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Simulator Fidelity Requirements: The Case of Platform Motion[1]

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Simulators Needed for All Airlines

Today, the use of airplane simulators in pilot training and evaluation is universal. Simulators not only enable savings in training cost, but they have also practically eliminated training accidents for major airlines. They allow the training of emergency maneuvers which are inherently unsafe in the aircraft; and they permit crews to gain experience in operationally realistic scenarios that focus on both technical and crew resource management skills. In fact, initiatives such as the Federal Aviation Administration's (FAA) Advanced Qualification Program (SFAR 58, 1990), which heavily relies on crew resource management and need-based proficiency objectives, would be unthinkable without ready access to a full flight simulator. Nevertheless, some regional airlines elect to do at least their recurrent training in the airplane. In part, this situation is due to a shortage of qualified simulators, especially for certain turboprop airplanes where the flight test data is not readily available. A second, and perhaps even more important, reason can be found in the high rental and purchase costs for full flight simulators, which, for small turboprops, may even exceed the cost of the airplane.

Simulator Qualification Standards Review

As a first step in addressing the availability and affordability problems of airplane simulators, the FAA convened a group of experts from industry, academia, and government to review the existing simulator qualification

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standards contained in Advisory Circular AC 120-40B (Federal Aviation Administration, 1991; Transcripts, 1996; Longridge, Ray, Boothe, & Bürki-Cohen, 1996). The subject of this review was the Level B simulator, which can be used for 100 percent recurrent training and evaluation of qualified airline pilots. The mandate was to examine the standards for ways to simplify the requirements such as to achieve a reduced-cost simulation without loss in safety. A first symposium focused on the aeromodel validation standards. The participants envisioned a savings of up to 50 percent on the flight test data package by simplifying the validation test and flight instrumentation and using some predictive modeling for flight data estimation.

A second symposium focused on the motion requirements for the Level B simulator. The international panel of experts felt that motion may have an important alerting function in maneuvers entailing sudden motion-onset cueing, such as loss of engine during initial segment climb, where visual references are limited. Currently, the Advisory Circular requires motion in three unspecified degrees of freedom (DOF). The panel recommended that for motion to have a beneficial effect, it should at least encompass four DOF, namely, pitch, roll, sway, and heave. Also, the panel advised that the allowable motion transport delay should be reduced from 300 to 150 ms. Both of these suggestions ran somewhat counter to the FAA's goal of finding a safe way to make simulators more affordable, and are indicative of the conflict apparent throughout the symposium discussions between recommending the "best available motion" and "motion good enough" for the intended purpose.

Simulator Fidelity Requirements

In the past, technical constraints provided a natural limit to the fidelity of a simulation. Today, however, technical capabilities have expanded to a point where they may enable a degree of fidelity that may exceed the one required for a particular purpose. This may lead to a situation where the benefit resulting from increased fidelity no longer justifies its cost. Our focus thus needs to shift from ever more sophisticated virtual reality technology to the level of fidelity required to train and evaluate to a specific safety standard.

When determining the required fidelity of a device for a particular purpose, we have to distinguish between objective and perceptual fidelity (Advisory Group for Aerospace Research and Development, 1980). **Objective fidelity** of a flight simulator is relatively easy to determine. Using carefully calibrated instruments, simultaneous

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recordings of all pertinent variables of both the airplane simulator and the simulated environment are compared with the corresponding measurements from the pilot's seat in the actual airplane (Ashkenas, 1985). The closer the match, the more objectively faithful the simulator is to the airplane. A more valid measure, however, may be **perceptual fidelity**. It is defined as a match between not only pilots' subjective perception of the simulator and the airplane, but also between pilots' performance and control strategy in the simulator and the airplane. Its determination requires carefully controlled experiments.

As a second step in its effort to increase the availability and affordability of airplane simulators, the FAA is addressing the question of what level of fidelity is required to simulate airplane motion in pilot recurrent training and evaluation, and how it can best be achieved.

Can Vision Alone Evoke Faithful Perception of Motion?

Motion occurs in space and over time. The most important systems for the perception of self-motion are the vestibular system and the visual system. The vestibular system resides in our inner ear and perceives angular velocity and linear acceleration (Hall, 1989). Our visual system perceives motion from changes in position, and velocity and acceleration by additionally taking time into account (Sedgwick, 1986). For the perception of self-motion, the peripheral visual system is especially important (see, e.g., McCauley, 1984; Dichgans & Brandt, 1978). Both the vestibular and visual systems are being stimulated in airplane simulations to induce the perception of self-motion. The tactile or somatic systems also perceive self-motion and have been stimulated in the past with dynamic seatpans, but these have been abandoned for the time being (see, e.g., Martin, 1985).

The phenomenon of perceiving illusory self-motion from vision alone is called vection. A familiar example of such an illusion may occur while seated in a stationary car. When the neighboring car moves forward, people in the stationary car perceive their car as moving backward. In an experimental setting, a subject is put in a patterned drum moving around her. At first, the subject correctly perceives the drum to rotate, but very rapidly the illusion of self-rotation develops. It is this illusion that may enable vision to replace physical motion in the simulator. However, the delay in the onset of the illusion may undermine the possibility of using vision alone because a primary role for physical motion in simulators may be as an <u>early</u> alerting system (e.g., Gundry, 1976).

The Need for Objective Empirical Evidence

Operational personnel, especially those who favor the view that motion is not required, have said that when they have forgotten to turn simulator motion on, nobody noticed. The problem with such anecdotal evidence is that we are often not aware of how we are affected by our environment. Background low-level noise, e.g., is often ignored when focusing on the task at hand, but may still result in exhaustion at the end of the day. In fact, most of human information processing is subconscious, as the originators of the now outlawed subliminal advertising techniques were well aware of. Just as we are able to prevent unwanted information from distracting us, pilots may also be very good at compensating for cues that are missing perhaps by simply working harder, while remaining unaware of both the missing cues and the extra effort.

For the FAA, whose primary concern is passenger safety, to even consider a change in regulations that have been historically validated, compelling evidence from controlled studies addressing the role of motion in airplane simulations is needed. We will start with a look at the existing evidence.

Acceptability of Simulator

The consensus is that pilots prefer simulators with motion. For example, Reid and Nahon (1988) and Hall (1978) used different simulators and different acceptability ratings and yet both found that pilots prefer that the simulator move. Interestingly, however, motion appeared to be most important when there was no visual information available besides instruments. Also, there is still some question as to the impact of motion on acceptability ratings because in most studies the pilots were informed of the simulator's motion state and that knowledge could have influenced their ratings as much as the actual state of the simulators. Indeed, when Lee and Bussolari (1989; Bussolari, Young, and Lee, 1987) did not inform the pilots of the motion state of the simulator, these pilots did not prefer the simulator with six DOF motion. However, this study is not fully conclusive either because of an additional change they made: Instead of turning the motion off completely, they let the simulator vibrate at an amplitude of 1 cm in heave.

Thus, it is not clear whether the general preference among pilots for motion is due to an actual preference or the presence of a preconceived bias towards motion. Additionally, even if there is a real preference, it may be possible to eliminate it by simply adding vibration to the no-motion simulator.

Performance/Control Behavior *in Simulator*

More important than subjective preference is which simulator configuration results in best flying performance and behavior. The vast majority of studies examining this question obtained data in the simulator only.

When investigating the role of motion cues when controlling an airplane, it is important to differentiate between two general kinds of tasks, tracking tasks and disturbance tasks. In a **tracking task** the crew is asked to track a random signal, such as a specific flight path or the lead airplane in formation flight. In this sort of task the signal affects only the central visual cues and not the peripheral or the motion cues. Motion cues become relevant only after the pilots' response to the signal, by giving feedback on the pilots' control actions.

In a **disturbance task** the crew needs to correct for a random perturbation of the controlled system, such as stabilizing the airplane in turbulence or compensating for a mechanical failure (e.g., an engine failure). In this case the random signal affects the entire controlled system (i.e., the motion system as well as the visual systems and instruments). Thus, platform motion provides an early alerting cue to the disturbance which could potentially enable a more rapid response with motion than without motion.

Given these differences in the role of motion for the two kinds of tasks, it is important to examine the role of platform motion individually for each. For tracking tasks, Hall (1978) and Hosman & van der Vaart (1981; Hosman, 1996) found only a small effect of motion on performance. Pilots provided with motion cues showed slightly less roll angle error than pilots without. Moreover, control behavior was affected by motion cues only with unstable aircraft. In that case, there was an increase in stability for pilots with motion, but there was a concomitant loss in gain.

In contrast, there was a large effect of motion with disturbance tasks. Hosman & van der Vaart (1981) found that pilots who received motion cues performed much better, in terms of roll angle, than the pilots who didn't. Furthermore, the presence of motion cues improved control behavior for all aircraft, whether stable or unstable, by increasing gain without impacting stability.

In addition, Hall (1978) and Hosman & van der Vaart (1981) each examined the interaction between vision and motion cues. For both kinds of tasks they found that the effect of motion was strongest when there was no visual information available. That is, visual information could compensate for the lack of motion to a certain extent. Even so, vision alone, even with peripheral vision included, was not as good as vision and motion together.

Thus, both Hall (1978) and Hosman & van der Vaart (1981) concur in finding that the presence of motion improved pilot performance and behavior in the simulator. Hosman & van der Vaart (1981) further demonstrated that the effect of motion is mediated by the kind of maneuver, both in terms of the strength of the effect and the type of the effect. That is, the performance results indicate that the need for motion is greater with disturbance maneuvers than with tracking maneuvers; and the control behavior assessment indicates that the effect on disturbance maneuvers is an increase in pilot gain, whereas the effect on tracking maneuvers is an increase in stability (and a loss of gain).

Training Transfer *to Simulator* (Quasi Transfer)

So far, all we have learned is that platform motion may benefit performance and behavior in the simulator. The real task, however, is flying the airplane. For simulator motion to be useful in training, it would have to increase the proficiency of the pilot after the training session, in the airplane. Similarly, pilot evaluations conducted in the simulator with motion would have to better reflect pilots' proficiency in the airplane than evaluations conducted without platform motion.

Using simulators for experiments, however, shares some of the same advantages as using simulators in training and evaluation, that is, enabling controlled conditions in a safe and cost-effective setting. Consequently, some scientists compared the training effectiveness of competing simulator configurations by evaluating which elicits the best transfer to a configuration that more faithfully represents the airplane. This paradigm is called "Quasi-Transfer" because it does test transfer, but not to an actual airplane.

Levison (1981; Levison and Junker, 1977) used a quasi-transfer paradigm to study the effects on training of different types of simulator motion, including vision-only, synchronous vision and motion, and three conditions where motion lagged vision by 80, 200, and 300 ms, respectively. Subjects were trained to control roll angle in gust-like disturbances. During training, large roll angle reductions were observed in all conditions, but especially in the 80 ms lag and synchronous motion conditions. In fact, the synchronous motion group achieved asymptotic performance so early that transfer testing was omitted for this group.

When testing transfer of this training using the synchronous motion condition as a stand-in for the airplane, all groups showed immediate improvement, but only the 80 ms group appeared to transfer their training to the new condition, catching up with the synchronous motion group on the first post-transition trial. The vision-only group caught up eventually, but for the two groups with larger lags, any motion benefit during training was lost. The group trained with 300 ms motion lag actually performed worse than in training, showing that badly synchronized motion is worse than no motion at all. Thus, the performance benefit of simulator motion experienced during training did transfer to the higher-fidelity simulator, provided that motion and vision were nearly synchronized.

The same was true also for control behavior. Subjects' efficiency in processing synchronized visual and motion cues when transferred to a higher level device was better if they had been exposed to no-lag or short-lag motion cues during training. Presumably, "subjects trained initially with the 80-msec delayed motion cues were exposed to a perceptual situation more like the transfer task than were subjects trained fixed base, and were therefore able to more quickly learn to process faithful motion cues and adopt the appropriate control strategy in the transfer condition."

In sum, the Levison (1981) study significantly extends the findings that motion increases proficiency in the simulator. It showed that this motion advantage transfers to a higher-fidelity device, suggesting that it may transfer to the airplane as well.

Training Transfer *to Airplane:* Tracking and Disturbance Tasks

Despite the inherent constraints on transfer-to-airplane studies, several people have attempted them (e.g., Koonce, 1974; Jacobs, 1776; Ryan et al., 1978; Martin, 1981). In nearly all cases, the advantage of simulator motion during training within the simulator, seen in most simulator-only and quasi-transfer studies, is confirmed. In addition, the effectiveness of simulator training , regardless of motion state, on proficiency in the airplane was also supported. In contrast, the indication from the Levison (1981) study that the advantage of motion would transfer to real airplanes was not borne out in any of these studies. Each of the studies, however, has some form of methodological shortcoming; some beyond the control of the scientists such as the state of technology at the time of the experiment and the problems inherent in using airplanes.

Summary of Empirical Evidence

In sum, there were many benefits of platform motion within the simulator. First, it improved the acceptability of the simulator, at least when pilots were aware of the motion manipulation (but the amount of motion required may be very small). Second, it improved pilot performance and control behavior for disturbance tasks.

Third, it improved behavior during a tracking task with an unstable vehicle. Finally, it was particularly useful when visual information was limited. Some of the benefits of platform motion transferred to a higher fidelity simulator. In contrast, motion did not help in the critical case, the transfer of training to the airplane.

All of the transfer-to-airplane studies, however, share a number of problems that may have diminished their diagnosticity. Many of these problems also apply to the simulator-only and the quasi-transfer studies as well. First, many studies used outdated motion and visual systems. These studies did show that even a rudimentary visual system can compensate somewhat for the lack of motion, leaving open the question of whether a more sophisticated visual system could fully replace motion at least for some purposes. Similarly, they showed that an outdated motion system improved how the simulator was flown, raising the question of whether with a newer system, this improvement would transfer to the airplane.

Second, most of the experiments used tracking instead of disturbance maneuvers, the latter being both difficult and dangerous to test in the air. Only disturbance maneuvers, however, may be able to diagnose the advantage of exposure during training to the early alerting cues provided by motion.

Third, many of the experiments used non-representative subject samples, both with respect to number of subjects sampled and their flying experience. None of the studies cited so far analyzed the interpilot variability within groups to determine the number of pilots required to find a specific size of effect. Moreover, most of the studies used student pilots. There is evidence, however, that well-trained pilots may be more sensitive to the presence or absence of motion than beginner pilots (Young, 1967).

Fourth, only some of the studies analyzed both pilot performance and behavior. Pilots, if at all possible, will adapt to deficiencies in equipment by changing their control strategy. So pilots, to achieve the same performance in different equipment, may have to increase, e.g., the frequency and/or amplitude of their control interventions. Such differences may become critical in emergency situations.

Fifth, pilots and instructors were not naïve regarding the motion condition, which may have allowed bias to affect their performance or performance evaluation, respectively (Ebbinghaus, 1964).

Why Revisit Motion Fidelity Requirements Now?

Given all of these problems, it is not surprising that four decades of research do not provide conclusive evidence that vestibular motion cueing in simulators used for recurrent pilot training and checking is beneficial.

Technological advances, industry interest, as well as the lessons learned from previous research provide an excellent opportunity to readdress this question.

In the wake of “virtual reality”—or rather simulated reality—technology, progress was made especially with visual systems. In particular, the widening of the field of view (FOV), and resultant increase in stimulation of the peripheral visual system, has created “a more compelling visual display of motion” (McCauley, 1984). As we have seen, the advantage of motion observed in the simulator was often reduced with improved visual stimulation. In contrast, the last major advances with regard to motion cueing date back at least 15 years. They include the introduction of critical onset cues followed by subliminal washout, and of “gravity align” platform attitudes to simulate sustained acceleration (Brown et al., 1989). But these innovations still don’t overcome the limitations resulting from the fact that simulators are stationary. The question of interest is whether a state-of-the-art visual system wouldn’t simulate airplane motion at least as faithfully on a perceptual level as the inherently limited physical simulator motion does.

One *caveat* that needs to be raised here, however, is simulator sickness. A widely accepted explanation of simulator sickness is the sensory conflict resulting from discrepancies between visual and vestibular cues (see, e.g., McCauley, 1984; Oman, 1991). As the quality and, in particular, the FOV of the visual system increase disproportionately compared to the motion system, so will the sensory conflict between visual and vestibular motion cues. Guedry (1987) suggests that this, coupled with an overall increase in simulator use, is one of the main reasons for the increase in reports of simulator sickness over the past decade. McCauley, Hettinger, Sharkey, & Sinacori (1990) cite evidence found by McGuiness, Bouwman, & Forbes (1981), indicating that more experienced pilots may be more susceptible to simulator sickness than novice pilots, just as they may be more likely to rely on vestibular motion cues (Young, 1967). Potentially, then, even if a sophisticated visual system alone were to provide sufficient motion cues for recurrent pilot training in the simulator, forgoing physical motion may still be unacceptable due to the effects of the ensuing sensory conflict on pilots.

Regional airlines in the U.S. are increasingly interested in the question of whether a Level 6 flight training device (i.e., a fixed base simulator) with an enhanced visual system could be employed to satisfy FAA requirements for recurrent training and checking. This would permit airlines now conducting such training in the aircraft to take full advantage of the more comprehensive maneuver-oriented and scenario-based training opportunities available in a simulator. The argument is that this would enhance the overall safety of regional airlines, provided that equivalent safety of training and evaluation with visual motion cues alone can be empirically confirmed. A first step in such an empirical investigation is a careful definition of the research scope.

Research Question

The FAA is revisiting the issue of platform motion in the context of regional airline recurrent pilot training and checking. Given a pilot who is already qualified as a crew member in the aircraft and who has been serving in line operations in that aircraft for at least six months, the FAA is interested in obtaining data pertinent to the following questions. Broadly, does the training conducted in a fixed-base simulator with a wide FOV, cross-cockpit-view visual system produce results equivalent to those produced in a like system having platform-motion cueing? Specifically, with regard to disturbance tasks, does recurrent training that is accomplished without motion cueing have any measurable effect on the pilot's capacity to respond in a timely and appropriate manner in the airplane? And finally, from a regulatory perspective, do recurrent proficiency checks conducted in a visually equipped fixed-base simulator verify the line-operational readiness of airline pilots without compromising the safety of the flying public?

Burden of Proof

It is much easier to prove the existence of a requirement than its non-existence. A single positive finding would prove the need for a requirement. In contrast, any number of negative findings would only support that it is unnecessary because the single positive finding could always be just around the corner. Thus, it is imperative that every effort be made to find any positive evidence that may exist. With this in mind, a research strategy is described that is biased towards finding an effect of motion. Not only is this good research design, but it is consistent with the FAA's need to be biased towards keeping motion for the sake of safety unless a watertight case for change can be made.

Research Strategy

In planning the design, every effort should be made to find an effect of motion. That is, every aspect of the study should be geared towards maximum diagnosticity. Therefore, a simulator with the best available motion platform (i.e., a modern six DOF freedom synergistic system) should be used, comparing full motion with no motion. In addition, the best available visual system (i.e., a wide-angle collimated cross-cockpit system) must be used.

The maneuvers chosen should also be as diagnostic of the need for motion as possible. The previous literature suggests that pilots should fly disturbance (closed-loop) maneuvers that are asymmetric and high in thrust, gain, workload, and unpredictability. Maneuvers involving engine failures would be good candidates. The flight tasks should entail the lowest level of outside-world visual cues (e.g., loss of engine during initial segment climb) encountered in recurrent training and checking (cf. Hall, 1978; 1989).

In addition, both subjective and objective data should be collected during both training and testing. The subjective data should include a grade provided by the instructor for each maneuver as well as opinions from the crew and instructor on control precision, control strategy and technique, gaining proficiency, physical and mental workload, comfort, and acceptability. The objective data should be collected at a high sampling rate and should be analyzed in both the time and frequency domains. It should include variables measuring stimulation of the pilot (e.g., motion, force feedback, instruments, and visual display), pilot behavior (e.g., control inputs, throttle inputs, and brake pedal inputs), and pilot performance (e.g., ground path control precision and flight path control precision).

In order to evaluate these measurements once they are collected, diagnostic performance standards must be developed. They need to include each maneuver and measurement. Additionally, they need to include the earliest period of the performance envelope in order to be diagnostic of the potential alerting function of motion. They must define the smallest operationally relevant differences so as to provide a way to evaluate whether differences found between the two motion conditions are meaningful. Finally, they must define the acceptable risk of reaching the wrong conclusion. In this case the definition must take into account that in the name of maintaining optimal safety, motion should be required unless there is excellent evidence to the contrary.

Along with being as diagnostic as possible, the experiment should be designed to minimize any possibility of mistaking spurious findings as effects of motion. Thus, there should be no differences between the motion condition and the no-motion condition, additional to the presence or absence of motion. Accordingly, a homogeneous pilot sample from the population of interest (e.g., regional airline pilots qualified on the simulated airplane) should be used. They should be “fresh from the airplane” to ensure no bias from recent simulator experience. The number of subjects required should be determined on the basis of the smallest operationally relevant effect size and the naturally occurring variability between subjects. Following standard practice, any uncontrollable variables that may affect performance, such as time of testing, should at least be counterbalanced across the two conditions. Finally, the equipment must be carefully calibrated at the beginning and end of the experiment to demonstrate that simulator performance is the same in both motion conditions and that the motion is as specified. To catch any intermediate drift , there should also be an abbreviated daily calibration (e.g., a visual comparison with the initial motion calibration and a subjective inspection of the visual system).

Experimental Design

With this strategy in mind, the experimental design can be constructed. To assess the simulator as a training tool, a forward transfer paradigm should be used. This will measure how well training in the simulator transfers to the airplane. To assess the simulator as an evaluation tool, a reverse transfer paradigm should be used (Cross, 1991). This measures how well pilots' proficiency in the airplane is reflected in their performance and behavior in the simulator.

As already mentioned, experiments in a real airplane are dangerous, impossible to control, and costly. Given that the FAA has been allowing total training and checking for qualified pilots in a high-fidelity simulator (Level C/D) for almost twenty years (Advanced Simulation Plan, 1980), we feel that such a simulator has been validated as a stand-in for the airplane. We thus recommend that both the forward transfer and reverse transfer studies use a quasi structure. That is, in the quasi-forward transfer study, pilots should be trained in the simulator, with or without motion, and then tested in the simulator with motion. The assumption is that the simulator training configuration that produces the best results during testing provides the best training for airplane flying as well. In the quasi-reverse transfer study because pilots can't be originally evaluated in the airplane, a sample of homogenous, experienced pilots should be used (on the assumption that they would perform similarly and well in the airplane). They should be evaluated in the simulator with and without motion. The assumption is that the simulator configuration that produces the best performance and behavior provides the most accurate reflection of pilot skills in the airplane. Combining these two approaches, quasi forward transfer and quasi reverse transfer, could strengthen the validity of results, provided that they are in agreement

Follow-Up Work

If no effect of simulator motion on transfer is found, a follow-on study examining different maneuvers, simulators, and pilots should be conducted to validate the results. In addition, some validation using transfer to and from the airplane should be done. If it is found that motion does affect transfer, the question should be further pursued by examining whether anything less than a full six DOF motion platform system could also impart the required cues. That is, the question of how faithful platform motion needs to be would still be open. Possible avenues of exploration are stroke length, DOF, and the special role of vibration.

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