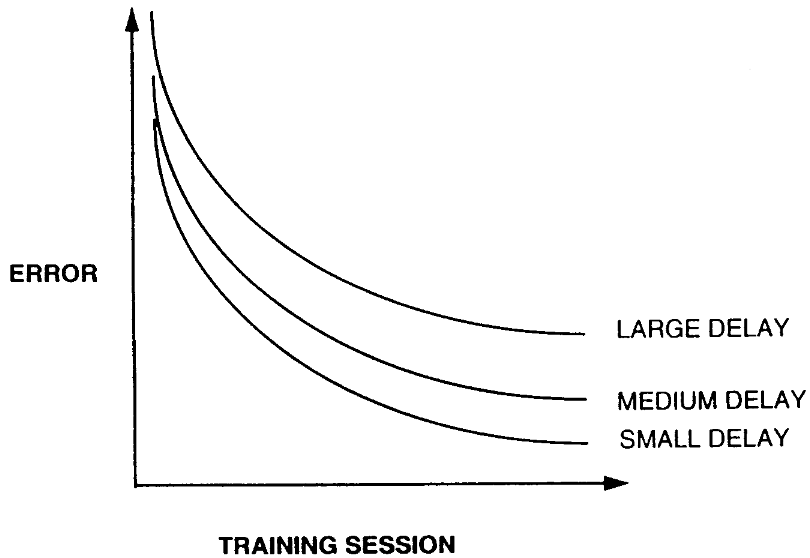


FIGURE 22. TYPICAL LEARNING CURVES WITH DIFFERENT AMOUNTS OF TRANSPORT DELAY.

Standards For Cue Synchronization

Despite the relatively large database concerning the effects of synchronization errors on pilot performance, clear standards exist only for commercial aircraft simulators. At least two problems contribute to this situation. First, most of the systematic research has used inconsistent criteria to determine "acceptable delays", has used very few subjects, and has employed idealized tasks which are difficult to generalize to a complex full-mission simulator. Second, the state-of-the-art in CIG power still makes it difficult to achieve even the tentative standards the research suggests. Naturally, we are reluctant to set standards that cannot be realized at an acceptable cost. If there is a consensus among experts, it appears that a value of 100 ms is most likely to be quoted as a maximum acceptable delay for high performance aircraft (USAF Scientific Advisory Board, 1978; Ricard and Puig, 1977). Although not explicitly stated, one may assume that this delay may be added to the response time of the simulated aircraft.

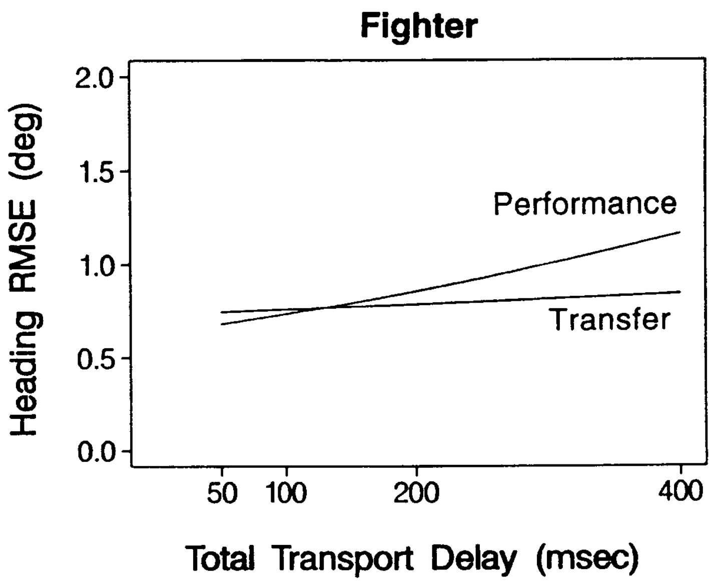


FIGURE 23. COMPARISON OF TRANSPORT DELAY EFFECTS ON PERFORMANCE AND QUASI-TRANSFER OF TRAINING WITH A SIMULATED FIGHTER AIRCRAFT. The curve labeled Performance represents heading control error with the delays shown. The curve labeled Transfer represents heading control error with a 50 msec delay following 50 training trials with the indicated delays. (From Riccio, Cress and Johnson, 1987)

With the advent of digital fly-by-wire aircraft and complex flight control computers, the effects of higher order dynamic modes and inherent transport delays have been of great concern to the aircraft design community. Based upon research addressing this issue, 100 ms has been established in the military specification for piloted-vehicle handling qualities (MIL-F-8785C) as the total equivalent and/or transport delay that may be included between control input and aircraft response. This requirement is independent of aircraft size and mission. This specification does not address the issue of how much additional delay can be added in a flight simulator before performance, training, or pilot acceptance is degraded. It does point out that a faithful aircraft model may include a significant amount of delay before simulation artifacts are added. To pilots, the source of delay is largely irrelevant. They only experience the effect of the total amount of delay.

One published standard for cue synchronization applies only to commercial airline simulators. In Advisory Circular AC 120-40B (FAA, 1991) simulator response standards are specified for Level A, B, C, and D simulators. For Level B simulators, which only permit certification of certain landing tasks, the FAA specifies that the visual system response time to pilot control inputs shall not be more than 300 ms longer than the actual aircraft response. For Level C systems, which permit transition and upgrade certification, 150 ms is the maximum added response time for any of the display systems. In addition, the rule specifies that the visual scene changes shall not occur before the acceleration response of the motion base. The same synchronization standard applies to Level D simulators, which permit all but the line check, the static airplane requirements, and the flight experience requirements to be performed in the simulator. The reader should note that if the aircraft being simulated has equivalent or transport delays that meet MIL-F-8785C, the total delay in a Level D simulator could be 250 ms.

As we have seen in previous sections of these notes, acceptable transport delay depends on the specific task being performed, whether pilot performance or training transfer is the primary metric, and other factors. Therefore, what is needed are systematic data which provide functional relationships between transport delay and (1) performance, (2) transfer of training, and (3) handling qualities ratings, for different flight tasks and aircraft dynamics. With such data, the user could determine what level of performance or training degradation they are willing to accept in return for transport delay.

Although I believe that this is a more useful approach than providing specific delay criteria, users do need rules of thumb to guide their thinking. Based u]2on the currently available data, I would suggest the following rules of thumb:

(1) To ensure Level I handling qualities in the simulator, the sum of aircraft model equivalent delays, aircraft model transport delays, and added simulator delays should not exceed 150 ms. This value is up to 100 ms more stringent than the FAA Level C and D value since it considers the delays included in the aircraft model.

(2) To minimize delay effects on pilot performance in the simulator, the sum of aircraft model delays and simulator delays should not exceed 200 ms. For an aircraft which just meets MIL-F-8785C, this value is equivalent to the expert consensus mentioned above.

(3) To promote good transfer of training, the sum of aircraft model delays and simulator delays should not exceed 300 ms.

(4) At this time no delay guideline can be proposed with respect to simulator sickness issues.

(5) The same guidelines apply to cargo and fighter aircraft, since military transport pilots often have high task demands.

Delay Prevention

The management of transport delay problems should begin with the systems engineering design of the simulator (Cardullo and Brown, 1990). One must assure that there are no unnecessary latencies due poor ordering of software operations. Asynchronies between processors produced by incompatible iteration rates should be eliminated. Finally, selection of appropriate integration algorithms can eliminate a variety of temporal distortions. If the system design has been optimized and unacceptable delays still exist, several techniques are available to compensate for the remaining delay. This is the subject of the next section.

Delay Compensation

Compensation Approaches

Numerous compensation and prediction techniques have been proposed to eliminate or minimize the effects of unwanted simulator delays. They range from simple extrapolations based upon current aircraft velocity to more complex predictors that utilize models of the human-machine system.

Single Interval Lead. One simple approach that may be applied to digital simulations is known as "single interval lead" (Gum and Albery, 1977). This technique capitalizes on the fact that in certain numerical integration algorithms, such as second-order Adams, there is enough information in a given frame to determine the position of the simulated aircraft one full frame ahead. This technique is illustrated in Figure 24. The second-order Adams integrator uses information from the two previous time frames to calculate the current position value. The single interval lead simply uses information from the current and one previous frame to calculate the upcoming position value. The only negative effect of this technique is the additional computational burden, which is small. The "prediction interval" is limited to the time frame of the computer performing the aerodynamic calculations, which is usually 20-30 ms.

Taylor Series. Longer prediction intervals may be generated with a Taylor Series extrapolation. The major problem with this approach is that it has unacceptable noise amplification properties. Where it has been used with apparent success, it has been necessary to add low-pass filters to reduce the noise (Ricard and Harris, 1980).

Lead Generating Filters. Lead generating filters have probably received the most study, particularly with respect to their effects on pilot performance. The most commonly tested filter is a first-order lead/lag of the form:

$$G_F = K(T_n s + 1)/(T_d s + 1)$$

where K is the filter gain factor, and Tn and Td are the lead and lag time constants, respectively. This filter is the continuous domain counterpart of a Taylor Series extrapolation. Phase lead is generated when Tn > Td. The Bode plot for such a filter is shown in Figure 25. The typical location of such a filter in a simulator loop is shown in Figure 26. As can be seen in Figure 25, the desirable phase lead produced by this filter is always accompanied by an undesirable gain distortion. This gain increase causes an amplification of high frequency inputs, making control more difficult and the system more prone to instability. In addition, the gain increase will corrupt the simulation of the aircraft dynamics, reducing the fidelity of the simulation. The design problem, then, is to select the filter parameters such that the phase lead and gain distortion effects are optimally balanced.

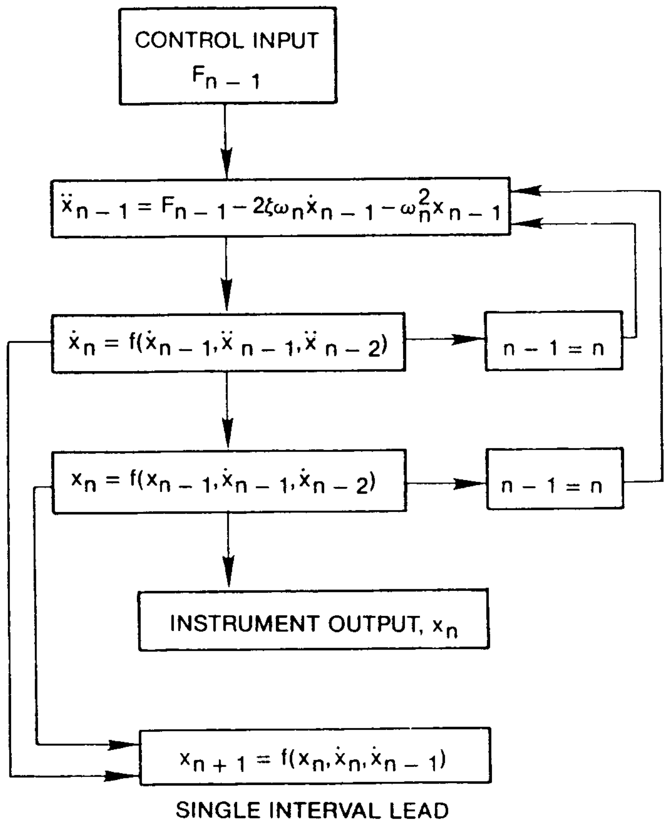


FIGURE 24. IMPLEMENTATION OF THE SINGLE INTERVAL LEAD TECHNIQUE. (From Gum and Albery, 1977)

Ricard and Harris (1980) suggest setting the lead time constant, T_n equal to the lag to be compensated. Then the lag time constant, T_d, is systematically adjusted to yield the best pilot flight control performance. While this approach can be effective, it is not clear that the goal of producing pilot performance like that in the undelayed system will be achieved. Crane (1983) suggests a procedure for selecting the parameters which is designed to restore the closed-loop phase margin to that of the undelayed human-machine system. It is assumed that this will eliminate the need for the pilot to generate the added lead required by the delay, and thus minimize the performance and workload penalties otherwise produced by the delay. Specifically, Crane recommends the following procedure:

(1) Place the filter zero, $1/T_n$ at the estimated crossover frequency, ω_c.

(2) Select the lag time constant, T_d, using the following equation, which equates the amount of lead generated by the filter to the amount of lag produced by the transport delay, t_d, at the crossover frequency:

$$\tan^{-1} \omega_c T_d - \tan^{-1} \omega_c T_d = \omega_c T_d$$

(3) Choose K so that the filter gain is unity at the crossover frequency.

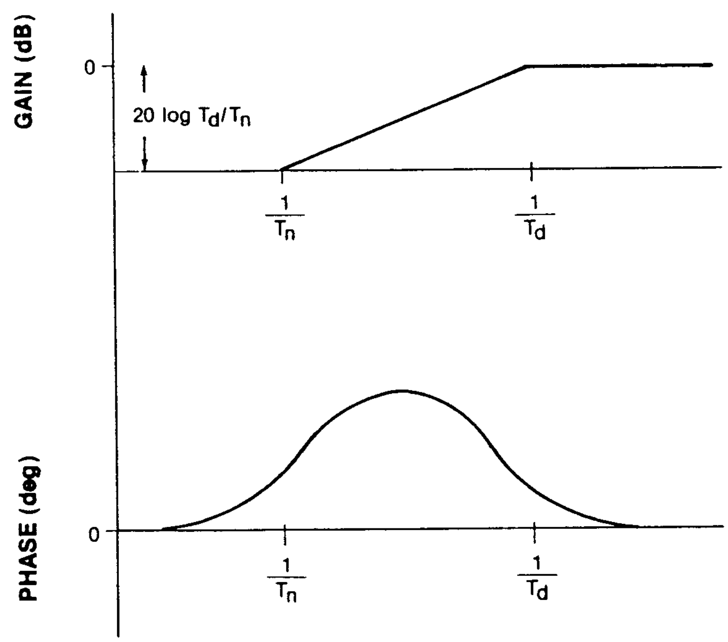


FIGURE 25. BODE PLOT FOR A FIRST-ORDER LEAD/LAG FILTER.

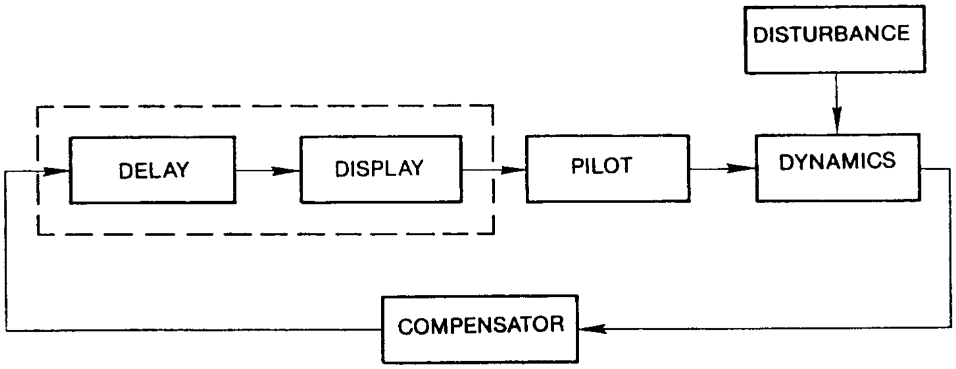


FIGURE 26. DIAGRAM SHOWING LOCATION OF COMPENSATOR.

Crane's approach thus maximizes the phase correction and minimizes the gain distortion in the crossover frequency region. This region has been shown to be most critical for pilot control (McRuer and Krendel, 1974), and for pilot ratings (Figure 27) of the fidelity of dynamic simulations (Wood and Hodgkinson, 1980).

McFarland Compensator. A recent algorithm, developed by McFarland (1986, 1988) at NASA/Ames Research Center for use in helicopter simulations, has generated much interest. The form of his compensator is as follows:

$$X_{n+P/T} @ X_n + b_0(dX/dt)_n + b_l(dX/dt)_{n-1} + b_2(dX/dt)_{n-2}$$

where X is aircraft position, dX/dt is aircraft velocity, P is the transport delay to be compensated, T is the cycle time of the computer, n is the current time frame of the computer, and bn are the weighting coefficients. Thus, the algorithm uses current aircraft position plus the current and two previous velocities to predict aircraft position P seconds into the future. Details on the derivation of the coefficients are

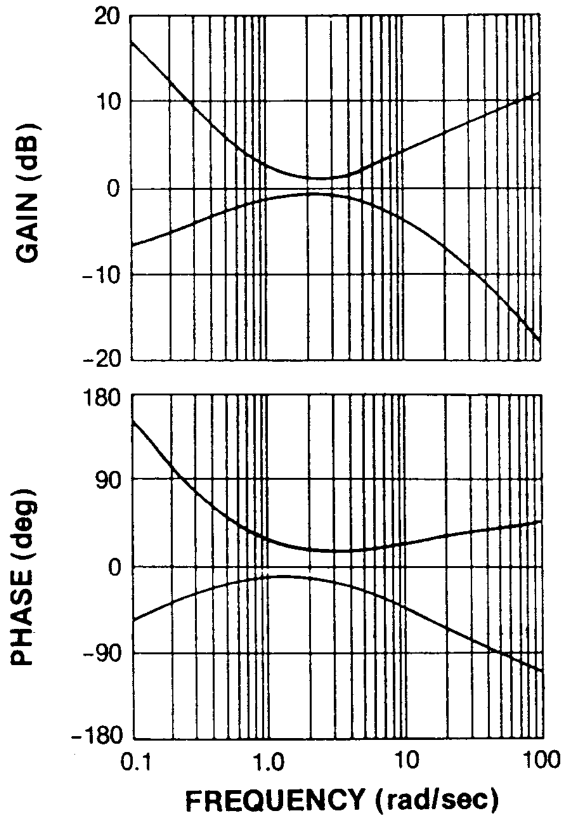


FIGURE 27. PILOT SENSITIVITY TO ADDED DYNAMICS. Pilots are relatively insensitive to changes in gain and phase over the ranges shown between the heavy lines. Note the narrow range around 2-3 rad/sec. (From Wood and Hodgkinson, 1980)

given in the McFarland references. The coefficients are constrained to give perfect prediction at zero frequency (constant velocity), and at a cutoff frequency typically set a 2-3 Hz. Within this pass band, the algorithm generates excellent phase correction and minimal gain amplification (Figure 28). Beyond this pass band phase lead and significant gain distortion are observed. McFarland points out that little pilot control is seen beyond 2 Hz, and that this pass band should be sufficient. McFarland proposes solutions for specific problems he has observed, namely, transients on landing touchdown and high frequencies in turbulence spectra.

Sobiski-Cardullo Predictor. Sobiski and Cardullo (1987) used state space techniques to design a more complex compensation scheme, which is based on the transition matrix of the human-simulator system. In effect, their approach uses a model of the system to improve the accuracy of the predictor. This is done at the expense of an additional computational burden. Cardullo and George (1993) compared this approach to the lead/lag filter and to the McFarland compensator. Both the Sobiski-Cardullo and McFarland techniques were considerably superior to the lead/lag filter. The differences between the Sobiski-Cardullo and McFarland techniques were not as large, particularly for delays up to about 200 ms. However, the results suggest that the Sobiski-Cardullo technique can effectively compensate for delays up to 800 ms (Figure 29).

Compensator Effects on Performance

Ricard and Harris (1980) report the effects of first-order lead/lag filters, designed according to their procedure, on the performance of a two-axis tracking task. Their data demonstrate that an optimum ratio of lead to lag can be determined, and that pilot performance can be significantly improved with the proper settings. However, no comparison to an undelayed case is presented.

Crane (1983) tested his procedure on several flight control tasks, ranging from single-axis tracking to control of a six-degree-of-freedom aircraft simulation. For the roll-axis disturbance regulation task, a delay of 108 ms was inserted in the loop. Compared to the undelayed case, tracking error increased by 38% in the presence of the delay., Crane's compensator reduced this to an increase of 19%. Frequency analyses indicated that the compensator reduced the lead generated by the pilot to within 8% of the undelayed case. While these data suggest that the compensator was producing the desired effects, practical application of this technique may be difficult in the case of complex simulations. Application requires that the pilot's crossover frequency be estimated for the undelayed situation, and that it remains stable across the task or tasks to be simulated. Obviously, some approximation must be used, and the sensitivity to the quality of this approximation is not known,

Jewell et al. (1987) evaluated the McFarland compensator on the NASA/Ames Vertical Motion Simulator, and confirmed that it was performing as predicted by the developer. No test of compensator effects on pilot behavior was reported, however.

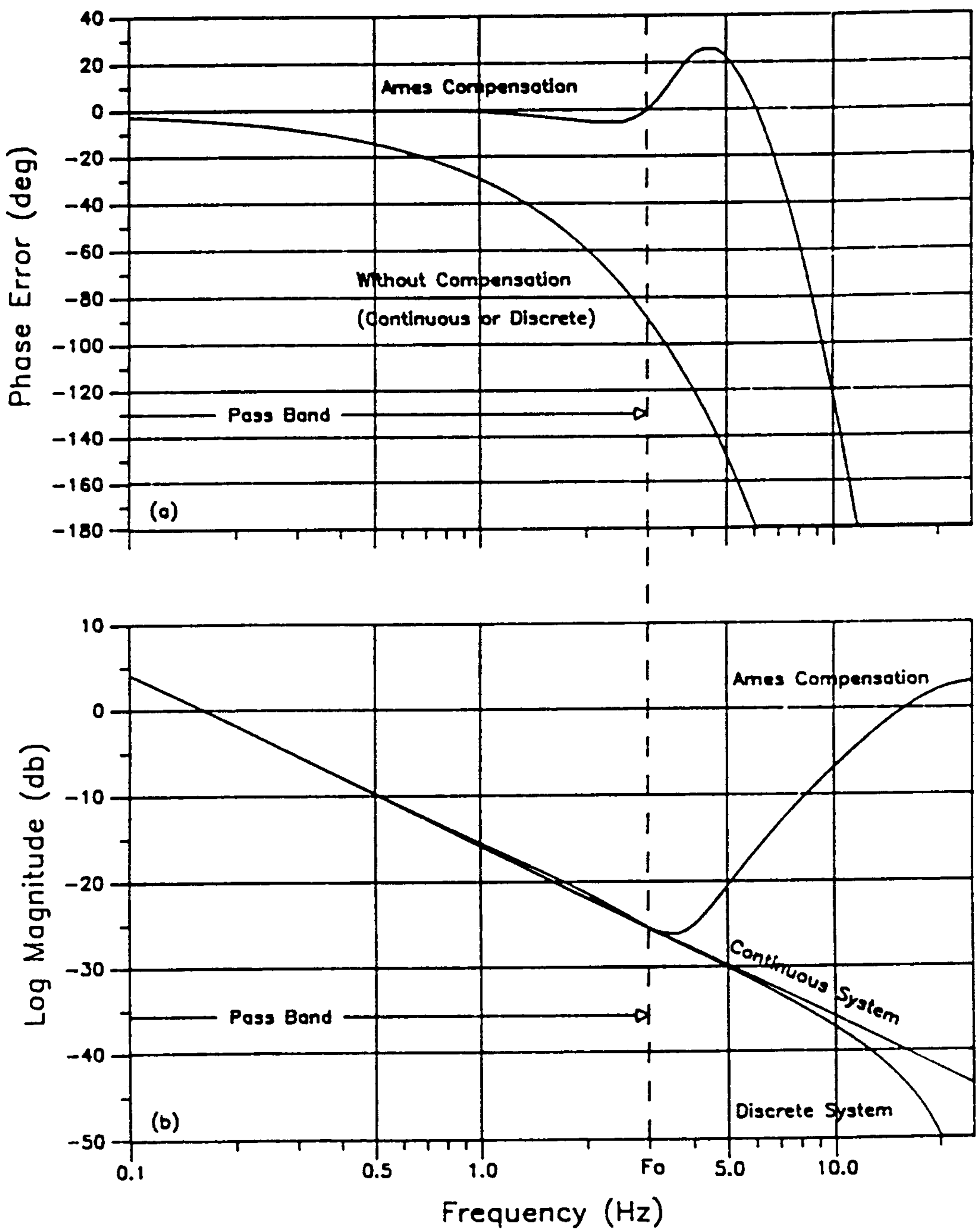


FIGURE 28. PERFORMANCE OF THE McFARLAND COMPENSATOR. Cycle time of the computer equals 20 ms. Time delay to be compensated equals 83 ms. Cutoff frequency equals 3 Hz. Gain responses of an ideal continuous system and a digital simulation without compensation are shown also. (From McFarland, 1988)

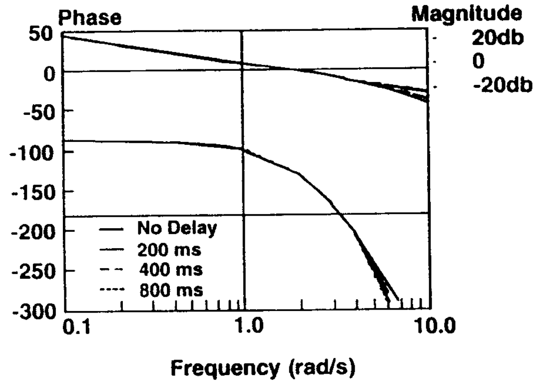


FIGURE 29. PERFORMANCE OF THE SOBISKI-CARDULLO COMPENSATOR. The frequency response of a fourth-order roll-axis control system without transport delay is compared to the frequency response of this system when 200, 400 and 800 ms delays are compensated with the Sobiski-Cardullo technique. (From Cardullo and George, 1993)

Sobiski and Cardullo (1987) compared human roll-axis tracking performance with four types of compensation: (1) none, (2) the lead/lag filter defined by Ricard and Harris (1980), (3) a reduced-order Sobiski-Cardullo predictor, and (4) the full eleventh-order Sobiski-Cardullo predictor. The roll-axis disturbance regulation task used a sum-of-sines input and fourth-order roll dynamics typical of an executive class jet aircraft. The baseline delay was 67.5 ms and transport delays of 0, 200, 400, and 800 ms were added to this baseline. The results are shown in Figure 30.

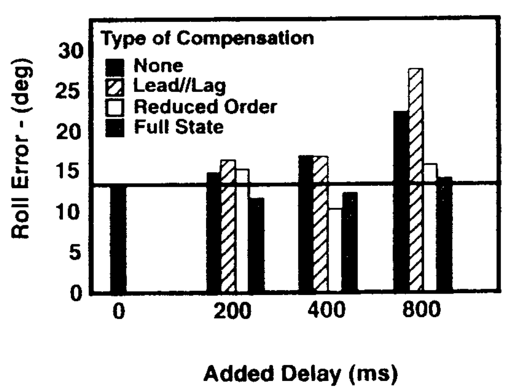


FIGURE 30. STANDARD DEVIATION OF ROLL ERROR IN AN EXPERIMENT COMPARING LEAD/LAG AND SOBISKI-CARDULLO COMPENSATION. The baseline delay was 67.5 ms and transport delays of 0, 200, 400, and 800 ms were added to this baseline. (From Cardullo and George, 1993)

Cue Synchronization Issues in Simulator Networks

Networked simulators include a new source of temporal distortion communication time between simulators. Within-simulator delay distorts feedback to the pilot about the response of his or her own aircraft. Between-simulator delay distorts information concerning the position and movement of other players on the network. There is no reason to expect that the same delay standards will apply to within- and between-simulator delay. Also, given the communication protocols currently being developed for distributed interactive simulation, variable delays due to competition for network access are likely. Variable delay complicates the design of optimal compensators.

Little research has been conducted on the effects of between-simulator delay. Malone et al. (1987) asked experienced air-to-air combat pilots to make tactical judgments concerning videotaped engagements that were played back with delay imposed between the attacker's and defender's displayed positions. Both gun and missile engagements were evaluated. The pilots passively viewed the engagements, and did not participate in them. Their comments suggested that they would not change tactics with delays of up to 500 ms, although a first-order (constant velocity) predictor scheme was required for delay compensation in some cases.

Johns (1988) employed man-in-the-loop simulation to evaluate network delays. Two dome simulators at Northrop Corp. were used for this study. Delay effects were quantified in terms of the difference in kill probabilities when scoring was done from the attacker's or defender's displayed geometry. His results indicated that 100 ms delays seriously degraded the fairness of gun engagements, but that delays of up to 300 ms could be compensated for using a second-order (constant acceleration) predictor. Missile engagements were not particularly sensitive to network delay. Apparently the missile model was able to guide itself to similar endgame conclusions from quite different shot situations. However, simulation limitations did not permit the defender to engage in any hard maneuvering at endgame. Had this been possible, the missile engagements might have been more sensitive to delay.

Uliano and Kearns (1992) report a preliminary investigation of between simulator delays using active F-16 pilots and two Avionics Situational Awareness Trainers (ASAT) built by Perceptronics. The ASAT is designed primarily for beyond visual range training and includes a 23 by 23-degree FOV out-the-window display, radar controls and displays, and flight controls and displays. After an extensive familiarization period, the pilots flew I vs. I missions with four between-simulator delays: 0, 250, 500 and 750 ms. Both missiles and guns were employed and no limits were placed on maneuvering. Missile scoring was done using the defender's geometry. It is not clear how gun scoring was accomplished. Analysis of the pilots' subjective ratings showed that they were largely insensitive to delay effects, especially at 500 ms or less. The objective results indicate that at 0 and 250 ms, most of the kills were produced with missiles, while at 500 and 750 ms, most were produced by guns. The authors suggest that 250 ms was the significant threshold for delay. They note that these result may have been principally determined by the weapons logic and communication structure of the ASAT. If gun scoring was done using the attacker's geometry (not stated by authors) and missile scoring was done using the defender's geometry (stated by authors), this may account for the findings. This arrangement would tend to decrease missile effectiveness and increase gun effectiveness with delay.

Without additional information, it is not possible to directly compare the results of Johns (1988) and Uliano and Kearns (1992). Given the divergent findings, no guidelines for acceptable network delays can be proposed at this time.

Cue Synchronization in Helmet-Mounted Displays

Research on the effects of transport delays in helmet-mounted displays (HMD) is just beginning. The focus of this work has been on in-flight, rather than simulator applications. So and Griffin (1991) at the University of Southampton in England used a two-axis tracking task presented on a monocular HMD with a 17 by 17 degree field of view. The aiming reticle was fixed in the center of the display. Tracking inputs were made by means of head movements sensed with a helmet tracking system. The baseline transport delay between head movement and target image movement was 40 ms. Median radial tracking error significantly increased when delays greater than, or equal to, 40 ms were added to this baseline (Figure 31).

The authors also evaluated three delay compensation techniques, two of which are shown in the figure. The image deflection approach displaced the target image by a constant visual angle to account for image displacement produced by the delay. As shown in Figure 31, image deflection can restore performance to baseline levels. The negative side effect is that the display FOV is reduced and parallax errors are produced in 3-D displays. The second technique employed a combination of image deflection and head position prediction. The head position predictor was first-order (constant velocity). In a later study, So and Griffin (1992) evaluated lead generating filters and found that, with proper parameter selection, they could be effective also. As other investigators have found, the high frequency gain distortion (Figure 25) associated with these filters can produce display jitter problems.

The results of a more recent study (So and Griffin, 1993) are shown in Figure 32. This experiment used a two-axis tracking task presented on a monocular HMD with a 20 by 20 degree field of view. The aiming reticle was fixed in the center of the display. Tracking inputs were made by means of head movements sensed with a helmet tracking system. The baseline transport delay of the system was 17 ms. Delays of 0-167 ms were added to this baseline. Added delays greater than, or equal to, 33 ms significantly increased radial tracking error. A sharp increase in error with delays greater than 133 ms was observed in this study, but not in the 1991 research. The reader should note that Figures 31 and 32 use different scales on the ordinate because of this effect.

The control-display configuration employed in the So and Griffin studies is very different from that of the typical simulator. Because of these differences it is not possible to compare the results in a rigorous manner. Nevertheless, the results suggest that humans may be more sensitive to delays in the HMD environment than with external displays. The display delay evaluated above represents only one of several possible delay sources in HMD systems. For example, the aiming reticle in some systems displays the instantaneous position of a head-slaved gun. In such cases lags produced by the gun dynamics will be present. In other systems, eye movements control the position of a high-resolution area-of-interest inset. In some systems the display imagery is updated both by head movements and by control inputs from a joystick. Different delays are likely to be present in these subsystems. Readers interested in further details should consult So and Griffin (1992) for a review of the available research. As the authors point out, there is little research addressing the interaction of the many possible delay sources in HMD systems.

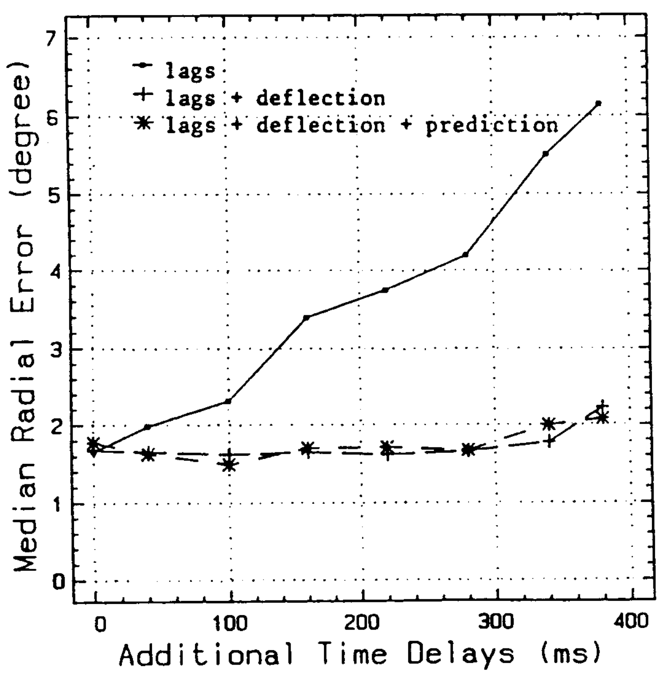


FIGURE 31. EFFECTS OF TRANSPORT DELAY AND TWO DELAY COMPENSATION TECHNIQUES ON TRACKING PERFORMANCE WITH A HELMET-MOUNTED DISPLAY. A two-axis tracking task was employed. The baseline delay was 40 ms and the delays shown were added to this baseline. (From So and Griffin, 1991)

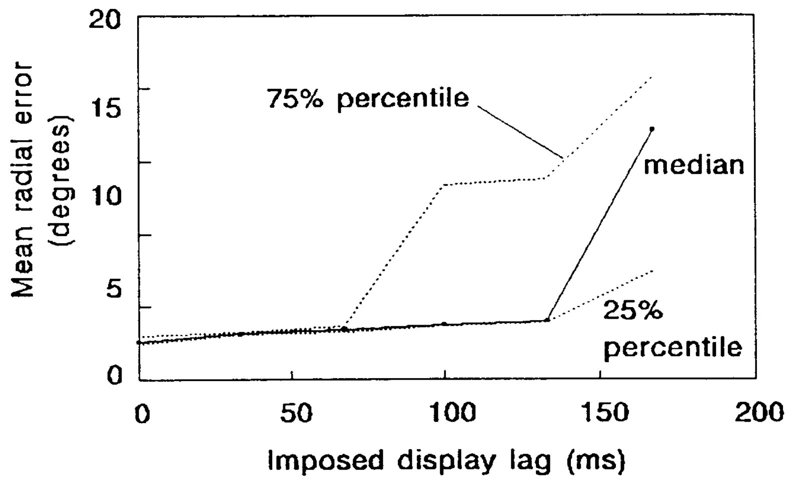


FIGURE 32. EFFECTS OF TRANSPORT DELAY ON TRACKING PERFORMANCE WITH A HELMET-MOUNTED DISPLAY. A two-axis tracking task was employed. The baseline delay was 17 ms and the delays shown were added to this baseline. (From So and Griffin, 1993)

REFERENCES

Bailey, R.E., Knotts, L.E., Horowitz, S.J., and Malone, H.L. (1987). Effect of time delay on manual flight control and flying qualities during in-flight and groundbased simulation. *Proceedings of the AIAA Flight Simulation Technologies Conference*, Washington, DC: American Inst. of Aeronautics and Astronautics.

Baltzley, D.R., Kennedy, R.S., Berbaum, K.S., Lilienthal, M.G., and Gower, D.W. (1989). The time course of postflight simulator sickness symptoms. *Aviation, Space and Environmental Medicine, 60,* 1043-1048.

Barrette, R., Dunkley, K., Kruk, R., Kurts, D., Marshall, S., Williams. T., Weissman, P., and Cantos, S. (1990). *Flight simulator: Advanced wide field-of-view, helmet-mounted, infinity display system* (AFHRL-TR-89-36). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Bickley, W.R. (1980). *Training device effectiveness: Formulation and evaluation of a methodology* (ARI Research Report 1291). Ft. Rucker, AL: Army Research Institute.

Boff, K.R., and Martin, E.A. (1980). Aircrew information requirements in simulator display design: The integrated cuing requirements study. *Proceedings of the Second Interservice/Industry Training Equipment Conference,* National Security Industrial Association.

Boff, K.R., and Lincoln, J.E. (1988). *Engineering Data Compendium: Human Perception and Performance.* Wright-Patterson Air Force Base, OH: Crew System Ergonomics Information Analysis Center.

Browder, G.B., and Butrimas, S.K. (1981). *Visual Technology Research Simulator visual and motion system dynamics* (NAVTRAEQUIPCEN IH-326). Orlando, FL: Naval Training Equipment Center.

Buckland, G.H., Monroe, E.G., and Mehrer, K.L. (1980). *Flight simulator runway visual textural cues for landing* (AFHRL-TR-79-81). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Butrimas, S.K., and Browder, G.B. (1987). A unique approach to specification and testing of simulators. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Cardullo, F.M., and Brown, Y.J. (1990). Visual system lags: The problem. The cause. The cure. *Proceedings of the IMAGE V Conference,* Williams Air Force Base, AZ: Air Force Human Resources Laboratory.

Cardullo, F.M., and George, G. (1993). Transport delay compensation: An inexpensive alternative to increasing image generator update rate. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Caro, P.W. (1979). The relationship between flight simulator motion and training requirements. *Human Factors, 21,* 493-501.

Casali, J.G. (1986). *Vehicular simulation-induced sickness, Volume I: An overview* (NTSC-TR86-010). Orlando, FL: Naval Training Systems Center.

Casali, J.G., and Wierwille, W.W. (1980). The effects of various design alternatives on moving-base driving simulator discomfort. *Human Factors, 22,* 741-756.

Cooper, F.R., Harris, W.T., and Sharkey, V.J. (1975). *The effect of delay in the presentation of visual information on pilot performance* (NAVTRAEQUIPCEN IH-250). Orlando, FL: Naval Training Equipment Center.

Crane, D.F. (1983). Compensation for time delays in flight simulator visual-display systems. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Crosby, T.N., and Kennedy, R.S. (1982). Postural disequilibrium and simulator sickness following flights in a P3-C operational flight trainer. *Proceedings of the 53rd Annual Meeting of the Aerospace Medical Association,* Washington, DC: Aerospace Medical Association.

Crowley, J.S. (1987). Simulator sickness: A problem for Army aviation. *Aviation, Space, and Environmental Medicine, 58,* 355-357.

DeBerg, O.H., McFarland, B.P., and Showalter, T.W. (1976). The effects of simulator fidelity on engine failure training in the KC-135 aircraft. Paper presented at the *American Institute of Aeronautics and Astronautics Visual and Motion Simulation Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

FAA Advisory Circular No. 120-40B. (1991). *Airplane simulator qualification.* Washington, DC: Department of Transportation.

Frank, L.H. (1981). *Simulation sickness.* Invited Address, Moffett Field, CA: NASA Ames Research Center.

Frank, L.H., Casali, J.G., and Wierwille, W.W. (1988). Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. *Human Factors, 30,* 201-217.

Frank, L.H., and Crosby, T.N. (1982). *Psychophysiological disturbances in the 2FI17A, CH-46A WST* (Memo N-712:LHF). Orlando, FL: Naval Training Equipment Center.

Frank, L.H., Kennedy, R.S., Kellogg, R.S., and McCauley, M.E. (1983). *Simulator sickness: Reaction to a transformed perceptual world. I. Scope of the problem* (NAVTRAEQUIPCEN TN-65). Orlando, FL: Naval Training Equipment Center.

Fowlkes, J.E., Kennedy, R.S., and Algood, G.O. (1990). Biomedical evaluation and systems-engineering for simulators (BESS). *Proceedings of the International Training Equipment Conference and Exhibition (ITEC),* Birmingham , UK.

Gower, D.W., and Fowlkes, J. *(1989). Simulator sickness in the AH-IS (Cobra) flight simulator* (USAARL Report No. 89-20). Ft. Rucker, AL: Army Aeromedical Research Laboratory.

Gower, D.W., Lilienthal, M.G., Kennedy, R.S., Fowlkes, J.E., and Baltzley, D.R. (1987). *Simulator sickness in the AH-64 Apache combat mission simulator* (USAARL Report No. 88-1). Ft. Rucker, AL: Army Aeromedical Research Laboratory.

Gray, T.H. (1982). *Manual reversion flight control system for A-10 aircraft: Pilot performance and simulator cue effects* (AFHRL-TR-81-53). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Gum, D.R., and Albery, W.B. (1977). Time delay problems encountered in integrating the Advanced Simulator for Undergraduate Pilot Training. *Journal of Aircraft, 14,* 327-332.

Gum, D.R., and Martin, E.A. (1987). The flight simulator time delay problem. Paper 87-2369-CP presented at the *AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Hartman, B.O., and Hatsell, C. (1976). *Field study: SAAC simulator.* Brooks Air Force Base, TX: USAF School of Aerospace Medicine.

Havron, M.D., and Butler, L.F. (1957). *Evaluation of training effectiveness of the 2FH2 helicopter flight trainer research tool* (NAVTRADEVCEN 1915-00-1). Port Washington, NY: Naval Training Device Center.

Hays, R.T., and Singer, M.J. (1988). *Simulator Fidelity in Training System Design: Bridging the Gap Between Reality and Training.* New York: Springer-Verlag.

Hennessy, R.T., Sharkey, T.J., Matsumoto, J.A., and Voorhees, J.W. (1992) Simulator induced alteration of head movements (SIAHM). *Proceedings of the AIAA Flight Simulation*

Technologies Conference, Washington, DC: American Institute of Aeronautics and Astronautics.

Hettinger, L.J., Berbaum, K.S., Kennedy, R.S., Dunlap, W.P., and Nolan, M.D. (1990). Vection and simulator sickness. *Military Psychology, 2,* 171-181.

Holman, G.C. (1979). *Training effectiveness of the CH-47 flight simulator (ARI* Research Report 1209). Alexandria, VA: Army Research Institute.

Horowitz, S.J. (1987). *Measurement and effects of transport delays in a state-of-the art F-16C flight simulator* (AFHRL-TP-87-11). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Hosman, R.J.A.W., and van der Vaart, J.C. (1981). Effects of vestibular and visual motion perception on task performance. *Acta Psychologica, 48,* 271-287.

Irish, P.A., and Buckland, G.H. (1978). *Effects of platform motion, visual and g-seat factors upon experienced pilot performance in the flight simulator* (AFHRLTR-78-9). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Irish, P.A., Grunzke, P.M., Gray, T.H., and Waters, B.K. (1977). *The effects of system and environmental factors upon experienced pilot performance in the Advanced Simulator for Pilot Training* (AFHRL-TR-77-13). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Jacobs, J.W., Prince, C., Hays, R.T., and Salas, E. (1990). *A meta-analysis of the flight simulator training research* (NAVTRASYSCEN TR-89-006). Orlando, FL: Naval Training Systems Center.

Jenkins, D.J. Jr. (1982). *Simulator training effectiveness evaluation* (Final Report, TAC Project 79Y-001F). Nellis Air Force Base, NV: Tactical Fighter Weapons Center.

Jewell, W.F., Clement, W.F., and Hogue, J.R. (1987). Frequency response identification of a computer-generated image visual simulator with and without a delay compensation scheme. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Johns, L. (1988). A study of the effects of delay time in a dome-to-dome simulation link. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Kellogg, R.S., Castore, C.H., and Coward, R.E. (1980). Psychophysiological effects of training in a full vision simulator. *Proceedings of the 1980 Meeting of the Human Factors Society,* Santa Monica, CA: Human Factors Society.

Kennedy, R.S., Berbaum, K.S., Lilienthal, M.G., Dunlap, W.P., Mulligan, B.E., and Funaro, J.F. (1987). *Guidelines for alleviation of simulator sickness symptomatology* (NAVTRASYSCEN-TR-87-007). Orlando, FL: Naval Training Systems Center.

Kennedy, R.S., Lilienthal, M.G., Berbaum, K.S., Baltzley, D.R., and McCauley, M.E. (1989). Simulator sickness in U.S. Navy flight simulators. *Aviation, Space, and Environmental Medicine, 60,* 10-16.

Kennedy, R.S., Lilienthal, M.G., and Fowlkes, J.E. (1991). What needs doing about simulator sickness? *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Kleiss, J.A., Curry, D.G., and Hubbard, D.C. (1988). Effect of three-dimensional object type and density in simulated low-level flight. *Proceedings of the Human Factors Society - 31st Annual Meeting,* Santa Monica, CA: Human Factors Society.

Kruk, R. (1992). *Simulator sickness experience in simulators equipped with fiber optic helmet mounted display systems* (AIAA 92-4135). Paper presented at the AIAA Flight Simulation Technologies Conference, Washington, DC: American Institute of Aeronautics and Astronautics.

Lane, N.E., and Kennedy, R.S. (1988). *A new method for quantifying simulator sickness: Development and application of the simulator sickness questionnaire (SSQ)* (Technical Report EOTR-88-7). Orlando, FL: Essex Corporation.

Levison, W.H., Lancraft, R.E., and Junker, A.M. (1979). Effects of simulator delays on performance and learning in a roll- axis tracking task. *Proceedings of the 15th Annual Conference on Manual Control* (AFFDL-TR-79-3134). WrightPatterson Air Force Base: Air Force Flight Dynamics Laboratory.

Lintern, G., and Koonce, J.M. (1992). Visual augmentation and scene detail effects in flight training. *The International Journal of Aviation Psychology, 2,* 281-301.

Lintern, G., and McMillan, G.R. (1993). Transfer for flight simulation. In R.A. Telfer (Ed.), *Aviation Instruction and Training.* Brookfield, Vermont: Ashgate Publishing Company.

Lintern, G., and Roscoe, S.N. (1980). Visual cue augmentation in contact flight simulation. In S.N. Roscoe (Ed.), *Aviation Psychology.* Ames, Iowa: Iowa State University Press.

Lintern, G., Roscoe, S.N., Koonce, J.M., and Segal, L.D. (1990a). Transfer of landing skills in beginning flight training. *Human Factors, 32,* 319-327.

Lintern, G., Roscoe, S.N., and Sivier, J.E. (1990b). Display principles, control dynamics, and environmental factors in pilot training and transfer. Human *Factors, 32,* 299-317.

Lintern, G., Sheppard, D.J., Parker, D.L., Yates, K.E., and Nolan, M.D. (1989). Simulator design and instructional features for air-to-ground attack: A transfer study. *Human Factors, 31,* 87-99.

Lintern, G., Thomley-Yates, K.E., Nelson, B.E., and Roscoe, S.N. (1987). Content, variety, and augmentation of simulator visual scenes for teaching air-toground attack. *Human Factors, 29,* 45-59.

Lusk, S.L., Martin, C.D., Whiteley, J.D., and Johnson, W.V. (1990). Time delay compensation using peripheral visual cues in an aircraft simulator. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Malone, H.L., Horowitz, S., Brunderman, J.A., and Eulenbach, H. (1987). The impact of network delay on two-ship air-to-air combat simulation. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

McCauley, M.E. (1984, Ed.). *Research Issues in Simulator Sickness: Proceedings of a Workshop.* National Academy of Sciences/National Research Council, Committee on Human Factors, Washington, D.C.

McCormick, D.C. (1983). Visual simulation task and cue analysis. *Proceedings of the Second Symposium on Aviation Psychology,* Columbus, OH: The Ohio State University.

McDaniel, W.C., Scott, P.G., and Browning, R.F. (1983). *Contribution of platform motion simulation in SH-3 helicopter pilot training* (TAEG Report 153). Orlando, FL: Training Analysis and Evaluation Group.

McFarland, R.E. (1986). *CGI delay compensation* (NASA TM 86703). Moffett Field, CA: NASA/Ames Research Center.

McFarland, R.E. (1988). *Transport delay compensation for computer-generated imagery systems* (NASA TM 100084). Moffett Field, CA: NASA/Ames Research Center.

McGuinness, J., Bouwman, J.H., and Forbes, J.M. (1981). *Simulator sickness occurrences in the 2E6 Air Combat Maneuvering Simulator (ACMS)* (NAVTRAEQUIEPCEN 80-C-0135- 4500-1). Orlando, FL: Naval Training Equipment Center.

McRuer, D.T., and Krendel, E.S. (1974). Mathematical models of human pilot behavior. *AGARDograph AG-188.* Paris: Advisory Group for Aerospace Research and Development

Merriken, M.S., Johnson, W.V., Cress, J.D., and Riccio, G.E. (1988). Time delay compensation using supplementary cues in aircraft simulator systems. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Middendorf, M.S., Fiorita, A.L., and McMillan, G.R. (1991). The effects of simulator transport delay on performance, workload, and control activity during low-level flight. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Wash., DC: American Institute of Aeronautics and Astronautics.

Miller, J.W., and Goodson, J.E. (1958). *A note concerning "motion sickness" in the 2-F2-H Hover Trainer* (Research Project NM 1701 11: Subtask 3; Report 1). Pensacola, FL: Naval School of Aviation Medicine.

Miller, J.W., and Goodson, J.E. (1960). Motion sickness in a helicopter simulator. *Aerospace Medicine, 31*, 204-212.

Miller, G.K., and Riley, D.R. (1976). The effect of visual-motion time delays on pilot performance in a pursuit tracking task. *Proceedings of the AIAA Visual and Motion Simulation Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Money, K.E. (1980). *Flight simulator motion sickness in the Aurora CP 140 FDS* (Technical Communication No. 80-C-44). Downsview, Ontario, Canada: Defence and Civil Institute of Environmental Medicine.

Naval Training Systems Center (1988). *Simulator Sickness: Field Manual Mod 3.* Orlando, FL: Naval Training Systems Center.

O'Conner, F.E., Shinn, B.J., and Bunker, W.M. (1973). Prospects, problems, and performance. A case study of the first pilot trainer using CGI visuals. *Proceedings of the 6th NTEC/Industry Conference* (NAVTRAEQUIPCEN IH-226). Orlando, FL: Naval Training Equipment Center.

Orlansky, J., and String, J. *(1977). Cost effectiveness of flight simulators for military training. Vol I: Use and effectiveness of flight simulators* (IDA Paper No. 1275). Arlington, VA: Institute for Defense Analyses.

Osgood, R.K., and Wells, M.J. (1991). The effect of field-of-view size on performance of a simulated air-to-ground night attack. *Proceedings of the AGARD Symposium on Helmet-Mounted Displays and Night Vision Goggles.* Neuilly sur Seine, France: Advisory Group for Aerospace Research and Development.

Queijo, M.J., and Riley, D.R. (1975). *Fixed-base simulator study of the effect of time delays in visual cues on pilot tracking performance* (NASA TN D-8001). Hampton, VA: NASA Langley Research Center.

Ricard, G.L., and Harris, W.T. (1980). Lead/lag dynamics to compensate for display delays. *Journal of Aircraft, 17,* 212-217.

Ricard, G.L., Norman, D.A., and Collyer, S.C. (1976). Compensating for flight simulator CGI system delays. *Proceedings of the 9th NTEC/Industry Conference* NAVTRAEQUIPCEN IH-276). Orlando, FL: Naval Training Equipment Center.

Ricard, G.L., and Puig, J.A. (1977). *Delay of visual feedback in aircraft simulators* (NAVTRAEQUIPCEN TN-56). Orlando, FL: Naval Training Equipment Center.

Riccio, G.E., Cress, J.D., and Johnson, W.V. (1987). The effects of simulator delays on the acquisition of flight control skills: Control of heading and altitude. *Proceedings of the Human Factors Society - 31st Annual Meeting,* Santa Monica, CA: Human Factors Society.

Riccio, G.E., and Stoffregen, T.A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology, 3,* 195-240.

Semple, C.A., Hennessy, R.T., Sanders, M.S., Cross, B.K., Beith, B.H., and McCauley, M.E. (1981). *Aircrew training devices: Fidelity features* (AFHRL-TR-80-36). Brooks Air Force Base, TX: Air Force Human Resources Laboratory.

Sevier, J.A., Minturn, D.B., Bernard, D.W., and Pollard, T.J. (1984). The effect of computational time-delays on pilot performance in real-time flight simulation. *Proceedings of the AIAA 22nd Aerospace Sciences Meeting,* Washington, DC: American Institute of Aeronautics and Astronautics.

Sharkey, T.J., and McCauley, M.E. (1991). The effect of global visual flow on simulator sickness. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Sharkey, T.J., and McCauley, M.E. (1992). Does a motion base prevent simulator *sickness? Proceedings of the AIAA Flight Simulation Technologies Conference*, Washington, DC: American Institute of Aeronautics and Astronautics.

Shirachi, D.K., and Shirley, R.S. (1977). The effect of a visual/motion display mismatch in a single axis compensatory tracking task. *Proceedings of the 13th Annual Conference on Manual Control* (NASA CR-2921). Moffett Field, CA: NASA Ames Research Center.

So, R.H.Y., and Griffin, M.J. (1991). Effects of time delays on head tracking performance and the benefits of lag compensation by image deflection. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

So, R.H.Y., and Griffin, M.J. (1992). *Effect of lags on human performance with headcoupled simulators* (ISVR Contract Report No. 92/33). Southampton, UK: Institute of Sound and Vibration Research, University of Southampton.

So, R.H.Y., and Griffin, M.J. (1993). *Modelling the effects of computer image generation lags on head tracking performance and predicting the effects of reticle lags phase 1: Model testing* (ISVR Contract Report No. 92/36). Southampton, UK: Institute of Sound and Vibration Research, University of Southampton.

Sobiski, D.J., and Cardullo, F.M. (1987). Predictive compensation of visual system time delays. *Proceedings of the AIAA Flight Simulation Technologies Conference,* Washington, DC: American Institute of Aeronautics and Astronautics.

Stoffregen, T.A., and Riccio, G.E. (1991). An ecological critique of the sensory conflict theory of motion sickness. *Ecological Psychology, 3,* 159-194.

Uliano, K.C., and Kearns, J.D. (1992). The effects of intersimulator delay on pilot performance in low-cost aviation simulators: A preliminary investigation. *Proceedings of the Interservice/Industry Training Systems and Education Conference,* National Security Industrial Association.

Uliano, K.C., Kennedy, R.S., and Lambert, E.Y. (1986). Asynchronous visual delays and the development of simulator sickness. *Proceedings of the Human Factors Society - 30th Annual Meeting,* Santa Monica, CA: Human Factors Society.

USAF Scientific Advisory Board Ad Hoc Committee on Simulation Technology (1978). Committee report, April, 1978. Washington, DC: United States Air Force Systems Command.

Van Hoy, B.W., Allgood, G.O., Lilienthal, M.G., Kennedy, R.S., and Hooper, J.M. (1987). Inertial and control systems measurements of two motion-based flight simulators for evaluation of the incidence of simulator sickness. *Proceedings of the IMAGE IV Conference,* Williams Air Force Base, AZ: Air Force Human Resources Labo-atory.

Westra, D.P. (1982). *Simulator design features for carrier landing: II. In simulator transfer of training* (NAVTRAEQUIPCEN-81-C-0105-1). Orlando, FL: Naval Training Equipment Center.

Westra, D.P., Lintern, G., Sheppard, D.J., Thomley, K.E., Mauk, R., Wightman, D.C., and Chambers, W.S. (1986). *Simulator design and instructional features for carrier landing: A field transfer study* (NAVTRASYSCEN 85-C-0044-22). Orlando, FL: Naval Training Systems Center.

Westra, D.P., Sheppard, D.J., Jones, S.A., and Hettinger, L.J. (1987). *Simulator design features for helicopter shipboard landings: II. Performance experiments* (NTSC-TR87-041). Orlando, FL: Naval Training Systems Center.

Westra, D.P., Simon, C.W., Collyer, S.C., and Chambers, W.C. (1982). *Simulator design features for carrier landing: I. Performance experiments* (NAVTRAEQUrPCEN-78-C-0060-7). Orlando,FL: Naval Training Equipment Center.

Whiteley, J.D., and Lusk, S.L. (1990). The effects of simulator time delays on a sidestep landing maneuver: A preliminary investigation. *Proceedings of the Human Factors Society - 31st Annual Meeting,* Santa Monica,CA: Human Factors Society.

Wood, J.R., and Hodgkinson, J. *(1980). Definition of acceptable levels of mismatch for equivalent systems of augmented aircraft.* (MDC Report A6792).