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Simulator Platform Motion—The Need Revisited

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Abstract

The need to provide increased access to flight simulator training for U.S. regional airlines, which historically have been limited by cost considerations in the use of such equipment for pilot recurrent training, is discussed. In light of that need, the issue of whether more affordable fixed-base simulators, identical to full flight simulators in all respects except for absence of platform motion, might provide an equivalent level of safety when employed for recurrent training, is examined. Pertinent literature from the past two decades is reviewed. The paper observes that no definitive conclusion can be drawn that would warrant modification of current qualification requirements for platform motion in full flight simulators. The article concludes that this situation will remain unchanged unless new research is undertaken, which takes into account the lessons learned from past research, and the opportunities engendered by new technology. Broad guidelines for an appropriate research design are discussed.

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Platform Motion—A Need To Re-Examine The Requirement

The use of full flight simulators for pilot training and evaluation is universal among major air carriers in the United States, all of whom have, within their own corporate resources, access to full flight simulators equal to both the maneuver and scenario oriented requirements of Federal Aviation Administration (FAA) approved training programs. Flight simulators not only enable savings in training costs, they also 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. One might well conclude that this type of training is essential to safety, and should therefore be required of all air carriers under CFR 14, Part 121 and Part 135 operations (National Transportation Safety Board, 1993). The use of flight simulators remains optional, however, in the United States. U.S. airlines electing to conduct training and checking in the aircraft are free to do so, subject to FAA approval of their respective programs, including acceptable provisions for windshear training. Indeed, under current regulations U.S. airlines not conducting initial or transition training under CFR 14, Part 121, Appendix H (Advanced Simulation Plan, 1980), or under SFAR 58 (Advanced Qualification Program, 1990), **must** complete certain checking requirements in the aircraft. Many U.S. regional airlines conduct their pilot training programs on that basis.

Compared to U.S. major airlines, regional airlines, most of which do not own their own training equipment, have historically not had equal access to full flight simulators. Regional airlines electing to use flight simulators for training must establish contractual arrangements with training centers, or with other air carriers, who have the appropriate simulation equipment. As it turns out, the cost of such contractual arrangements, when coupled with the travel expenses for cockpit crew, can exceed the per hour cost of conducting training in some regional aircraft. Moreover, for some regional aircraft operated in the U.S., the worldwide availability of qualified flight simulators may be extremely limited. As a result, though most U.S. regional airlines would clearly prefer to conduct all their training in flight simulators, many such carriers have found it necessary to either conduct all training in the aircraft, or to limit the use of simulators to initial and transition training. The cost and limited availability of flight simulator access for recurrent pilot training has simply been prohibitive for small airlines. For many of these U.S. regional carriers, recurrent proficiency checks, and recurrent flight operations training, if any, are conducted in the aircraft. However, the need for flight simulation training for regional airline pilots is at least equal to that for pilots in major airlines, when considered in light of the fact that (a) the experience levels of regional pilots tend to be lower, (b) pilot turnover tends to be higher, (c) certain regional airport environments are less well equipped with navigation aids, (d) U.S. regional aircraft certification standards entail certain reduced system redundancy requirements, and (e) the procedures for powerplant malfunction or engine failure in turboprop aircraft can be more demanding than for jet aircraft. Clearly it is in the interest of safety to consider what measures can be taken to increase the accessibility of simulation equipment for regional air carriers.

In recent years the cost of full flight simulators has fallen significantly, and the availability of even less costly flight training devices (FTDs) has grown. At the upper end of the FAA defined continuum of approved FTDs (AC-120-45A, FAA 1992), the equipment fully duplicates a flight simulator, except for visual and platform-motion cueing requirements, which are optional. Since the cost of high fidelity simulator visual image generation and display equipment has also become more affordable, U.S. regional airlines are increasingly interested in the question of whether an FTD equipped with such a visual system (i.e., a fixed-base simulator) could be employed to fully accomplish the FAA requirements for recurrent training and checking, which constitutes a major cost consideration for such airlines. Allowing complete credit for the use of such devices in recurrent training could reduce the cost of access, or permit the direct acquisition of such equipment by regional airlines to accomplish their own training. It 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 overall safety of regional airlines could thereby be enhanced.

The FAA is therefore undertaking to revisit 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 field-of-view (FOV) visual system produce a result equivalent to that which would be obtained in a like system having platform-motion cueing? Specifically, with regard to the sudden onset of asymmetrical thrust, does recurrent training accomplished in the absence of motion-platform cueing have any measurable effect on the pilot’s capacity to respond in a timely and appropriate manner in the aircraft during maneuvers entailing powerplant failure? And finally, from a regulatory perspective, do recurrent proficiency checks conducted in a visually equipped fixed-base simulator provide an equivalent opportunity to verify the line-operational readiness of air-carrier pilots?

In the interest of obtaining information pertinent to the issue of simulator-motion fidelity requirements for recurrent training, the FAA has convened two workshops comprised of recognized experts in aeromodeling, and in platform-motion cueing, respectively (Transcripts, 1996; Longridge, Ray, Boothe, & Bürki-Cohen, 1996). It was generally concluded from these meetings that while certain economies in existing simulator qualification standards could be achieved without significantly degrading the cueing effectiveness of such equipment, an absence of platform-motion cueing is likely to have a detrimental effect on pilot control performance in fixed-base devices, particularly in maneuvers entailing sudden motion-onset cueing, such as loss of engine during initial segment climb, where visual references are limited. It was also noted, however, that there is no evidence that training conducted in such an equipment configuration would lead to degraded control performance in the aircraft. It was observed that pilots readily adapt their control strategies to the equipment at hand, whether in the direction of simulator to aircraft, or vice versa.

The FAA has also sponsored a comprehensive review of the past two decades of research literature pertinent to the contribution of simulator platform motion to training effectiveness, selections from which are summarized below.

The FAA Perspective

A flight simulator is intended to imitate or simulate, from the point of view of the pilot, both the physical characteristics and the behavior of an airplane and its environment, on the ground and in the air. A simulator that "successfully imitates" the airplane will, on the one hand, effectively train a pilot for flying the airplane and, on the other hand, accurately reflect a pilot's proficiency in the airplane. Substituting the simulator for the airplane in training and qualification of airline pilots avoids training accidents, enables controlled flight scenarios including emergencies, helps identify and satisfy individual training needs, and, dependent on the nature of the air carrier's operations, can reduce costs.

It is important to note that the use of flight simulators in air-carrier training and checking activities goes beyond the standard transfer-of-training paradigm. When used as a substitute for the aircraft, the evaluation of pilot performance in the device constitutes a determination of the readiness of the pilot to perform immediately in line operations involving the flying public. That is, unlike many classical transfer-of-training situations, the simulator-trained air-carrier pilot is expected to perform within satisfactory standards of proficiency in the aircraft from day one. Consequently, the simulator must be capable of supporting 100 percent transfer of performance to the aircraft. **Anything less would compromise safety**. The existing standards for full flight simulator qualification, all of which entail a requirement for platform-motion cueing, have a twenty year record of meeting the requisite criterion for transfer of performance. In the absence of compelling evidence to the contrary, it is therefore prudent to maintain these standards in the interest of public safety. Regulatory authorities will therefore continue to require platform motion for flight-operations training and checking conducted in higher-end devices, even under the more flexible requirements of SFAR 58, as long as there is any reasonable indication that simulator platform motion is beneficial, and, concomitantly, the FAA will continue to limit the credit permitted for use of non-motion equipped Flight Training Devices (FAA-S-8081-5B).

An Alternative Viewpoint

While it is certainly the case that there is no compelling evidence that platform-motion cueing can safely be eliminated from present flight simulator qualification requirements, it can also be observed that the evidence in favor of the requirement is itself less than compelling, and therefore warrants reexamination. As Bussolari, Young, & Lee comment in 1989, "[t]he requirement for platform motion is ostensibly based on the assumption that physical fidelity is highly correlated with training effectiveness. Since airplanes are capable of motion in all six axes (three translational, three angular), it is believed that the absence of motion in the simulator would significantly reduce its training effectiveness." Since there are hardly any objective criteria available, however, on what type of motion is required (given the fact that a simulator can never duplicate the range of motion cueing experienced in an aircraft), the existing regulations in FAR Part 121 Appendix H and the guidance given in the Advisory Circular on Airplane Simulator Qualification AC-120-40B (FAA, 1991; and its draft revision AC-120-40C) are largely based on subject matter expert opinion. While the Advisory Circular recommends extensive subjective evaluation by trained FAA flight inspectors, the reliability and validity of this subjective evaluation strategy has never been subject to systematic quantification. The principle argument in favor of present qualification standards for simulator motion—that they have stood the test of time—is weak. To the extent that continued adherence to these standards may actually preclude a significant segment of the air-carrier industry from the safety benefits of flight simulator training, it is reasonable to suggest that, unless objective criteria for motion requirements can be obtained, the requirement has no justifiable basis in fact.

Objective Vs Perceptual Fidelity

Since Edwin Link conceived his "Blue Box" in the late twenties, simulator engineers and engineering psychologists have been grappling with the question of what makes a simulation successful. The North Atlantic Treaty Organization's Advisory Group for Aerospace Research & Development distinguishes between objective (i.e., physical) and perceptual fidelity of a flight simulator (Advisory Group for Aerospace Research and Development, 1980). **Objective fidelity** of a flight simulator is relatively easy to determine. Using precise instruments that are free from the limitations and distortions of the human perceptual system, simultaneous 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 the more elusive **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 or behavior in the simulator and the airplane. Its determination requires carefully controlled experiments.

The discussion of objective versus perceptual fidelity is especially pertinent in the context of simulator motion, which is inherently limited in its objective fidelity despite substantial technological advances. Even as late as 1989, Brown, Cardullo, & Sinacori (p. 78) state that "[b]arring an unforeseen revolution in the technology of force and motion cueing, it is evident that it is hopeless to attempt to provide realistic force and motion stimuli in the sense that the acceleration forces produced by the aircraft can be replicated in the simulator." In particular, it is impossible to simulate sustained acceleration without sustained displacement, and any direct application of whole body acceleration forces will require inappropriate counter forces. The only way out of this dilemma is to focus not on the reality of the force and motion stimuli, but on the perceptions associated with force and motion, i.e., perceptual fidelity. The question that needs to be answered is how can pilots best be stimulated to perceive airplane motion in the simulator.

Motion occurs in space and over time. The most important sensor of motion occurring in the world around us is our visual system, perceiving motion from changes in position; and velocity and acceleration by additionally taking time into account (Sedgwick, 1986). Vision is also important for the perception of our own motion and posture, especially in the case of sustained, constant motion as often occurs when riding within a vehicle. Psychophysical evidence points to the ambient or peripheral visual system as especially important for processing dynamic and orientation information (see, e.g., McCauley, 1984; Dichgans & Brandt, 1978). However, we also rely on our tactile and somatic (perceiving pressure changes on skin and organs), our kinesthetic (perceiving joint position and muscle forces), and, more importantly, on our vestibular system (registering angular velocity and linear acceleration) for the perception of self-motion (Hall, 1989). All four of these perceptual systems have been called upon, either together or in isolation, to stimulate pilots to perceive motion in airplane simulators, and the degree of their success has been the subject of extensive research and controversy. Although there have been some promising results from tactile and somatic stimulation via dynamic seat pans (see, e.g., Martin, 1985), such devices have not gained much popularity beyond the armed forces. We will therefore restrict this discussion to a comparison of airplane simulations using either whole-body motion or visual displays or both to stimulate pilots to perceive motion.

Acceptability Of Simulator

As we will see, there are few points of general agreement in the discussion of whether whole-body motion is a required stimulus for successful training and qualification in the simulator. One area of consensus, however, is that pilots prefer vestibular motion cues to be present in the simulator. This has been confirmed both in informal discussions with pilots and in controlled experiments (but see Lee & Bussolari, 1989, discussed below).

Acceptability Of Several Motion Algorithms With Limited Visual Stimulation

In 1988, e.g., Reid & Nahon compared nine motion conditions (three different motion algorithms, each with three different parameter sets) with no motion using a B-747 simulator with a state-of-the-art six degrees-of-freedom (DOF) synergistic motion base incorporating hydrostatic bearings. Although the presence or absence of motion did not appear to affect pilots' performance and control behavior, it definitely affected their opinion regarding the simulation environment, both in their comments and ratings. Pilots were asked to "judge the quality of the motion cues and not any other aspects of the simulation," on two different rating scales. The University of Toronto Institute for Aerospace Studies (UTIAS) scale was used to assess the quality of motion associated with control inputs on the column, wheel, rudder pedals and throttle, as well as with turbulence and ground contact. The Massachusetts

Institute of Technology (MIT) scale rated smoothness, sense, amplitude, phase lag, discomfort, disorientation and overall impression. The summary of average UTIAS rankings by the seven pilots shows that the no-motion condition was consistently in the last place for all items but for turbulence, where it was in the second to last place. In the MIT ratings, the no-motion condition fared somewhat better, although it still was in the last position for overall impression. Disorientation was experienced second to worst without motion; and sense, discomfort, and phase lag occupied middle rankings. With regard to discomfort, for all three algorithms the parameter set resulting in the largest travel was rated worse than the no-motion condition. Smoothness of the simulator, of course, was rated best without motion, as amplitude was worst. Taking into account both ratings and comments from pilots, the authors conclude that "[t]he pilots preferred physical motion to be present in the simulator. They felt that it added to the realism of the simulation and was helpful in the piloting task."

Acceptability Of Motion Vs No Motion With A Wide Field Of View

One explanation for the preference for motion in the Reid & Nahon study might be that the visual stimulus was very sparse, thus requiring platform motion to provide the necessary cues to achieve the best percept of motion. They used a collimated out-the-window CRT with a narrow FOV (40 degrees horizontally and 30 degrees vertically) on which they displayed a yellow line drawing indicating depth and path on a black background. Hall (1978), however, extended the FOV to 200 degrees horizontally using a skyscape shadowgraph projector and found that even with this wide FOV (and less-than-perfect motion cues), the pilots still preferred the motion to the no-motion conditions for controlling a vehicle with an unstable Dutch roll. Specifically, he used a simulated Harrier GR Mk 3 with a three DOF motion system (roll, pitch, and heave) that was "suffering from backlash, low gain and hence reduced perception thresholds." The pilots rated lateral control in transition from hovering to jet-borne forward flight on a Cooper-Harper scale, where 10 is the worst score and means that the vehicle is uncontrollable. Unfortunately, Hall reports no queries regarding pilot comfort. There were eight different conditions resulting from all possible combinations of the presence or absence of motion, TV monitor, and skyscape (which provided the additional peripheral view). All conditions also included an instruments display (both head-down and head-up). Pilot C's results were provided as an example of the overall results. Each of the motion conditions was preferred to the corresponding no-motion condition, including the case in which the best vision was available. That is, the condition with motion, TV monitor, and skyscape (6, unsatisfactory) was preferred to the condition with no-motion, TV monitor, and skyscape (7, unacceptable). Interestingly, however, motion appeared to be most important when there was no visual information available besides instruments. Here, removing motion worsened the rating from 7 (unacceptable) to 9 (unacceptable and just controllable). Thus, Hall's study confirms Reid & Nahon's finding that pilot acceptance of a simulator depends on the presence of motion, extending it to simulators including a wide FOV visual system.

Acceptability Of Full Motion Vs Special-Effects Vibration With A Wide Field Of View And "Naïve" Pilots

Lee & Bussolari (1989, also reported in Bussolari, Young, & Lee, 1987) also looked at the effect of motion on pilot acceptance. They used a Boeing 727 Phase II (now Level C) simulator with a wide FOV (75 degrees horizontal and 30 degrees vertical per pilot seat) (FAR Part 121, Appendix H). There were two significant differences, however, between their study and Hall's (1978). First, the pilots in the Lee & Bussolari study did not know when the motion was on and off. Second, Lee & Bussolari used a "special-effects" condition instead of an actual no-motion condition. In this condition, the motion platform heaved at an extremely small amplitude (0.25 inches). This slight movement was intended to provide cues for the touchdown bump; runway roughness; buffets associated with flap, gear, and spoiler extension; and Mach and stall buffets. This condition was compared to full six DOF motion and to two DOF motion (heave and sway). In contrast to the other studies, Lee & Bussolari found that there were no differences in pilots' ratings of workload, control responsiveness, utility for training and checking, and overall realism, between any of the three conditions (or in performance and control behavior either). No information on simulator sickness is given. Young, however, in response to a question after his presentation at the Aerospace Medical Panel Symposium on Motion Cues in Flight Simulation and Simulator Induced Sickness in Brussels (Bussolari et al., 1987), reported that informal queries revealed no simulator sickness. These results indicate that the preference for motion found in the other experiments might be due to pilots' **expectation** that motion would be better, not to actual preference (see, e.g., Ebbinghaus, 1964). Another possible explanation is that some vibration as feedback for certain events is important for pilot acceptance, but that large displacements are not required.

Clearly, motion improves pilot acceptance of the simulator in some cases. Whether that improvement is due to a real preference or just a positive bias towards motion, and whether a full motion platform is required, are less clear.

Performance/Control Behavior Assessment In Simulator

The studies discussed in this section examined whether the preference pilots expressed for simulators including a motion platform over fixed-base simulators manifests itself also in improved performance and control behavior in the presence of vestibular motion cues compared to visual cues alone.

Motion Vs Visual Cues For Control Of An Unstable Vehicle

The Hall (1978) study previously described examined the impact of motion on pilots' control of Dutch roll oscillations in addition to pilot acceptance. Recall that Hall compared the effect of a less-than-perfect three DOF motion system with the effect of a central visual display (TV monitor) and the effect of a peripheral visual display (skyscape) on lateral control of a Harrier GR Mk 3 without autostabilizers. He measured aileron deflection or stick activity, roll rate, bank angle, and sideslip while transitioning from hovering to jet-borne forward flight. As with the Cooper-Harper ratings, the motion condition fared better than the corresponding no-motion condition regardless of whether there were both, only one, or no visual displays added to the instruments. This is seen in consistently higher-amplitude residual oscillations without motion in all measurements for pilot C (sideslip was not given for any of the conditions with skyscape). As with the pilot ratings, the difference appeared most pronounced for the instruments-only condition.

Hall concludes that even a "practical" motion system is "as good or better (in terms of performance) than nominally perfect peripheral vision for controlling a vehicle with an unstable Dutch roll." He continues to explain that this was due to the inability to generate sufficient lead to reduce the amplitude of the oscillations to an acceptable level in the absence of motion cues. It appears, though, that this explanation results from a comparison of the instruments-only conditions with and without motion, rather than from a comparison of the conditions including visual cues.

Motion Vs Visual Cues For Disturbance and Target Following (Tracking) Tasks

Hosman & van der Vaart (1981) also compared the effect of central and peripheral visual cues with motion cues on pilot performance and control behavior. In addition, they compared two different types of control tasks, a disturbance task and a target following task. In a **disturbance** task a random signal perturbs the controlled system and requires correction. This can be compared to a pilot stabilizing an airplane in turbulence. The signal affects all information displays the same, including the motion system. In a target-following or **compensatory tracking** task, a displayed random signal needs to be tracked. This task corresponds to a pilot following another airplane in formation flight. The lateral control task in the Hall (1978) study would also qualify as a compensatory tracking task, where pilots "track" a straight and level flight path. In fact, all flying tasks that do not involve any weather or mechanical failures can be looked upon as compensatory tracking of a flight path. Here, the signal goes only to the central display (or instruments), and **not** to the peripheral display or the motion system. The **maneuver** motion experienced during a compensatory tracking task contributes to the pilots' perception of the handling qualities of the simulator (or airplane) and of the effect of their control actions.

Hosman & van der Vaart (1981) included both kinds of tasks because motion is assumed to serve different functions in each case. Gundry (1976, for example) asserts that disturbance motion, but not maneuver motion, is generally assumed to serve an alerting function. Maneuver motion, on the other hand, provides feedback on pilot control behavior, but even so may be necessary only when controlling unstable vehicles, especially under high gain (cf. Hall, 1978; 1989).

Peripheral visual cues were provided by two CRTs displaying a moveable checkerboard pattern against the side windows of the simulator. Vestibular motion cues were provided using a three DOF (pitch, roll, and heave) system with hydrostatic bearings and "low noise motion characteristics." Three qualified jet transport pilots were tested. For both kinds of maneuvers, subjects had to correct for a quasi-random signal with a standard deviation of 1.875 degrees affecting roll attitude. In the disturbance task, the signal affected all available cueing systems, i.e., motion and peripheral and central visual displays, the CRT providing the central visual cues displaying the roll angle as the difference between airplane attitude and artificial horizon. In the tracking task, the signal affected only the central display, which showed the difference between the quasi-random signal and the roll angle of the simulator, i.e., the roll angle error. For both tasks, pilots were to minimize the difference displayed on the central CRT, using a spring-centered side stick controller.

Hosman & van der Vaart (1981) examined both the performance and control behavior of the pilots. Performance was reported as the standard deviation of roll angle for the disturbance task and the standard deviation of roll angle error for the tracking task. The results show that in both kinds of tasks, the addition of vestibular motion cues had a more significant impact on performance than the addition of peripheral visual cues. This was especially pronounced for the disturbance task.

For the control behavior assessment, pilots' frequency responses describing the relation between roll angle or roll angle error and pilots' side stick deflections were calculated for all conditions. For the purpose of the present discussion, we will report only the results for crossover frequency and phase margin, which were "markedly" different for the two tasks. A high **crossover frequency** reflects high controller **gain** over a wide bandwidth, and will thus result in good performance for both tasks. The **phase margin** reflects the remaining margin of **stability** of the human-machine system and is therefore also important for good performance. Generally, a trade-off relationship exists between phase margin and crossover frequency. Hosman (1996) reports that for the **disturbance task**, "the crossover frequency increased only slightly as a result of the peripheral displays, but strongly as a result of cockpit motion" in comparison with central visual cues alone. Phase margin was affected by neither the addition of peripheral visual or vestibular motion cues. That is, in the disturbance task, vestibular motion provided the primary cueing enabling pilots to increase gain without losing stability. In contrast, for the **tracking task**, crossover frequency decreased when motion cues alone, or motion and peripheral cues together, were combined with central visual cues. This was offset, however, by a large increase in phase margin when motion cues were present (or only a slight increase when peripheral vision was combined with central vision). That is, in the tracking task, vestibular motion also provided the primary cueing, but in this case it resulted in an increase in stability with a concomitant loss of gain. This, combined with Gundry's (1976) report that maneuver motion is only useful in controlling unstable vehicles, suggests that the primary role of motion during tracking tasks is increasing stability.

Thus, the Hall (1978) and the Hosman & van der Vaart (1981) papers concur in finding that the presence of motion improves pilot performance and behavior in the simulator, and that this improvement cannot be duplicated by the presence of peripheral vision in the absence of motion. In addition, Hosman & van der Vaart 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 Assessment in Simulator (Quasi-Transfer)

None of the studies considered thus far have examined the impact of motion on the **training** of pilots. That is, at best they have shown that motion is important for the flying **of simulators**. But, pilots are not trained to fly simulators—they are trained to fly airplanes. To discern whether simulator motion is valuable in the training of pilots, it is necessary to examine whether the presence of motion **in a simulator** improves pilot performance and behavior **in the airplane** above a baseline effect of simulator training without motion.

However, for the same reasons that it is difficult to use airplanes for the full training of pilots, it is also difficult to use airplanes in experiments. That is, it is impossible to control the weather, it is extremely difficult to do multiple repetitions of individual maneuvers, the degree of danger is too high for certain maneuvers such as responding to system failures, and airplane time is very costly. Consequently, some scientists have chosen to test the validity of simulator training by training pilots in a simulator and then testing the acquired skills in a different simulator or in the same simulator running under a different configuration. The assumption is that the new simulator (or simulator configuration) is more like an airplane than the trained-on simulator. This paradigm is called “Quasi-Transfer” because it tests for transfer of training, but not to an actual airplane.

Quasi-Transfer Of Training Of A Simple Tracking Task Under Different Motion Conditions

Levison (1981) used a quasi-transfer paradigm to study the effects on training of simulator motion and of the time lags between simulator vestibular motion and visual cues. He used the Multi-Axis Tracking Simulator at the Air Force’s Aerospace Medical Research Laboratory, which was simulating a single seat cockpit. Presumably, only the roll-axis motion capability was used in this experiment, and visual information was presented on a television monitor (Levison & Junker, 1977). Subjects were to keep the simulator in straight and level flight during gust-like disturbances and were described as “naïve to the task” (no other information on subjects is given). Each subject was trained under one of five conditions, vision-only, synchronous vision and motion, and three lag conditions. In the lag conditions, motion lagged vision by 80, 200, or 300 ms. During training, large reductions of mean-squared tracking error (roll angle) were observed in all conditions, but especially in the 80 ms lag and synchronous motion conditions.

The subjects in all lag and in the vision-only conditions were then tested in the synchronous motion condition as a stand-in for the real airplane (the group trained with synchronous motion had reached asymptotic performance very early in the training and was thus not tested again). All groups showed immediate improvement with synchronous motion, but only the group trained with the very short motion lag (i.e., 80 ms) appeared to transfer their training to the new condition, achieving the equivalent of the asymptotic performance of the synchronous motion group on the first post-transition trial. The vision-only group achieved the same performance after three more trials. With large lags, however, the positive impact of motion on training was gone or reversed. Specifically, after transition to the synchronous condition, the subjects trained with a 200 ms motion lag performed barely better than the vision-only group; and the subjects trained with a 300 ms motion lag actually performed worse, still trailing behind all other groups after seven post-transition trials. This shows that badly synchronized motion is in fact worse than no motion at all. One interesting note is that the advantage of near-synchronized motion was much smaller after transfer to the synchronized condition than it had been prior to transfer. Most likely, this is due to a floor-effect. That is, because the 80 ms delay group could not have improved any further (having immediately reached the best possible performance as defined by the synchronous group), differences between the 80 ms delay group and the other groups may appear smaller than they really are. Alternatively, it is possible that the attenuation of group differences is not an artifact, but indeed indicates that if there is a motion advantage in the simulator, only a small portion will be transferred to a higher-level device (and, presumably, the airplane). In either case, it is clear that the presence of motion, if closely aligned with vision, had a positive impact on the training of subjects, not just on their performance within the original simulator configuration.

Pilot behavior was assessed by obtaining frequency response measures from selected subjects. For our purposes, we will only report the comparison between the control behavior of the vision-only and the 80 ms motion lag groups during the early post-transition trials. The parameter of interest is observation noise, which is an Optimal Control Model parameter reflecting subjects' information-processing limitations. The observation noise/signal ratios were lower for subjects trained with motion than for subjects trained with only visual cues. This indicates that the presence of delayed motion during training, if the delay is short (i.e., 80 ms), improves the subjects' efficiency in processing synchronized visual and motion cues when transferred to a higher level device, compared to having had no motion at all 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."

Quasi-Transfer Of Engine-Failure (Disturbance) Training Under Different Motion Conditions

A few years earlier, DeBerg, McFarland, & Showalter (1976) had used a quasi-transfer design to study the effect of motion and visual cueing on take-off engine-failure training. Recovery from a take-off engine failure is exactly the high-gain, asymmetric, closed-loop disturbance task where vestibular motion cues may serve as an early alert. Thirty-six KC-135A aircraft commanders who were matched for initial proficiency were trained in one of four simulator configurations, resulting in nine pilots per condition. The National Aeronautics and Space Administration's Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center was used because of its "unique ability to generate the types of aircraft motion cues which an outboard engine failure would generate," namely "yaw, roll, and lateral motion." The four training phase configurations ranged from maximum cueing with visual and motion cues to minimal cueing with neither motion nor visual cues, via motion-only and vision-only configurations. For the training configurations, the FSAA motion was restricted to "an envelope roughly analogous to that of a six-post synergistic motion system." The visual system was described as a "six-degree of freedom system in which a color television camera is mounted on a gantry and moves relative to a fixed-model board. The scene is presented to the pilot, through collimation optics, on a cathode-ray tube situated in the forward cockpit window." After training, transfer was assessed in the unrestricted motion configuration with the full visual system.

The authors maintain that their experiment shows an increase in training effectiveness both with the addition of a visual or a motion system, and a synergistic improvement in training when both are used together. Neither subjective pilot opinion nor the analysis of the performance variables measured during the evaluation phase fully warrant this claim. Pilots rated both the "sufficiency of cues to negotiate engine failures" and the "cueing system as a training device" twice, once after the training and once after the assessment phase. When rating, on a scale from one to five, the **sufficiency of cues** to negotiate engine failure after the training phase, pilots indeed rated the configuration with both motion and vision most positively (4.89). After they had experienced also the assessment phase with the full simulator capabilities, however, they gave the configuration with neither motion nor visual cues the highest rating! The motion-only condition was rated lowest after either phase (3.89 and 4.33, respectively). As a **training device**, the no-motion/no-vision configuration was rated least favorable after both phases (3.22 and 3.33, respectively), in each case followed by the motion-only configuration. After training, pilots rated vision-only highest (5); and after assessment, they rated vision with motion highest (5). It appears, then, that the only claim consistent with all results would be that, in most cases, pilots favor simulator configurations including a visual system.

To assess performance, the authors claim to have measured 34 variables during the evaluation phase. But most of their conclusions are based on mean total roll and total yaw, which "best discriminated between the four cueing systems employed," as determined by "multivariate statistical analyses" (a somewhat obscure analysis of variance is also presented). For ground engine failures (at 140 knots), De Berg et al. correctly state that performance deteriorated with vision or motion alone compared to the configuration with neither vision or motion. Vision and motion combined, however, was no better than the no-vision/no-motion condition, at least for roll (for yaw there was indeed a slight improvement). For flight engine failures (at 47 feet altitude), visual and motion together were indeed best, followed by motion alone, neither motion nor vision, with vision in the last position. Thus, with regard to performance, motion may be beneficial, but only for flight engine and not at all for ground engine failures. With the *caveat* that pertinent data may have been lost in the analysis procedures, all we can conclude from the uneven results of this study is that nine pilots in each condition may not be quite enough to allow true differences between groups to emerge from the variability of pilots within groups.

In sum, the Levison (1981) study confirms the previous results (Hall, 1978; Hosman & van der Vaart, 1981; Reid & Nahon, 1988) that demonstrate a benefit of motion in simulator training, yet extends those findings in a significant way. Levison (1981) showed that the advantage of motion in the simulator transfers to a higher level device, suggesting that it may transfer to the airplane as well. DeBerg, McFarland, & Showalter's (1976) results, however, which were obtained using more realistic equipment, real transport aircraft pilots, and a highly diagnostic task with the quasi-transfer paradigm, do not fully confirm Levison's conclusions.

Training Assessment in Airplane (Transfer)

Despite the inherent constraints on transfer-to-airplane studies, several people have attempted them. In contrast to the Levison (1981) quasi-transfer study, in all cases the motion benefit found in the simulator was completely lost in the airplane. However, each of the studies has some form of methodological shortcoming; some out of the control of the scientists such as the state of technology at the time of the experiment and the inherent problems of airplane experimentation. Below is a brief description of several such studies.

Transfer Of Training—Tracking Maneuvers

Jacobs (1976) trained 27 subjects in a non-visual Singer-Link GAT-2 trainer with three DOF (presumably roll, pitch, and heave). He then tested them, as well as a group of control subjects who received no training, in a Piper Cherokee Arrow airplane. The subjects who received training were evenly divided into three groups. One group was trained in the simulator without motion, another with normal washout motion in bank with sustained pitch angles, and the third with directionally-random motion (i.e., "washout banking motion in which the direction of motion relative to that of the simulated airplane was randomly reversed 50% of the time as the cab passed through a wings-level attitude"). Subjects in each of the three experimental groups were trained on 11 tasks, all tracking maneuvers (straight and level flight, straight and level power changes and airspeed transitions, climbs and descents, constant bank angle and standard rate turns, airspeed transitions during turns, climbing and descending turns, instrument navigation patterns). Training performance was evaluated through experimenter observation of number of "errors," i.e., violation of FAA private-pilot flight check standards. Transfer was evaluated through time and trials to FAA performance criteria and number of errors. Jacobs found that during simulator training the group with washout motion had fewer errors than the other groups, demonstrating again that in the simulator good motion is advantageous—even with tracking maneuvers. However, after the subjects transferred to the airplane, although all three groups performed better than the control group with no simulator training on all of the three dependent variables, there were no significant differences between the three experimental groups. That is, simulator training improved performance in the airplane, but motion in the simulator (whether no motion, "bad" motion, or "good" motion) had no additional effect on performance in the airplane.

Although the results from this study appear to be straightforward, their credibility is undermined by at least two factors. First, the motion platform on a Singer-Link GAT-2 trainer is much less advanced than the motion platforms available now. Even if that type of simulator motion did not affect airplane performance, current motion might be able to. That is, it may be that skills learned under the more realistic motion cues available today would transfer better to real flight than skills learned under any of Jacobs' motion conditions. Second, Jacobs used tracking maneuvers. Although this choice is understandable considering the safety and logistical problems of performing disturbance maneuvers in real flight, it undermined his goal of evaluating the usefulness of motion. An additional factor that may have obscured a potential training advantage of motion is that student subjects used in the study received fixed amounts of training in the simulator instead of being trained to asymptotic performance.

Transfer Of Training—Disturbance Maneuvers

Ryan, Scott, & Browning (1978), on the other hand, used a more diagnostic set of maneuvers to investigate the effect of simulator motion on performance in the airplane, consisting of instrument maneuvers and take-offs and landings with and without engine failures. The asymmetric engine failures create a sudden disturbance that the pilots must recognize and correct in the shortest possible time (Hall, 1989). The subjects were first-tour naval aviators that had recently completed multi-engine undergraduate training and possessed "Standard Instrument Cards." They were trained in a P-3 "Operational Flight Trainer" with a narrow-angle television for (modelboard) visual cues and a six DOF motion system that was disabled for the no-motion group. All 39 no-motion students and four of the motion students transferred to a S-2, a small twin reciprocating-engine airplane. Six motion students transferred to the T-44 twin turboprop airplane. Questionnaires revealed that student and instructors "strongly favor[ed] having motion cues available," but did not indicate any motion sickness associated with either condition. Performance was rated by instructors. These results show that even with these maneuvers, the results were again the same as in the Jacobs study. That is, the presence of simulator motion improved performance in the simulator, but had no bearing on performance in the airplane. A footnote is that the presence of a sudden disturbance did, indeed, increase the diagnosticity of maneuvers—the engine abort on take-off[1] was the **only** maneuver that demonstrated the motion advantage **in the simulator**.

[1]It is unclear whether the take-off was rejected or continued.

Prediction Of Performance In The Airplane From Performance In The Simulator

Koonce (1974) had used the same non-visual simulator as Jacobs (1976) (i.e., GAT-2, but with just pitch and roll) for a study examining transfer of training to a Piper Aztec-D. In this study, he trained three groups of thirty pilots with multi-engine and instrument ratings on five maneuvers representative of those usually performed under instrument flight rules (IFR) (cruise on a VOR airway, holding at a VOR station, ADF approach, ILS approach, missed approach) and five maneuvers usually performed under visual flight rules (VFR) (take-off and climbout; 360 degrees steep turn; chandelle; lazy eight; landing). In addition to the no-motion and washout-motion conditions, he used a sustained motion condition where the simulator moved in the appropriate direction and then stayed there until pilot control activity indicated a change. Koonce found the exact same results as Jacobs (1976). That is, "simulator motion tends to increase the subject's acceptance of the device, lower performance error scores, and reduce workload on the subjects and the observers through the aiding effects of the motion onset cues. But the differential effects of motion on the simulator performance does not transfer to the performance in the aircraft." Additionally, however, Koonce examined under which condition performance in the airplane best predicted performance in the simulator. He found that the sustained motion condition had the most predictive power. In sum, although all three conditions trained the pilots equally well for flying the airplane, the pilots' performance in the airplane could be best predicted from their performance in a simulator with sustained motion. He argued that this is due to greater stability of performance in this simulator condition. Unfortunately, this study suffers from the same flaws as the Jacobs study, outdated motion platform and non-diagnostic maneuvers.

Air Force Human Resources Laboratory Transfer Studies

The only other widely-known studies using transfer-of-training to real airplanes were conducted by the Operations Training Division of the Air Force Human Resources Laboratory. Martin (1981; Waag, 1981) reviewed six of these studies. Each used a simulator with six DOF, five studies used the Advanced Simulator for Pilot Training (ASPT) located at Williams Air Force Base (AFB) and one used the Simulator for Air-to-Air Combat (SAAC) located at Luke AFB. Most of the studies varied only the presence or absence of motion during training, one varied also the FOV (without finding an effect). A variety of different maneuvers were used, such as basic contact maneuvers (including stalls), aerobatics, basic fighter maneuvering, and air-to-surface weapon delivery. As with all other transfer-to-airplane studies, there was no benefit of simulator motion in the airplane despite a benefit of motion in the simulator for some of the studies. Bussolari, Young, & Lee (1989) conclude that "while it is arguable that the motion systems in these studies were of the highest quality, the absence of motion effects across such diverse training environments and simulator equipment considerably weakens the case for requiring elaborate motion platform systems in flight simulators used for training pilots in fixed wing aircraft operations."

Summary of Transfer-Of-Training Studies

In sum, several investigators have examined transfer of training from the simulator to the airplane. 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. However, the indication from the Levison (1981) study that this advantage would transfer to real airplanes was not borne out in any of these studies. The only benefit of simulator found was an increase in the predictability of airplane performance from simulator performance (Koonce, 1974). This result, however, will need to be confirmed with state-of-the-art motion and visual systems.

The failure of these studies to find an impact of simulator motion on airplane flying might be due to aspects of the experiments, as opposed to a real lack of benefit of simulator motion. This is of particular concern due to the fact that all of these studies suffer from the same set of problems. First, all used outdated equipment, in particular with respect to the motion and visual systems. Also, most of the equipment suffered from large transport delays, bad synchronization of the visual and motion systems, and lack of calibration of the motion system. Second, in most cases they used non-diagnostic maneuvers. Disturbances are difficult or impossible to initiate and to terminate in the real world and dangerous to maneuver. However, disturbance maneuvers are required for testing the value of simulator 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 determine a specific effect size. 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 or non-pilots (Young, 1967). Fourth, pilots and instructors were not naïve regarding the motion condition, which may have allowed bias to affect performance or performance evaluation, respectively (Ebbinghaus, 1964). Fifth, all of the studies measured only performance. Control behavior and subjective responses, however, may be more sensitive to the effects of motion. In fact, these problems are not limited to the transfer-to-airplane studies; many of them affect the simulator-only studies and quasi-transfer of training studies, as well.

Why Revisit Motion Fidelity Requirements Now?

The question of whether to require vestibular motion cueing in simulators used for flight training has been researched for at least four decades. A marked decline in research activity in the nineties may be attributed to the failure of this extensive research to resolve the issue. Our endeavor to readdress this question is spurred both by the failure of previous work to adequately address the motion fidelity requirements issue for current air-carrier pilots and equipment as well as changes in the research environment and opportunities.

Major technological advances have occurred in the wake of the recent “virtual reality”—or rather simulated reality—frenzy in the entertainment industry. Due to its marketing value, efforts mainly focused on the visual system. The most advanced image generators and display systems are at a point where they can almost perfectly reproduce the visual stimulation resulting from real airplane motion. In particular, the widening of the FOV resulted in increased stimulation of the peripheral visual system, resulting in “a more compelling visual display of motion” (McCauley, 1984). As we have seen even in the research showing an advantage of motion, at least in the simulator, this advantage was often reduced with improved visual stimulation. In contrast, the last major advances with regard to motion cueing date back to at least the early eighties. They include the practice of providing critical onset cues followed by subliminal washout, and to use “gravity align” platform attitudes (Brown et al., 1989). These techniques do indeed help to achieve some perception of sustained acceleration, but still do not overcome the inherent limitations in simulating vestibular motion cues. It is possible, then, that today’s visual systems provide such high quality motion cues as to render the inherently imperfect vestibular motion cues superfluous, at least for recurrent pilot training.

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). Experienced pilots' increased reliance on vestibular cues may make them more sensitive to sensory conflicts and thus simulator sickness. Potentially, then, even if a sophisticated visual system alone were to provide sufficient motion cues for recurrent pilot training in the simulator, forgoing motion may still be unacceptable due to the effects of the ensuing sensory conflict on pilots.

The final reason for returning to the question of how best to simulate airplane motion is the ever increasing use of flight simulators in air-carrier training. Not only does this increase the urgency of this reexamination, but it also has greatly improved research opportunities. One result of the increased experience with and improved quality of flight simulators in air-carrier training is the practice of total training and checking in a Level D, and, with appropriate pilot experience prerequisites, a Level C simulator, sometimes referred to as "zero-flight-time training." Total recurrent training can be accomplished in either of these levels of simulators. This practice was established in the Advanced Simulation Plan put forth by the FAA in 1980 (FAR Part 121, Appendix H). While the difficulty of doing transfer-of-training experiments remains, the experience with zero-flight-time training represents a *de facto* validation of high-level full-platform-motion simulators as a stand-in for the airplane in quasi-transfer studies.

The Need for Further Research

It is clear from a review of the pertinent literature that no definitive conclusion can be drawn that would warrant modification of current qualification requirements for platform motion in full flight simulators. The FAA believes that this situation will remain unchanged unless new research is undertaken, which takes into account the lessons learned from past research, and the opportunities engendered by new technology.

The research literature suggests certain potentially fruitful strategies to be considered in developing a practical research design. To assess training effectiveness, the research might employ a quasi-transfer paradigm, testing transfer of training to an FAA-certified stand-in for the airplane for recurrent "zero-flight-time" training. To assess evaluation, the study design could employ a modified backward or reverse-transfer paradigm, that is, it could measure how well pilots' control performance and behavior in the simulator reflect their proficiency in the airplane (Cross, 1991). Such a research design would allow a determination of the extent to which there are control strategy differences now between qualified full flight simulators and their target aircraft, since this represents an existing baseline which constitutes an accepted standard of safety. Combining these two approaches, quasi-transfer and reverse transfer, could strengthen the validity of results, provided that they are in agreement.

In setting up the experiments, the study design should build on the lessons from previous work: It should use a state-of-the-art, FAA qualified Level C simulator with a wide-angle collimated cross-cockpit visual system and a modern six DOF freedom synergistic motion system that is carefully calibrated before each experimental session. It should use a homogeneous pilot sample from the population of interest, that is, regional airline pilots qualified on the simulated airplane. It should seek to prevent pilot or instructor bias by concealing both the purpose of the experiment, and the specific simulator motion/no-motion condition to be applied (through automated programming of motion conditions, with an identical motion platform initialization sequence). Pilots should be asked to fly highly diagnostic disturbance (closed-loop) maneuvers that are characterized by high-gain, high-workload and unpredictability. As a worst case, 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). The study should examine both control performance and control behavior by collecting objective data at a high sampling rate, as well as pilot and instructor subjective data on the most pertinent variables, including pilot queries regarding simulator sickness. The study should compare the extremes of the continuum from full six DOF platform motion to no motion at all. If no effect of simulator motion on transfer is found, a follow-on study should be conducted to validate the results. Should it be determined 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.

In conclusion, the findings to date do not solve the FAA’s questions regarding the role of platform-motion cueing in regional airline recurrent pilot training and checking. Previous investigations have been extremely useful, however, in defining the type of experimental design that would best address these questions. Moreover, technological advances and improved research conditions provide the ideal opportunity for pursuing this research. It is hoped that by readdressing these questions, simulator availability and affordability will be improved, resulting in better training with a concomitant increase in overall safety.

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