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Training Value of a Fixed-Base Flight Simulator with a Dynamic Seat

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In this paper, we first explain that pilots experience airplane motion via multiple perceptual systems, which makes motion a candidate for simulation via stimulation of only a subset of these systems. Next, we discuss the relative merit of vestibular cues when piloting an airplane. This is followed by a comparison of the vestibular cues received in the airplane and those possible, or practicable, in an airline-pilot training simulator, considering also the history of flight-simulator motion and alternative technologies. We conclude that a vast body of research has shown that accurate cues are not achievable at present, and that those available have not been shown to improve transfer between airplane and simulator. We then examine the cost of motion, and posit that it may prohibit some airline pilots from reaping the benefits of simulator training, with a concomitant loss in passenger safety. This consideration is especially pertinent given the world-wide training needs. Moreover, the equipment, facility, and maintenance costs associated with hexapod-platform motion systems may serve to discourage operators from upgrading the simulator's fidelity in other important areas, such as assuring that the simulator cockpit does in fact match the equipment in the target aircraft, and that the simulation includes realistic operational representation of the national air space, including the air-traffic-control environment. We describe current and planned research on the training effectiveness of an alternative approach, which provides trainees with visual motion and heave-onset cues in what otherwise corresponds to an FAA Level D Full Flight Simulator in terms of data fidelity. This includes the results of a "proof-of-concept" phase that culminated in the successful type-rating of six pilots on a twin-engine turboprop airplane.

Nomenclature

$	=	United States dollars
ft	=	foot/feet
g	=	acceleration of gravity
˚H	=	degrees horizontal
kg	=	kilogram
m	=	meters
s	=	seconds
V_1	=	take-off decision speed; the minimum speed in the take-off, following a failure of the critical engine, at which the pilot can continue the take-off and achieve the required height above the take-off surface within the take-off distance
V_1 *cut*	=	engine failure at or above V_1 with continued take-off
˚V	=	degrees vertical

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I. Motion Cue Sensation and Perception

TRANSPORT AIRPLANES move through the air. Some of this movement is commanded by the pilots in their effort to follow a predetermined flight path. Some of it is generated by outside disturbances, such as weather or airplane systems.[1-3] According to many authors (see, e.g., Ref. 4), the first type of motion, which provides pilots with feedback on their control actions, matters only when controlling inherently unstable vehicles, such as helicopters. Because the scope of this paper is the training of pilots of stable air-transport category airplanes, we will focus on the second type of motion, which alerts pilots of events that require corrective action from the pilot. Before discussing how and whether to simulate motion stimulation during airline-pilot training, we need to understand how pilots use motion cues. How do they sense ownship movements? What sensations or combination of sensations do they use to perceive the status of their airplane and fine-tune their control actions?

These questions are critical to determine the requirements for tools that efficiently and effectively train pilots who are trusted with the safety of the flying public. It has been long established that ground-based simulator training is both safer[5] and more effective than in-air training because pilots can fly, with the possibility of corrective repetitions, carefully designed scenarios simulating the most critical in-air eventualities (Line Oriented Flight Training, LOFT). This includes extreme weather and system failures requiring advanced control skills, but also situations requiring excellent cognitive, managerial, and interpersonal skills. Examples for the application of the latter are situations requiring rapid decision making based on complex and often incomplete information, managing of insufficient, overlapping, or unpredictable crew and automation resources, and resolution of disagreements with crew members or air traffic control on how to resolve a situation.

A. Multimodal Perception of Motion Cues

The most controversial issue in determining flight simulator requirements is how and whether to simulate airplane motion. Unlike the representations of the out-the-window view, the instruments, the movement and resistance of the control-input devices, and the sound, which are predominantly perceived by one single human sensory system, airplane motion is sensed by multiple receptors (see, e.g., Refs. 6 and 7):

1) The photosensitive receptors in the retina of the eye are responding to changing size, shape, and texture as well as successive changes in position of targets moving across the out-the-window view as a function of airplane motion. From this information, the brain indirectly derives velocity and acceleration. The same receptors also register the changes in the instruments indicating airplane position directly or indirectly, such as altitude, airspeed, vertical speed, and attitude (roll, pitch, heading). Unlike the mechanoreceptors described below, photoreceptors do not habituate to repeat stimulation.

2) The vestibular apparatus in the inner ear contains mechanoreceptors that send direct signals to the brain when they are deflected as a function of changes in head accelerations in the six degrees of freedom (DOF). The receptors for head rotations are located in three roughly orthogonal semicircular ducts reminiscent of a rate gyro. When the head is slightly tilted forward, the lateral duct lies in the horizontal plane, its receptors registering yaw accelerations. The planes of the anterior and posterior ducts are approximately vertical and offset by 45 degrees from the sagittal and coronal planes. Their sensors signal pitch and sway accelerations. Linear head movements, including those resulting in a change of the head's orientation towards gravity, are transduced via the two otolith organs, the utricle and the saccule. The sensory area (macula) of the utricle is approximately parallel to the lateral semicircular duct in the horizontal plane. The macula of the saccule is roughly parallel to the sagittal plane of the head.

3) Pilots also perceive airplane motion via mechanoreceptors distributed over the body (tactile and proprioceptive sensors). If pilots use the perceptions resulting from such stimulation to control an airplane, they are sometimes somewhat pejoratively referred to as "flying by the seats of their pants," i.e., without the use of the instruments.[8] For transport airplanes, which are inherently stable, the direct or mechanical sensations of motion may indeed primarily occur via the mechanoreceptors in the skin and the supporting tissues of the parts of the body touching the seat and the back of the pilot's chair (tactile receptors). Occasionally, particularly strong accelerations or decelerations jerk pilots forward or push them into their seats, which would additionally stimulate proprioceptive sensors registering the state of muscles and joints.

4) Finally, the inner ear registers changes in pitch and intensity of engine noise, which also may contribute to an indirect perception of motion (see, e.g., Ref. 9). The sound waves are collected by the outer ear and sent, via the eardrum, to the ossicles of the middle ear, where the signal is amplified to apply pressure on fluid in the cochlea of the inner ear, which in turn stimulates pressure-sensitive hair cells.

B. Vection: The Illusion of Motion from Vision

It is this multimodality of ownship-motion perception that sets the simulation of airplane motion apart from the simulation of the perceptions experienced when flying an airplane. While the out-the-window view, the instruments, and the feel and force-feedback received from the control-input devices must be directly simulated to result in a percept that is comparable to the one experienced in the airplane (e.g., there is no perception of an out-the-window view without an image generator simulating it), simulator motion can be perceived without actual physical motion stimulating the vestibular and the proprioceptive systems, as long as the eye perceives the changes that would be expected from motion in the out-the-window view. This illusion of motion is called vection.

Most of us have experienced vection: while waiting at a traffic light, we might catch the movement of a neighboring car in our peripheral field-of-view, and step on our brake to avoid violating a signal. The perceived changes in our position relative to the one of the neighboring car tricks us into believing that it is our car that is moving, presuming that it is the other car that remains stationary.

The phenomenon of vection is the first of four reasons why the need for vestibular motion simulation in the presence of a wide-field-of-view visual system is increasingly a subject of debate, while the need for an out-the-window view, force feedback, and sound has been taken for granted despite the fact that their effect on transfer of skills and behavior between the airplane and the simulator has also not been fully documented. The remaining reasons for this debate are, second, the potential dangers of relying on vestibular motion cues to determine aircraft attitude and required control actions; third, the limitations of how sustained accelerations and decelerations can be realistically simulated and the effectiveness of these attenuated cues; and fourth, the cost of providing pilots with effective motion cues. These questionable reasons will be discussed below, before describing an effort by a turboprop airplane manufacturer to provide its world-wide customers with high-quality training via an alternative to a six-DOF motion Full Flight Simulator (FFS).

II. Vestibular Motion Cues—Friend or Foe?

The short answer to the question of whether vestibular motion cues help pilots while flying an airplane is yes and no. Under normal flight conditions for a stable transport airplane, where motion cues result from pilots' control inputs, it is generally agreed that pilots can easily dispense with vestibular feedback on their control actions, so in this case, vestibular cues are neither friend nor foe. In the case of outside disturbances from weather or malfunctions, however, vestibular cues may be processed faster than visual cues.[1-3] This has been documented theoretically[10,11] and in our research, where pilots responding to V_1 cuts in a fixed-base simulator compared to pilots in a motion simulator showed a pedal-response time delay even when they knew that an engine failure would occur, as well as which engine would fail.[12,13] However, the response delay was less than half a second, much smaller than what would be expected from looking at the literature, which mentions vection effect-latencies in the order of seconds (referring to the more complex computation process of deriving accelerations from position and time). This may be due to the fact that pilots were already immersed in and actively controlling the illusionary motion before the failure occurred.[14] Other factors that may have shortened pilots' response times include a wider field of view, lower visual accelerations, a difference in axes of the perceived motion compared to those tested in the laboratory in earlier studies,[15] or the naturalistic scene instead of the more abstract geometrical patterns of earlier studies.[16] Also, even if stimulation of the vestibular system should result in somewhat faster response times, a potentially equally important advantage of the visual system is its lack of habituation, which in the vestibular system leads to a loss of sensitivity with repeat stimulation.[6] All this indicates that in some situations encountered in airline operations, physical motion cues may be a friend, but neither an important, or, for that matter, a reliable one.

Finally, due to the limited reliability of the vestibular system, there are situations where it is recommended that pilots ignore any but the visual cues gathered from the instruments. The vestibular system fairly accurately perceives motion only as long as the motion sensations are experienced within normally occurring limits.[17] In terms of piloting, this means that sensations in flight that are outside of the normal flight envelope may not be accurately interpreted by the vestibular system. Unusual attitudes and airplane upsets, for example, are uncommon flight experiences, and therefore often result in spatial disorientation during flight. Spatial disorientation has been defined as "[a failure] to sense correctly the position, motion or attitude of the aircraft or of him/herself within the fixed coordinate system provided by the surface of the earth and the gravitational vertical" (from Benson, 1988, as cited in Ref. 18). Examples of disorientation experienced in flight include misperceptions of the magnitude or direction of actual rotation resulting in false sensations of rotation (angular, or somatogyral, illusions such as the "graveyard spin" or the Coriolis effect) or misidentification of a nonvertical force as a vertical force resulting in a false sensation of body tilt (linear, or somatogravic, illusions such as nose-high pitch experienced during forward acceleration or an inverted sensation that sometimes occurs when the airplane is leveled off suddenly after a climb in weather). Disorientation can also take the form of a combination of somatogyral and somatogravic illusions, such as the "leans," which can result in the often fatal "graveyard spiral."[19] These types of spatial disorientation have led to several loss-of-control accidents; in fact, they are the "only type of accident that is not reducing in world-wide statistics."[20] The urgency of effective training in the prevention, recognition, and recovery from unusual airplane attitudes is therefore increasingly recognized. Due to a lack of flight test data and the limitations of the conventional simulator motion platform, however, the use of conventional motion-base training simulators for upset recovery training is controversial. Without the accurate visual, instrument, and especially motion cues to simulate an upset, there is a possibility of negative training. False motion cues, for instance, could prime pilots to inaccurately identify actual in-air upsets. Moreover, they may distract trainees from acquiring a habit of focusing on their instruments, their only reliable reference during an in-air upset. When pilots are tricked by their vestibular system into disorientation, they must read their instruments to recognize the airplane's actual orientation in the air. Only then will they be able to take the appropriate control actions for recovery.

III. Comparison of Simulator and Airplane Motion

One could argue that if pilots are to ignore misleading motion cues for unusual attitudes in the airplane, they need to be trained to do so also in the simulator. However, it has been documented that such maneuvers lie outside the validated data envelope of today's training simulators, and even if the data were available, the motions required would lie outside the capabilities of the standard Stewart hexapod-motion platform used in training.[21] Airplane motion has relatively complex and rich dynamics even during normal flight. The complexity arises from various nonlinearities affecting the overall motion, while the richness is due to various sources of dynamics that may be excited during flight through the atmosphere. The motion that a pilot experiences inside the cockpit is not only the three dimensional nonlinear rigid-body motion of the airplane, but also the motion due to flexible structural dynamics. The latter may interact with the rigid-body dynamics. Various kinds of internal or external inputs, such as pilot commands or atmospheric disturbances that the airplane encounters during its flight, may excite all these dynamics at once.

If such complex and rich airplane-motion dynamics are to be completely simulated to achieve high physical fidelity, the dynamics model used must include and capture all aspects of the dynamics involved that contribute to the resulting dynamics. Even in the context of the transport-airplane category, which is the scope of the discussion here and the dynamics of which are considered quite benign in the whole aircraft spectrum, it would be very difficult and costly to build such a complete dynamics model. Moreover, in the context of creating a sufficient level of realism in the simulator cockpit for airline-pilot training, one can question whether such a complete dynamics model is necessary. Fortunately, in many cases a relatively high degree of subjective realism can be achieved by using a mostly rigid-body aircraft dynamics model with some special effects to simulate the other dynamics. The simplification of the flight dynamics model used in simulation removes certain parts of the airplane-motion dynamics and reduces the physical fidelity in the translation of real airplane motion to the presentation of motion in a motion-base flight simulator.

Another simplification or modification in the simulation of airplane motion is driven by the motion-system hardware limitations. It involves the generation of motion cues within the constraints of the motion-hardware capabilities. These hardware constraints have an even stronger impact on the physical fidelity of the resulting motion than the dynamics-model simplification just described. Most improvements of the motion platform since the inception of motion-base flight simulation have been in overcoming some of these hardware limitations, which translates into increased motion-platform capability, be it in the maximum displacement that it can produce or in the frequency bandwidth that it can dynamically cover. Most of the effort in improving the motion-cue generation is driven by the unsubstantiated opinion that better training can be achieved by immersing the pilots in higher motion realism. Also some regulatory bodies, such as the U.S. Federal Aviation Administration (FAA) or European Joint Aviation Authorities (JAA), still require pilot training and evaluation in motion-base flight simulators. Before discussing the fidelity level of the motion cues used in today's airline-pilot training and evaluation, various motion systems are reviewed below.

A. Motion Simulation Technology

1. Early Systems

The earliest flight simulator designs did employ some type of elementary motion, because "it was mistakenly believed during this period that the vestibular apparatus enabled a person to sense orientation in the air as well as on the ground (Robinson 1973). It was later realized that orientation depends largely on vision."[22] One example from this period was the Sanders Teacher of 1910, a modified airplane on a universal joint which relied on natural gusts of wind to rotate and move in all three rotational DOF.[22] Other examples moved in response to instructors' manually produced disturbances, such as the Antoinette trainer which could move in pitch and roll.[22,23] The Ruggles Orientator (1917) could move in pitch, roll, yaw, and heave via electric motors responding to the control inputs of the pilot and the instructor.[22] The motions provided by these early simulators, however, were far from accurately simulating the forces experienced in an actual aircraft.

The Link Trainer was perhaps the first system to impart some perception of realism (although its motion system came soon under scrutiny too, see below). It was developed by Edwin Link in 1930 and used compressed air bellows as actuators. These allowed for a more controlled actuation in the three rotational DOFs. Motors produced attitude disturbances while an electric suction pump controlled the stick and rudder responses. The Link trainer, however, had no instruments and no visual system.[22]

Around this time, instrument-flight training was introduced and many fixed-base devices were developed to teach instrument flying. Link, however, continued to employ motion in his newly developed instrument trainer, the so-called "Blue Box." The instruments of the Blue Box were controlled either pneumatically or mechanically and the fuselage could yaw 360 degrees.[22] Pitch and roll movements, however, were very limited.[24]

As instrument flying became more common, the training value of these early motion systems came into question. The Link Trainer, specifically, was criticized as unable to accurately simulate aircraft motions. Soon fixed-base simulators were preferred over motion simulators. This preference was bolstered by the argument that pilots should fly by instruments rather than by the "seat of the pants."[22] Although Ed Link continued to insist that "trainer motion was needed even if incorrect, since motion was present in flying," he eventually developed a fixed-base trainer based on electronic analogue technology that sold very well.[22]

Because of increased flight-test data requiring increased computing power, simulation almost completely shifted to digital computers, which allowed flight simulation to really take off. Most of these new simulators had no motion systems until the late 1950s,[22] when the Stewart platform came into use.

2. *Stewart Platform Motion*

Current state-of-the-art motion systems commonly used in airline-pilot training simulators employ six-DOF Stewart platform (hexapod) motion with six synergistically actuated legs. Also with modern computational power, the motion transport delay can be minimized and the generation of the motion cues can be much better synchronized with the other cues than in the simulators described in the previous section. That said, however, the fundamental limitation of such motion platforms is still there, i.e., they are not capable of generating the sustained acceleration cues found in flight. Because of the limited linear displacement capability of the actuators (typically 3 to 6ft), the motion cues are constrained by limits in duration and amplitude, regardless of what the flight-dynamics model commands. Various washout algorithms have been developed in order to generate "realistic" motion cues within these constraints. The general approach is to generate physical motion-onset cues intended to serve an alerting function and to rely on other cues, notably visual, for sustained motions.

Because of the fundamental limitations above, other approaches that are capable of generating better sustained motion cues have been developed. Four such approaches are described below. As we will see, however, they may not be practical for application to today's airline-pilot training regardless of their success in improving the simulation of motion cues.

3. *Vertical Motion Simulator (VMS)*

The VMS is located at the National Aeronautics and Space Administration (NASA) Ames Research Center. It consists of a four-DOF platform mounted on a two-DOF large-amplitude platform. It is capable of providing 35ft sway and 50ft heave displacements.[25] As its name implies, the largest amount of motion it can provide is in the vertical direction (heave) with up to 0.75g acceleration. With such a large vertical excursion, the VMS is capable of providing faithful g-loading of normal aircraft maneuvers, including those experienced by large transport aircraft in the critical approach and landing phases.[26] However, even the maximum loading produced by the VMS in its maximum acceleration is still only a fraction of the maximum design loads of a typical civilian (4g) or military (9g) aircraft.[27]

4. *Centrifuge Motion Simulator*

A centrifuge-type flight simulator, such as Wyle's Dynamic Flight Simulator (DFS), can produce a sustained high level of acceleration. The DFS consists of a 30ft balanced cantilever arm with a dual gimbal three-DOF gondola. It is capable of generating up to 15g acceleration. The primary axis of the gondola can be varied according to the gimbal orientation. Although the capability of generating sustained acceleration is desirable, such a centrifuge system may generate disorientation from pilots' head movements resulting in a vestibular Coriolis effect.[28]

5. *Desdemona*

The Desdemona simulator concept has been developed by the Dutch applied scientific research organization TNO and the Austrian simulator company AMST Systemtechnik. It combines the six-DOF platform motion concept with the centrifuge design. It consists of a fully gimbaled cockpit, capable of unlimited rotation in all directions, mounted on 8m horizontal and 2m vertical tracks. Desdemona can produce 0.5g horizontal and vertical accelerations along the tracks, and in centrifuge mode it can generate loads up to 3g.[29]

6. *In-flight Simulator*

As the name implies, in-flight simulation uses an aircraft as a simulator, and thus it does not have the same motion limitations as ground-based simulators. NASA and Calspan are among the pioneers in this area.[30,31] For use as an in-flight simulator, the aircraft-dynamic responses need to be modified to closely mimic the dynamics of the simulated aircraft. Hence, the simulation is only as good as the understanding of the characteristics of the simulated aircraft. Moreover, the limitations of the in-flight-simulator aircraft also restrict the flight envelope of the simulation. In-flight simulation is more difficult, more time-consuming, and usually more expensive than ground-based simulation and hence, it is reserved for those portions of the flight-training regime that cannot be adequately evaluated on the ground.[30]

Even though the four approaches described above are capable of overcoming some of the limitations of the Stewart motion platform, the costs to procure and maintain such systems are prohibitive for pilot training and evaluation. Therefore, for training and evaluation of airline pilots requiring "full" motion simulation, the Stewart platform is still the most common choice. But do such platforms provide effective motion cues, i.e., do they affect transfer of skills between simulator and airplane for training and evaluation of airline pilots?

B. Motion Fidelity in Airline-Pilot Training

When considering motion-fidelity requirements for airline pilot training, we have to differentiate between physical and perceptual motion fidelity. Physical motion fidelity is defined as the match between motion cues in the simulator and in the airplane. As indicated in the previous section and as we will describe in more detail below, there are limits to such physical fidelity imposed by the constraints on the Stewart motion platform. But what about the perceptual fidelity of motion simulation, achieved by stimulating all senses available to perceive motion? It is defined as a match between both pilots' subjective perception of the simulator and the airplane, and also between pilots' performance and control strategy or behavior in the simulator and the airplane. To determine this more quantitative definition of perceptual fidelity requires carefully controlled experiments involving many pilots. To avoid this obstacle, it has been suggested that perceptual fidelity can be deduced from the knowledge of how a human pilot senses motion, and that motion-cueing algorithms should be designed based on pilot-motion-perception models (see, e.g., Ref. 32). However, such models are far from complete, and will still have to be validated via the more cumbersome human-in-the-loop experimental process.

Several studies report on the degree of physical fidelity of the type of motion widely used in today's airline-pilot training (e.g., Refs. 12, 33, and 34). Refs. 33 and 34 compared the response of the motion platform with the actual aircraft response, or the predicted response from the aircraft dynamics model, using engine failures on take-off. Some results reported by Ref. 33 indicated that the simulator motion response using a typical six-DOF Stewart platform was much suppressed compared to the actual aircraft's response. They also indicated the presence of above-threshold opposite-direction motions in some DOFs due to the washout system (for engine failure at take-off, these appeared in roll, sway, pitch, and heave). Ref. 34 reported that the failure-induced lateral acceleration, arguably the most important motion cue to recognize engine failures at take-off, was not well represented by the motion system of the FAA Level C simulator of an airplane with wing-mounted engines used in that study. Not only was the response greatly attenuated, but visual inspection of the measured response did not lead to an easy distinction of failure-induced lateral acceleration, unlike the response derived from the flight-dynamics model (relatively high peak shortly after engine failure). If such motion cues are assumed to be the primary alerting cues, then all these data lead to the legitimate question of whether the motion cues provided by the Stewart platform are sufficient to provide the pilots with adequate levels of motion cueing. Due to concerns raised by the relatively low level of failure-induced lateral acceleration produced by the test simulator, data from other simulators representing aircraft with wing-mounted engines were obtained through the FAA National Simulator Program Office (NSPO). The NSPO manager sent letters to 30 operators of FAA AC120-40B[35] Level C/D simulators, with a surprisingly low response rate of fewer than 30 percent. Initial analysis was performed on eight data sets, concluding that "[t]he data pretty much confirm what we saw with the [Refs. 36 and 34] airplane; quite small [lateral accelerations]."[*]

* Email from E.M. Boothe to first and third author, October 26, 2000, 15:39

Unfortunately, only four data sets were available for further examination. Comparison of the failure-induced lateral accelerations produced by these simulators further suggested that the motion-system performance of the test simulator was not atypical.[37]

In a follow-up study[12] an FAA Level D research simulator at NASA was used. Without adjustments to the motion system, it fell in the low fidelity region for translational and rotational motions in all axes according to the Sinacori-Schroeder motion fidelity criteria for gain and phase error distortion.[38,39] With some adjustments, the translational-lateral axis, which was considered critical for the maneuvers tested, could be brought into the medium fidelity range (and the translational-vertical axis slightly improved), but not without trading off some of the fidelity of the rotational axes, especially yaw (see Fig. 1).

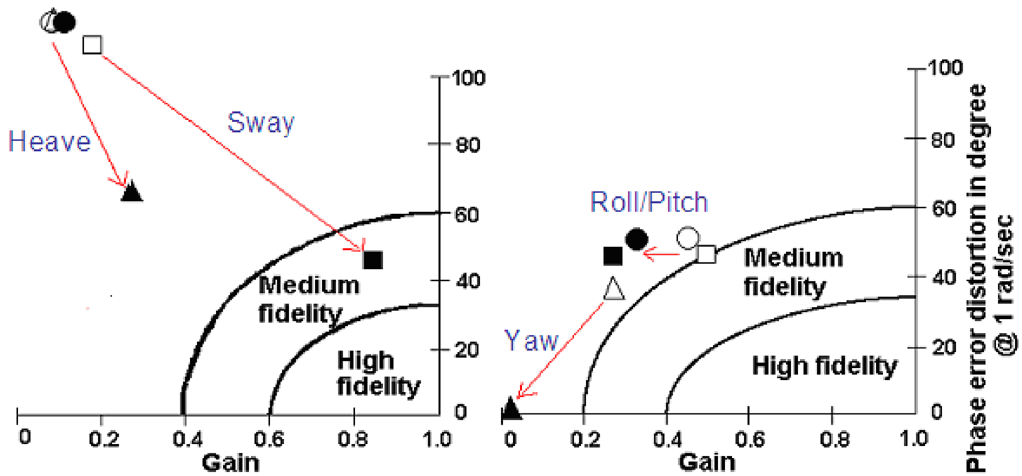

Figure 1. Example of trading off rotational axes to improve translational axes of Stewart platform motion (adapted from Ref. 12)

The above discussion suggests that the physical fidelity of the motion used in today's commercial pilot training is far from reflecting the real world. However, airline pilots have been successfully trained with these low levels of motion fidelity for many years. Also, virtually no scientific evidence supports the notion that flight-simulator platform-motion bases contribute to transfer of training across a range of aircraft types, missions, maneuvers, and measures (see, e.g., Refs. 12, 34, 40, and 41; for a review of older studies, see Ref. 42). This indicates that even if the physical fidelity of motion used in airline-pilot training is poor, when such motion is combined with other cues, it may deliver a sufficient level of perceptual fidelity. Whether this perceptual fidelity depended on the presence of physical motion cues was specifically tested in the studies reported in Refs. 12, 13, 34, 37, and 40. These studies systematically compared opinions, pilot-control inputs, and flight precision of pilots being tested and trained in a simulator with and without motion. Later, pilots were all tested again in a simulator with motion to examine whether there were differences attributable to whether or not they had received physical motion cues during training. High transfer of the skills acquired in the simulator was found regardless of the motion condition during training. With this in mind and with the current cost of motion-base training simulators that is beyond the budget of many small regional carriers, it is logical to shift the focus to the training effectiveness of the device rather than its physical motion fidelity.

IV. Cost of Simulating Motion Cues Via A Stewart Platform

For lack of empirical data supporting the need for vestibular motion cues for transfer of performance and behavior between the simulator and the airplane, supporters of the need for a Stewart platform-motion system often mention the success of over 25 years of using FAA Level B and C simulators for recurrent and Level D simulators for initial zero-flight-time training and evaluation, the former equipped with a three-DOF platform, the latter two with a six-DOF platform.

In reply to this argument, two issues need to be raised. One is the lack of definition of the performance of such systems. With regard to the Level B simulator, which is sufficient for complete recurrent zero-flight-time training and evaluation, the participants of the FAA/Industry Symposium tasked "to make updated recommendations concerning the limits, tolerance and dynamics of motion cuing…to reduce costs without compromising that essential motion cuing" ended up recommending, admittedly without empirical evidence but based on expert intuition, "a motion system having a minimum of four degrees of freedom which must be at least pitch, roll, sway and heave."[43] Regardless of this recommendation, it seems likely that experienced airline-pilots in the United States will continue to be trained and evaluated, even with future regulatory changes, in Level B simulators requiring no more than three-DOF motion systems. Moreover, even if pilots should be trained with six-DOF motion, the motion system will be tested only against the manufacturer's specifications and against its initial performance, which is not much of an improvement over the current predominantly subjective assessment. It seems that despite the strong sentiment in some circles that hexapod-platform motion is essential for pilot training and checking, that opinion is not matched by a willingness to require rigorous qualification standards for such systems.[44]

The second issue to be raised in response to proponents of the "if it ain't broke, don't fix it" stance is the cost of such an argument, and the resulting potential of depriving many passengers world-wide of the safety benefit gained from simulator training. In 2004, the 20-year life-cycle cost including procurement, maintenance, and electricity for a hydraulic motion system was estimated at approximately 1.32 million dollars per "training simulator." (The estimate for an electric system was 0.93 million dollars, mainly due to a reduction in operating costs.)[45] It is important to note that this does not include the construction and maintenance of a facility that can accommodate the size and weight of a motion-equipped simulator, nor does it include the labor of the highly trained technicians required to maintain the system. It also excludes the cost of the increased complexity of initial and recurrent qualification of the simulator. Travel costs of trainees to distant facilities (especially for simulators of which there is a shortage) and of time lost due to scheduling issues and/or motion-system malfunctions are also not included. This indicates that the real cost of motion is much higher than the number cited in Ref. 45.

For airlines that have to rent simulator time, estimates in rental increase due to motion range between 25 and 50 percent. Ref. 46 cites Level D simulator costs between \$550 and \$1,100 per hour in 2005. Rentals of FFSs simulating small airplanes may even be higher because of their scarcity, so commuter airlines are hit the hardest. For recurrent pilots training 10 hours per year mostly in Level D simulators (although a Level B would be sufficient), the yearly cost can be \$11,000 per year or more per pilot. For initial pilots, who spend about 32 hours in a Level D simulator, this cost can rise to \$35,200 or more per pilot. According to the Bureau of Labor Statistics, there were about 70,000 airline pilots in 2006 in the United States.[†] This means that for recurrent training in a rented simulator, U.S. airlines alone could spend an additional 385 million dollars per year for motion. Accounting for the increasing number of pilots overall and the new-hires due to attrition of existing pilots, the cumulative cost of motion amounts to billions of dollars in a few years just for the United States. The question is whether motion is really the best place to invest all these resources, when its practical transfer benefit, albeit theoretically plausible, remains elusive despite many decades of research attempting to prove otherwise.

V. World-Wide Training Needs

The original motivation for the FAA/Volpe Center investigation of air-carrier-pilot flight simulator requirements (see Refs. , 13, 34, 37, 40, 42, 43, and 47) had been the FAA's so-called "Commuter Rule," which was at the heart of the FAA's "One Level of Safety" initiative for all airlines, large or small.[47,48] The Commuter Rule was published in December 1995 and required all commuter airlines operating airplanes with a two-person crew (i.e., those with ten or more passengers) to train and qualify these crews under the same rules as the major airlines. Included in this rule was a requirement to extend the training and testing emphasis on predominantly stick and rudder skills, to the integration of manual skills with cognitive skills such as crew resource, automation, and task management. As mentioned in the introduction, such an increase in training and testing complexity can only be achieved by exposing pilots to carefully designed line-oriented scenarios in a flight simulator. The problem arising from this requirement was that for the smallest commuter airplanes, the cost of acquiring/renting an FFS, if it is even available, may exceed the cost of acquiring/operating the real airplane. Similarly, the cost and loss in revenue resulting from using the real airplane for training is much smaller than for large airplanes, so that in some cases, the use of the airplane as a training tool is a cost-effective alternative to renting time on an off-site simulator, which incurs additional costs of transporting and housing pilots to and at the training site. So, the ultimate goal of the FAA/Volpe Center flight simulator requirements program was to ensure that all cueing requirements applied to flight simulators do contribute to improving transfer of performance between simulator and airplane for effective training and evaluation. This is the best means to provide all airlines with access to effective simulator training and evaluation, while maintaining or improving quality of training and accuracy of evaluation.

† U.S. Department of Labor. Occupational Employment and Wages, May 2006. Bureau of Labor Statistics 2006 [cited 24 July 2007]; Available from: http://www.bls.gov/oes/current/oes530000.htm

This motivation applies at least as urgently to international training needs. There is a world-wide pilot shortage.‡ Pilots come from increasingly different backgrounds and may have very little prior experience, whereas the cognitive demands of operating an airplane continue to increase with increasing automation, congestion, and congestion-relief measures. The need for effective training tools is especially urgent in remote locations of the world, where aviation is the primary means of transportation and where it is especially important to bring quality training tools to the pilots.

VI. An Alternative Approach: Visual Motion With Heave Onset Cues

The considerations discussed in the previous sections motivated a leading turboprop manufacturer and world-wide provider of type-rating training to consider the question of whether it would be possible, by availing themselves of the latest research results and training-tool technologies, to stem the potential for a reduction in training opportunities due to the pressing need for pilots together with the high cost of qualified training tools. In concert with their National Aviation Authorities (NAA), a member of the JAA, they developed the concept of a high fidelity, fixed-base training device with a wide field-of-view visual system, referred to as a Full Flight Trainer (FFT), that presumably will be within the financial reach of many turboprop customers. The perception of motion in this device was generated mainly by the visual cues, assisted, in the FFT-X, by a dynamic seat providing some vestibular, proprioceptive, and tactile motion cueing.

An experimental type-rating program is in progress. Under close supervision by the NAA, a set of pilots with multipilot-airplane licenses has been fully type-rated on the simulated airplane using a protocol including ground school, simulator training on the FFT-1 and FFT-X (as a replacement for the FFS sessions in the provider's traditional training program), plus base flight training.

Phase 1, resulting in complete type-ratings of six pilots without any use of an FFS, proved the concept that a fixed-base training device, followed by standard training flights in the airplane, can prepare pilots for a successful type-rating. In addition to the type-rating qualification by the examiners, questionnaires were administered to the pilots and instructors after flying the FFT and the airplane, rating, as appropriate, the pilots or the FFT. A final debriefing session was also conducted, with some of the pilots having informally experienced the FFS before this debriefing. This phase will be described in detail below.

Phase 2 resulted in eight type-ratings. It followed the procedures developed for the first phase, without formal data analysis. This phase served as a test bed for collection of objective data for Phase 3 and will not be described.

Phase 3, which will represent a more formal evaluation of the training value of the FFT, is in the planning stages. In addition to questionnaire data, data on pilot-vehicle performance and behavior will be collected directly from the simulator. Moreover, two groups of pilots will be trained: one following the protocol of the first type-ratings, with pilots being trained in the FFT-X, the other following a traditional protocol where the training phase is done in the Level D FFS. Data will be collected by querying pilots and instructors and recording data on pilot-vehicle performance from the training tools. Pilots will be evaluated on the FFS in a quasi-transfer design before transferring to the airplane. Finally, for comparison purposes with the earlier studies conducted in the framework of the FAA/Volpe Center flight simulator requirements program,[12,13,34,37] some of the most diagnostic maneuvers from those studies will be added to the training and testing regime.

A. Phase 1 Procedures

1. Participants

The first set of type-rating candidates consisted of six employees of the NAA. Pilots were divided into two groups based on their experience, and the training regimes were adapted accordingly. Experience was defined in terms of multipilot-crew and airline experience. The two "Experienced" pilots held a multipilot type-rating license and had airline experience. They had flown a total of 14,000 and 11,000 hours respectively, of which 8,500 and 6,000 hours were as members of a multipilot crew.

The four "Nonexperienced" pilots held single-pilot type-rating licenses only and had no airline experience. Their total flight hours ranged between 6,000 hours (2,600 of which were in a military turboprop airplane) and 563 hours. One of them, with 4,500 hours, was a flight instructor.

The three simulator instructors and two airplane instructors were all employed by the training provider. The type-rating examiners were deployed by the NAA.

‡ Slobodan Lekic. Worldwide Pilot Shortage Affecting Safety, Analysts Say. 17 July 2007. Associated Press [cited 9 August 2007]; Available from: http://www.aviation.com/ap_070717_worldwidepilotshortage.html

2. Equipment

After ground school, pilots underwent training in two different training tools, the FFT-1 and the FFT-X. These FFTs simulate a 48-passenger airplane with two wing-mounted turboprop engines and 18,600kg maximum take-off weight capacity. Both FFTs feature 3-channel projection visual systems with a 180^{o}H×40^{o}V field-of-view. Their display systems are different, however. The FFT-1 uses an uncollimated cylindrical screen, while the FFT-X uses a collimated spherical screen. The FFTs are intended to elicit the same perceptions and thus provide the same training value as a Level D simulator, via Level D aerodynamics, engines and ground handling models, systems representation, sounds and visual system (the latter only for the FFT-X, because the FFT-1 image is not collimated).

In addition to providing visual motion cues, the FFT-X generates physical heave motion cues via three electric jacks in the seat pedestal. They follow a relatively simple model of touch-down, taxiing, and turbulence motion. Vibrations representing different propeller speeds are simulated via loud-speakers fitted under the pilots' seats. The purpose of these mainly proprioceptive/tactile motion cues is to provide a disturbance motion onset cue that can be directly perceived, instead of having to be differentiated using changes in position and shape over time.

The FFT-1 has been qualified by the NAA for Category (CAT) I operations, type-rating, and recurrent training. The FFT-X has been given training, testing, and checking credits equivalent to the ones usually granted to a Level B FFS, including low-visibility operations (CAT I, CAT II, low visibility take-off), captain upgrade, recency check (three take-offs and landings in the past 90 days), induction course, and Operator Proficiency Check (OPC).

3. Protocol

The protocol depended on the level of experience of the trainees, namely, whether they had airline experience or not. Experienced trainees completed a four-week training course and Nonexperienced trainees completed a six-week training course. Table 1 shows the training sequence and tools for the two levels of experience.

Before transferring to hands-on training, trainees acquired the theoretical knowledge required to fly the airplane by attending ground school. Training occurred via a course software instruction system developed by the training center, cockpit trainers, and classroom instruction by certified instructors using copyrighted materials developed by the training center. The curriculum included information on systems, operating procedures, limitations, and performances. It also included a safety course with cockpit-evacuation mockup sessions and a Crew-Resource-Management (CRM) course. Nonexperienced trainees additionally received theoretical instruction in specific Multi-Crew Coordination (MCC). Trainees had to demonstrate their knowledge in systems, safety, and performances by completing closed-book multiple choice tests before proceeding to the FFT-1.

After satisfactory completion of ground school, trainees proceeded to hands-on training in the FFTs. Each four-hour FFT session was introduced by a one-hour briefing and followed by a half-hour debriefing. Trainees spent half of each session as Pilot Flying (PF) and Pilot Not Flying (PNF) in their usual position (e.g., captains flew from the left seat). In the FFT-1, Experienced and Nonexperienced trainees were trained in normal, abnormal, and emergency operations and CRM in five sessions and eight sessions, respectively. Experienced trainees additionally experienced LOFT. For both groups, this was followed by four FFT-X training sessions preparing them for all operations and more complex CRM. The last session assessed their progress in an eventful LOFT (see Table 1). This was followed by the final Type-Rating Skill Test administered by NAA personnel.

Training in the airplane was conducted during the last day of the four or six-week course for Experienced and Nonexperienced trainees, respectively. In the airplane, each trainee acted as PF in his usual seat, with the instructor serving as PNF. Experienced pilots flew four take-off- and landing patterns, Nonexperienced pilots flew six patterns and additional training maneuvers including a simulated engine flame-out. The type-rating certificate was awarded after the FFT-X skill test and final reports from the airplane instructors to the NAA.

Table 1. Training sequence by level of experience

Tool	Experienced pilots	Nonexperienced pilots
Theoretical instruction	2 weeks	2.5 weeks
ACOS/Cockpit Trainer/Mock-ups	Systems, Safety	
Classroom	Operations, CRM	Operations, CRM, MCC
Full Flight Trainer	4 hours/session, excluding briefings and debriefings	4 hours/session, excluding briefings and debriefings
FFT-1	5 sessions preparing for normal and abnormal operations, icing conditions, recognition of stall conditions and recovery, effective cockpit management and communications	8 sessions preparing for normal and abnormal operations, icing conditions, Minimum Equipment List (MEL) dispatch, recognition of stall conditions and recovery, effective cockpit management and communications, decision making. Includes normal LOFT
FFT-X	4 sessions preparing for system failures, recognition of stall conditions and recovery MEL procedures, decision making and error management. Last session consists of LOFT with system failures, severe weather, traffic, stall conditions requiring go-arounds, diverting to alternate, emergency descents/evacuations	4 sessions preparing for system failures, recognition of stall conditions and recovery, Minimum Equipment List (MEL) procedures, decision making and error management. Last session is Toulouse-Montpellier LOFT with system failures, severe weather, traffic, stall conditions requiring go-arounds
FFT-X	A 4-hour (2 as PF and 2 as PNF) Type-Rating Skill Test approved by the NAA	
Airplane	1 day	2 days
	4 take-off-and-landing patterns, including full-stop and touch-and-go landings, with instructors reporting to NAA	6 take-off-and-landing patterns and additional exercises, including full-stop and touch-and-go landings, with instructors reporting to the NAA
		Complementary exercises including simulated engine-flameout on take-off at 400ft followed by a single-engine go-around, holding, Instrument Landing System (ILS) approach and landing
Total	4 weeks	6 weeks

4. Maneuvers Flown In the FFT

Table 2 shows the maneuvers trained in the FFT-X and evaluated during the check ride in the FFT-X (as required in Appendix 2 to JAR-FCL 1.240 and 1.295[49]).

To be considered mastered, maneuvers had to be flown smoothly and accurately within the airplane's limitations. The successful outcome of the maneuver must never be in doubt. The general limits to be observed were +/–100ft for altitude, +50ft/–0ft for starting a go-around at decision height, +50ft/–0ft for minimum descent height/altitude (MDH/A), +/–5 degrees for tracking on radio aids and half scale deflection for a precision approach, +/–5 degrees heading with all engines operating, +/–10 degrees with simulated engine failure, and +/–5 knots for speed with all engines operating, +10 knots/–5 knots with simulated engine failure.

Table 2. Maneuvers required for type-rating

Section 1: Flight Preparation	Taxiing in compliance with air traffic control or instructions of instructor
Section 2: Take-offs	Normal take offs with different flap settings, including expedited take off (only one flap setting required by the training center)
	Instrument take-off; transition to instrument flight is required during rotation or immediately after becoming airborne
	Crosswind take-off
	Take-off at maximum take-off mass
	Take-offs with simulated engine failure
	Rejected take-off
Section 3: Flight Maneuvers and Procedures	Turn with and without spoilers
	Windshear at take-off / landing
	Simulated cabin pressure / emergency descent
	Early recognition and counter measures on approaching stall
	Precision approaches down to a decision height (DH) not less than 60m (200 ft) manually without flight director
	Precision approaches down to a decision height (DH) not less than 60m (200 ft) manually with flight director
	Precision approaches down to a decision height (DH) not less than 60m (200 ft) with autopilot
	Precision approaches down to a decision height (DH) not less than 60m (200 ft) manually with one engine simulated inoperative
	NDB or VOR/LOC approach down to MDH/A
	Circling approach
Section 4: Missed Approach Procedures	Go-around with all engines operating
	Other missed approach procedure
	Manual go-around with the critical engine simulated inoperative
	Rejected landing at 15m (50 ft)
Section 5: Landings	Normal landing
	Landing with simulated jammed horizontal stabilizer
	Crosswind landing
	Landing without extended flaps

5. *Data Collection*

Participants' opinions were collected at various levels of formality. Most important of all was the type-rating certificate awarded by the NAA. Next were detailed questionnaires modified by the training center from those used in the FAA/Volpe Center studies. Additional forms gave an opportunity to express general opinions. Finally, participants were invited to a final round-table debriefing in the presence of the NAA decision makers. At that point, some of the trainees had experienced the FFS informally. No data were recorded from the simulator or the airplane. Table 3 shows the types of data collected. We are reporting the questionnaire data and a summary of the final debriefing.

Table 3. Types of data collected

Who	When	How	What
ATC simulator instructors	After each session in the FFT-X	Form with open question	General opinion
		Questionnaire with 5-point “worse-same-better” scales comparing FFT and FFS	Trainee’s performance, control strategies & technique, workload, gaining proficiency, own comfort for each maneuver
		Form with open questions	Trainee’s progress, FFT & maneuver adequacy, suggestions for improvement
	At final debriefing	Round-table discussion	General impressions
ATC airplane type-rating instructors	After airplane training	Form with open questions	Adequacy of initial and additional flight training
		Questionnaire with 5-point “worse-same-better” scales comparing FFT and FFS	Trainee’s performance, control strategies & technique, workload, gaining proficiency for each maneuver
	At final debriefing	Round-table discussion	General impressions
Trainees	After each session in the FFT-X	Questionnaire with 5-point “worse-same-better” scales comparing FFT and “expectations” of airplane; or 4 to 5-point “very bad-very good” scales rating FFT	Handling qualities, simulator cues, feel & response of controls, control strategies & technique, workload, comfort, acceptability, gaining proficiency for each maneuver
	After airplane training	Form with open questions	Adequacy of initial and additional flight training
		Questionnaire with 5-point “worse-same-better” scales comparing FFT with airplane; or 4 to 5-point “very bad/different-very good/same” scales rating FFT	Handling qualities, simulator cues, feel & response of controls, control strategies & technique, workload, comfort, acceptability, gaining proficiency for each maneuver
	At final debriefing	Round-table discussion after 4 of the trainees had informally experienced the FFS	General impressions

B. Results of Phase 1

The most significant result, of course, was the successful type rating of six pilots in a two-crew turboprop transport airplane, four of them without prior experience in a multicrew airline environment. This shows that the final performance of trainees in the FFT-X was, at a minimum, satisfactory. In the next sections, we will look at the opinions of the instructors and trainees, first on trainees’ performance and how they achieved it, then on the quality of the FFT-X as a simulator of the airplane. Before going into these details, however, it must be noted that these ratings were collected during actual training, where some pilots may rate a maneuver more than once and others may never rate the same maneuver. This is especially true for the ratings collected before the type-rating in the FFT-X. The maneuvers in the airplane were either rated by all six pilots or by all four Nonexperienced pilots.

1. Ratings of Pilot Performance and Behavior

In the airplane: The successful type-rating was wholeheartedly confirmed by the instructors rating the pilots in the airplane after their successful type-rating skill test. Not one pilot was rated as performing worse than a typical pilot for any of the eight maneuvers. For single-engine go-arounds and for the take-offs with engine flame-outs at 400ft above ground level (AGL), all pilots were rated as performing the same as a typical pilot in an FFS. For the two-engine take-offs and landings, the non-precision approaches, and the single-engine Instrument Landing System (ILS) approach and landing, two of the trainees performed "moderately better" than a typical pilot, whereas for zero-degrees landing flaps two trainees performed "much better."

Moreover, pilots' control strategy and technique was rated as "similar" or the "same as typical pilot's" for all of these maneuvers. The trainees themselves compared their control strategy and technique in the airplane to the one in the FFT-X, and rated it at least the same or similar for all but two of the eight maneuvers: two of the six pilots found their strategy and technique somewhat and very different, respectively, for the twin-engine take-off, and one found it somewhat different for the twin-engine landing.

Instructors rated trainees' workload as identical to experienced pilots in the same airplane for the same eight maneuvers. Again, the trainees themselves compared their airplane workload with their FFT-X workload and found the FFT-X workload the same or only "somewhat" higher or lower for all maneuvers, with the exception of one pilot who found the airplane workload much lower for the twin-engine take-off.

The instructors rated gaining proficiency as neither harder nor easier than for a typical pilot for five of the eight maneuvers. Two pilots each, however, obtained "somewhat easier" ratings for zero-flaps landings, single-engine ILS, and take-off with engine flame-out at 400ft AGL. Most trainees, comparing the ease of gaining proficiency in the airplane and the FFT-X, gave at least "neither harder nor easier" ratings to the FFT-X, with every maneuver also receiving one "much easier" rating. Two (landing with single and twin engines) of the eight maneuvers received one "somewhat harder" rating (but the combined ratings still averaged out to "neither harder nor easier"), and the twin-engine take-off received two "somewhat harder" ratings (but the ratings still averaged to "neither harder nor easier").

In the FFT-X: Performance was already remarkably good after transitioning from the FFT-1 to the FFT-X. Looking at the instructor performance ratings for all pilots across all maneuvers, 25 maneuvers (71 percent of the total 35 maneuvers) were consistently rated as being flown equally or better than by typical pilots in an FFS. Only three maneuvers (crosswind take-off, instrument take-off, and take-off with engine failure) were ever rated as having been flown "much worse than [a] typical pilot" in an FFS, and the average ratings for each of these was nearer to "same as typical pilot."

The instructors perceived the trainees' control strategy and technique consistently as at least similar, if not identical, to a typical pilot in an FFS in 71 percent of maneuvers trained in the FFT-X. Only two maneuvers (take-off at maximum weight and take-off with engine failure) obtained any ratings of being flown very differently. Trainees, who were asked to anticipate their control strategy in the airplane, consistently estimated that their control strategy in the FFT-X was no more than somewhat different than anticipated in the airplane for 89 percent of the maneuvers. Three maneuvers (crosswind landing and take-off and twin-engine landing) received one rating of "very different" from the airplane, but still averaged closer to "somewhat similar." Take-off at maximum weight was estimated as "very different" by two of the six trainees, but all others rated it as "somewhat similar."

Instructors consistently perceived trainee workload in the FFT-X as typical in 69 percent of the maneuvers. Two maneuvers were inconsistently rated as sometimes causing higher, then again as causing lower workload. Only five maneuvers were ever perceived as causing "much higher" workload than the workload typically experienced in an FFS, but all of these maneuvers also received ratings of the same or even lower workload (instrument, rejected, maximum-weight, engine-failure, and crosswind take-offs). Trainees were asked to compare their workload in the FFT-X to the workload that they would expect in the airplane (which they had never flown), and 37 percent of the maneuvers received ratings of higher workload, but all of these also received ratings of the same workload from at least as many trainees.

For gaining proficiency in the FFT-X, the lowest rating from any of the instructors was "somewhat harder" than for a typical pilot in an FFS for 20 percent of the maneuvers. In each case, however, this was balanced by "neither harder nor easier" or, in two of these maneuvers, "somewhat easier" ratings. The other 80 percent of the maneuvers were judged to be taught as easily, and in two ratings for go-arounds, as more easily than for to a typical pilot in an FFS. This was confirmed by the pilots, who found many maneuvers "somewhat easy" or "very easy" to learn. Fewer than 30 percent of the maneuvers had ratings of "somewhat hard," in most cases amply balanced by "easy" ratings. The only two maneuvers that broke even between "somewhat hard" and "somewhat easy" were crosswind take-offs and landings.

2. Ratings of FFT-X Overall Acceptability, Handling Qualities, and Control Feel

One very important aspect of the acceptability of a simulator is the comfort, in terms of absence of simulator-induced nausea or disorientation, experienced by instructors and especially pilots. The reason this is so important is that some research results have shown that discrepancies between visual and vestibular motion stimulation may induce discomfort (the so-called "sensory conflict" theory, described, e.g., in Ref. 50). Conflicts can occur even in a motion-base simulator, when the visual and vestibular cues do not match up.[51] It is all the more remarkable, then, that there was no evidence of discomfort in the FFT-X, where there is hardly any vestibular stimulation, causing the visual system to sense motion while the vestibular system does not. One reason may be that the effects of sensory conflict reportedly have been more pronounced in those who are not actively engaged in the flying task (See, e.g., Ref. 52, and earlier discussion of vection).

Despite a reasonable assumption that the FFT-X may produce sensory conflict, there was not one FFT-X instructor comfort rating that was lower than "neither lower nor higher" than in an FFS. Trainees were asked to make the comparison anticipating their comfort in the airplane, and rated their comfort in the FFT-X as equal or higher for 83 percent of the maneuvers. Instrument take-offs and single-engine landings had all equal ratings for comfort with the exception of one "somewhat lower" rating. Twin-engine landings had three "somewhat lower" vs. five equal ratings. Take-off at maximum weight earned one "much lower" comfort rating, with one more "somewhat lower" and four equal ratings. Crosswind landing and take-off each also earned one "much lower" rating, each also with four equal ratings. Although these results already testify to the high comfort experienced in the FFT-X, trainees' ratings of their comfort in the FFT-X after the actual experience of the airplane were even better; all FFT-X comfort ratings were marked as equal to the comfort experienced in the airplane, with the exception of one twin-engine take-off rating, for which one of the six pilots rated his comfort "somewhat lower" in the FFT-X than in the airplane.

Only the six trainees were asked to rate the overall acceptability of the FFT-X, both before and after they had flown the airplane. Before trainees had experienced the airplane, 77 percent of maneuvers in the FFT-X received one rating of "needs minor improvements" or better from all pilots. Seven of those maneuvers that received a "needs minor improvements" rating also received "excellent" ratings. Only four of the 35 maneuvers received more than one "needs major improvements" rating, and each of these was perceived as "satisfactory as is" by at least one of the other pilots. There was not a single rating of "uncontrollable." After having experienced the airplane, the FFT-X was rated excellent by at least one of the pilots for every single maneuver, and only one single maneuver got one "needs major improvements" rating.

Again only the trainees were asked to rate the FFT-X's handling qualities, the feel and response of the controls, and the visual, sound, and overall cues, again before and after experiencing the real airplane. When trainees compared the handling qualities of the FFT-X to the ones they imagined the airplane to have, they all rated the handling qualities during 25 of the maneuvers at least equal or in a few cases even better than the anticipated handling qualities of the airplane. For five of the remaining maneuvers, only one of the pilots rated the handling qualities as "somewhat less satisfactory." For the rest of the maneuvers, the take-off with engine-failure handling quality ratings averaged close to 0 (equal to airplane), but the handling quality ratings for the twin-engine and crosswind landing and the take-offs with crosswind and at maximum weight were all rated, on average, closer to -1, which meant somewhat less satisfactory than expected in the airplane (the worst single rating from any pilot was -2). But once trainees had experienced the airplane, only three of the eight maneuvers received any ratings of "somewhat less satisfactory," and only take-off with engine flame-out at 400ft AGL received more than one such rating.

The feel and response of controls was considered identical to the "imagined" airplane for 71 percent or 25 of the 35 maneuvers (this includes one maneuver where one "slightly less responsive" rating was canceled out by one "somewhat more responsive" rating). For seven more maneuvers, the controls were rated "slightly/somewhat" different by only one pilot. Of the remaining three maneuvers, none were farther than half a point from a rating of zero, which meant equal to the anticipated feel of the airplane's controls. Only during take-off at maximum weight and with crosswind were the controls of the FFT-X perceived as much less responsive by one pilot, and the low take-off with crosswind rating was somewhat counterbalanced by another pilot that found the controls somewhat more responsive. The controls during twin-engine landings were rated three times as slightly less responsive. After the experience of the airplane, however, practically all of these imagined differences disappeared. For twin-engine take-offs, one out of the six ratings described the FFT-X controls as "somewhat more responsive" than the airplane. The take-off with engine flame-out at 400ft AGL had one rating each of "slightly less/somewhat more" responsive that canceled each other out. During the seven remaining maneuvers, the controls were perceived as exactly like the airplane.

Before experiencing the airplane, trainees consistently rated the overall cues of the FFT-X as "standard-fair" or better for all maneuvers but landings and take-offs with crosswind or windshear, where the cues were rated "slightly deficient" by one of the pilots for each maneuver (but each of these maneuvers also received two ratings of "good"), and for twin engine landings, where two pilots rated the cues as "slightly deficient" (but these ratings were also balanced out by two "good" ratings). In all five of these maneuvers, the motion cues appear to have been the main reason for the "slightly deficient" ratings, although vision may have contributed for take-offs with windshear and sound may have contributed for twin-engine and crosswind landings: for take-off with windshear and crosswind landings, vision and sound, respectively, were given one "slightly deficient" rating each. The sound cues for twin-engine landings received three "slightly deficient" ratings. Windshear at landing motion cues appear to be the worst, with four "slightly deficient" ratings and an average rating between "standard" and "slightly deficient"; followed by landing with twin engines, with one "very deficient" and three "slightly deficient" ratings and an average rating closer to "standard." Third worst rated were the motion cues for windshear at take-off, with three "slightly deficient" ratings and an average close to "standard." These three maneuvers additionally received one, one, and two "good" motion ratings, respectively. After having experienced the airplane, however, there was not one overall rating that was lower than "slightly different from airplane," and with the exception of the twin-engine take-off with four "slightly different" vs. two "same as airplane" ratings, half or more of the ratings were "same as airplane." There were, however, two "very different from airplane" individual ratings for motion, one for the landing with the flaps at zero degrees and the other for the twin-engine landings. Each of these ratings was balanced by one "same as airplane" rating, however.

3. Final Debriefing

The final debriefing included all trainees, all but one instructor, officials from the NAA, representatives of the airplane manufacturer and training provider, and the first author. It took about seven hours, including a brief presentation by the first author of the FAA/Volpe Center research results and a preliminary discussion of the questionnaire results. Trainees and instructors took turns relating their experiences. Some of the trainees had informally experienced the FFS the evening before. The discussion took place in the native language of the trainees and comments were translated by the first author.

Trainee comments: The first two trainees to express their opinions were both employed by the NAA's accident investigation office, had only single-pilot experience, and had flown the FFS the night before. They both related that they had no problem adapting to the airplane after training in the FFT. Both mentioned that the sound in the FFT was better than in the FFS; the second trainee to speak extended this comment to the vibrations as well. The second and more experienced (in terms of total flight hours) speaker mentioned a problem with turbulence, and that the instruments were too bright. He felt that the engine failures were easier to handle in the airplane, and that the go-around was more abrupt in the airplane. He nevertheless concluded that the FFT was an excellent tool, elaborating that "few accidents are occurring because of a difference in reaction time [presumably he was relating to the 0.4s faster pedal reaction time in the simulator attributed to the alerting function of motion in Refs. 13 and 40]. Most accidents happen because of a lack of training."

The next two speakers were highly experienced, with 6,000 and 8,500 hours in an airline environment. They worked for the NAA's flight inspection and training and schools office, respectively. Both reported that they had been successfully trained to fly the airplane in the FFT-X, that the training progressed steadily, and that there were no transition problems. They both suggested improvements with regard to nose-wheel steering and flight director (too sensitive). One of them asked that the intercom be improved. He also said that the dynamic seat did not add anything and that he did not perceive turbulence from the instruments (the first two speakers interjected that they disagreed). He added that the visuals of the FFT-X were excellent. The other speaker mentioned that there were no mechanical noises in the FFT (presumably, he was referring to the landing gear).

The final two trainees were employed by the NAA's office of training and schools and by the NAA's flight training department, with 4,500 and 6,000 hours in a single-pilot environment only. They both said that they had no problem transitioning to the airplane and that the airplane was easier to fly than the FFTs. They mentioned a few additional problems, mostly tuning or "growing pains," such as with an airport visual model, signage, axis control, slow torque, rotor trim, turn coordinator ball, faster response to engine failure, and lack of lateral acceleration. As with the previous two less experienced pilots, the discussion digressed into the merit of increased access to simulators with increased affordability, and that this would help compensate for the steadily decreasing flight hours in new recruits.

Simulator instructor comments: A first instructor pointed out that although he had trained the experienced pilots, they had not been in a turboprop airplane for 25 years. He agreed with the need for improvement of the nose-wheel steering. Otherwise, he confirmed that there were no transition problems, mentioning that the improvement for the second failure was better in the FFT than in the FFS. He also experienced the job of the instructor to be easier in the FFT than in the FFS. The second simulator instructor agreed with the need for improvement of the intercom and of the earphones. Otherwise, he reported normal adaptation and standard progress similar to that of the FFS.

Airplane instructor comments: The airplane instructors reported that the experienced pilots needed two take-off and landing patterns each, whereas the less experienced pilots needed between three and five patterns. They added that "there doesn't appear to be a difference between FFS and FFT training." Pilots handled crosswind fine even after training without motion; they seemed very adaptable.

Conclusion: The NAA decision maker concluded that there were no training problems. However, a few technical adjustments were needed, especially for the flight phases near the ground. He proposed to continue the experimental type-rating phase without restrictions, provided, for international training, that the NAA of the trainees agreed. The representatives of the training provider pointed out that this was the world's first type rating on a fixed-base simulator. The NAA decision official reiterated that the focus in determining flight simulation standards should be on effective stimulation of the pilot, rather than emphasizing rote simulation of the airplane.

C. Plan for Phase 3

The first set of type ratings showed agreement between the type-rating examiners of the NAA, the training-center simulator instructors, airplane-type-rating instructors, and trainees employed by the NAA. They concluded that the FFTs effectively prepared trainees with and without multicrew-piloting experience for flying the airplane. The ability to use FFTs, in combination with a set of four to six structured familiarization patterns flown in the actual airplane instead of a Level D FFS, would greatly improve training opportunities world-wide. This would increase pilot proficiency especially at smaller airlines by greatly facilitating access to an appropriate training tool. Including motion in a simulation of an airplane that does indeed move, however, appears to have an almost irresistible appeal, despite the documented limitations of a hexapod and despite years of research unable to document an operationally relevant benefit of motion on transfer of training to the airplane. We are therefore planning to further examine the effectiveness of training in the FFT by a) comparing it directly with the corresponding FFS and b) collecting objective data in addition to participants' opinions.

1. Design

As mentioned above, the basic design of this study will be to compare two groups of pilots, one trained in the FFS, the other in the FFT. Data will be collected during training and evaluation in the respective device and, for all pilots, during transfer to the FFS as a stand-in for the airplane. Data will be recorded directly from the training tool on pilot-vehicle performance (pilot control inputs and flight precision). All participants (instructors, trainees, examiners) will also complete questionnaires tapping their opinions on the training tools and the effect of the tools on flying strategies, performance, workload, and comfort.

2. Hypotheses

The working hypothesis is that when all pilots are tested in the FFS (and subjectively rated in the airplane), the pilots also trained in the FFS will perform better, control the airplane more steadily and with lower workload, and will acquire skills faster and feel more comfortable than pilots trained in the FFT-X. This will not only be evident from the data recorded directly from the FFT-X and the FFS, but also from the type-rating results and the questionnaires administered to the type-rating examiners, simulator and airplane instructors, and trainees. The null hypothesis is that the two groups' performance, control behavior, and comfort when tested in the FFS will be similar, regardless of whether they were trained in the FFS or FFT-X. This also implies that the type-rating results and the opinion data collected will be similar for and from the two groups.

3. Design Challenges

The main challenge in this study will be to prevent the individual differences between the pilots trained in the two devices from masking a potential device effect. Similarly, any other differences within and between the two groups and their treatment can affect the statistical power to find a device effect, or even masquerade as such an effect. Sources for such differences can be found in all the participants (as applicable, type and level of experience, aptitude, attitude including bias towards one or the other device, stamina, technique, etc.) as well as in the two training regimes (four vs. six weeks) and any other, unintended differences in procedures and training regimes. It is therefore critical that all possible measures are taken to strengthen the power of the experiment, namely:

- Compare carefully matched crews based on training regime and experience
- Strictly regiment procedures and training administered
- Avoid instructor/examiner bias by concealing prior training tools

- Counterbalance all other participants across groups on relevant variables
- Record as much data as possible, at a high sampling rate

4. Independent Variables

The main independent variable is the training tool, i.e., training in the FFS or the FFT-X. A secondary independent variable will be the training regime, i.e., four weeks or six weeks. A third independent variable will be when the data will be collected, i.e., during training in the FFS or FFT-X, during type rating in the FFS or FFT-X, or during transfer testing in the FFS. The Training Tool (TT) is a between-groups variable with two levels, FFS and FFT-X. The Training Regime (TR) is also between-groups (and counterbalanced over the TT variable) with two levels, four vs. six weeks. The Phase (P) variable is a within-groups variable with three levels, training vs. type rating vs. testing. The design is therefore a 2 (TT between) by 2 (TR between) by 3 (within) factorial design.

5. Dependent Variables

Two types of dependent variables will be collected: opinions of participants (evaluators, instructors, and trainees) and recordings from the training. Opinions will be collected after training and type rating in the respective tools, transfer testing in the FFS, and airplane training. Recordings will be taken on pilots' flight precision and control inputs during training and type rating in the respective tools. To provide a means of comparison with earlier FAA/Volpe Center studies, a set of maneuvers that were trained and tested in these earlier studies will be added to the curriculum.

VII. Conclusion

In this paper, we have shown that pilots experience airplane motion via multiple perceptual systems, which makes motion a candidate for simulation via stimulation of a subset of these systems. Next, we discussed the relative merit of vestibular cues when piloting an airplane, and argue that a combination of visual information from the out-the-window view and the instruments combined with force feedback from the controls provide sufficient cues most of the time. Pilots are taught that under certain flight conditions ignoring the visual information from the instruments and relying on physical motion cues may lead them to misunderstand the attitude of the airplane and enter, or fail to recover from, unusual attitudes. Our research focused on determining the effectiveness of simulator hexapod-platform motion on a realistic sample of those flight maneuvers where motion cueing might be expected to be necessary for training effectiveness. We compared the veracity of the vestibular cues received in the simulator with those experienced in an airplane, considering not only current airline-pilot training simulators, but also those used in the past and those equipped with advanced technologies. We found that the motion practicable today, as in the past, falls far short of accurately simulating the motion cues experienced in the airplane and that pilots have been trained totally and successfully in simulators without adequate motion for longer than a quarter century. It could be argued, then, that this alone shows that full platform motion is not needed for a successful training outcome. Moreover, our studies have repeatedly shown that the type of motion available on an airline-pilot training and evaluation simulator does not improve transfer between airplane and simulator for a variety of airplanes and critical maneuvers where motion should serve an alerting function. We then found that the cost of motion may prohibit some airline pilots from reaping the benefits of quality simulator training, with a concomitant loss in passenger safety. This conclusion is especially pertinent given the world-wide need for effective simulators, driven by a shortage of pilots, a reduction in prior experience among new-hires, and an increase in the complexity of the flying task due to increased congestion and automation. The approach described in the final sections of the paper, with the FFT-X providing trainees with visual motion and heave-onset cues with an FAA Level D FFS data package, appears to hold promise in alleviating this situation and increasing flight safety world-wide. It is to be feared, however, that a confluence of such factors as the face-value of simulating airplane motion, the resources that have been poured into developing motion systems, the profits that can be gained from selling such systems, and the all too human reluctance of changing an apparently effective system of training, will nip such efforts in the bud. However, if the null hypothesis of the evaluation study for the FFT-X is confirmed, i.e., if once more training without a hexapod-motion platform is shown to be equivalent to training with motion, it would be a disfavor to world-wide safety to continue to require that sparse training resources be poured into acquiring and maintaining motion systems. Any savings on platform-motion hardware and facility costs should be applied to upgrade the fidelity in other important areas, such as assuring that the simulator cockpit does in fact match the equipment in the target aircraft, and that the simulation includes realistic operational representation of the national air space, including the air-traffic-control environment.[53]

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