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Flight Simulators and the Effectiveness of Transfer of Training in Aviation

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ABSTRACT: This project involved a review of existing research on flight simulators and transfer-of-training success. Flight simulators are often used in airline training and can also be a valuable tool during earlier stages of training, including instrument training. Simulators provide training for dangerous situations, such as spins, without any risk to pilots. However, to be useful, the skills acquired through simulator training must carry over to actual aircraft. Dozens of direct and related studies indicate that simulators confer a strong transfer-of-training benefit across the board. Some studies have suggested that specific tasks and skills translate better from simulators to real-world situations, while others have shown a more general application. Overall, adverse effects of simulators were not evident. Although motion in simulation is widely perceived as being more effective than simulation without motion, most research does not support this perception. Therefore, both no-motion and motion simulators are suitable for training purposes, and motion is unnecessary, consistent with the hypothesis. Further transfer-of-training research is recommended, especially quasi-experimental research on early flight training, which can lower training costs, facilitate training in recovery skills, and increase safety in training without diminishing any of the benefits.

KEYWORDS: flight simulators, aviation simulators, transfer-of-training, fidelity, simulators, high-fidelity simulation, low-fidelity simulation, simulator fidelity, simulation fidelity, motion simulators, no-motion versus motion simulators, simulator transfer of training, simulation transfer of training, aviation simulation

Introduction

Flight simulators have existed in some form or another since the mid-1900s and have been used widely in some aspects of training since the dawn of the jet age in the late 1950s (de Winter et al., 2012; Micheli, 1972; Neal et al., 2020; Vaden & Hall, 2005). In the United States, the Federal Aviation Administration (FAA, 2024) assigns ratings of Class A through D to full flight simulators (FFSs), with Classes C and D being the most realistic, high-fidelity, and full-motion simulator types available (Preudhomme et al., 2012). The certification process, however, likely misses key factors and lacks support in the prior research (Bürki-Cohen et al., 1998; White et al., 2013). While the use of simulators in training may not have evolved as quickly, the simulators themselves have evolved from rough mockups and basic desktop or pod units to full-motion and high-fidelity units that cost millions of dollars (Bürki-Cohen et al., 1998; Preudhomme et al., 2012; Vaden & Hall, 2005). While fidelity is a complex topic, high-fidelity simulators at the most basic level include motion and detailed visual scenes (Salas et al., 1998). Lower-end simulators improved greatly in the 2000s in terms of having better visuals. In some cases, the better visuals coupled with good fidelity levels and some motion are especially appropriate for environments such as flight schools in which the aircraft layout can easily be customized and adjusted, this being another improvement over the years (Preudhomme et al., 2012). While simulators are primarily used by airlines to train pilots for large passenger planes, the question of transfer of training has been raised time and again for every level of pilot training, including private pilot training (Birdsong & Reesman, 2024; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Causse et al., 2011; Micheli, 1972; Myers et al., 2018; Neal et al., 2020; Rantanen & Talleur, 2005; Sparko et al., 2010).

Simulations and simulators are not new, and medicine is another field in which they have proved useful. For instance, nurses can use simulators for training relating to medical emergencies, surgical interventions, and patient reactions (Boling & Hardin-Pierce, 2016). Another flight-related use is by the military, which has employed networked simulators to train pilots for dangerous missions, and air traffic controllers use them for collaborative training (Malakis et al., 2010; Schreiber et al., 2011). In both the medical and military contexts, the application of simulators can reduce the loss of life, and simulators are often used by low-time pilots (Schreiber et al., 2011). There are also simulators for waterborne vessels that include analyses of crew resource management styles (Hontvedt & Arnseth, 2013).

Transfer of training must be established to ensure the effective use of simulators in a given situation. Accordingly, it is often assumed that "more is better" or, in this case, that motion in flight simulators provide better transfer of training than no-motion simulators (Bürki-Cohen et al., 1998; de Winter et al., 2012; Zaal et al., 2015). Experienced pilots, though, can provide insights into improvements based on their knowledge of the aircraft handling, and review by professional instructors of the backward transfer of skills can facilitate the application of the skills from aircraft to simulators (Ross et al., 1990; Stewart, 1994). While there is little knowledge of the actual effectiveness of and need for fidelity, the aviation industry uses simulators more than other industries that also focus on safety training (Borden et al., 2024; Bürki-Cohen et al., 1998; Dahlström et al., 2009; Dyre et al., 2016; Hess & Malsbury, 1991; Myers et al., 2018; Micheli, 1972; Wang et al., 2023). Further research is needed regarding when simulators can effectively replace training time in the aircraft, in which case the transfer of training must be assessed for effectiveness and regulatory purposes. If three hours in a simulator are required to learn what can be learned in two hours in an aircraft, logically, the transfer of training is 100 percent with a time factor of 3:2. In this example, the most significant benefit would be in terms of cost. Second, if simulators do, indeed, provide a transfer-of-training benefit, it is critical to know how this training changes based on the simulator. While many simulator options are available, with various levels of fidelity, the easiest and most practical way to investigate this issue is by comparing no-motion simulators with full-motion simulators. The aim of the present study was to review thoroughly the transfer-of-training research comparing motion and non-motion flight simulators and the research on the fidelity of simulators. Researchers have discussed negative transfer and the importance of instructor quality in the use of simulators as other areas of both concern and research interest (Meyer et al., 2012; Myers et al., 2018; Pavel et al., 2015; Zeyada & Hess, 2003). Overall, though, the existing research indicates that simulators generally offer benefits nearly equivalent to aircraft use.

The research, some of it conducted over 15 years, has generally indicated that low-fidelity simulators such as FTDs have similar transfer benefits (Myers et al., 2018; Preudhomme et al., 2012; Sparko et al., 2010). However, recently, the focus has turned to the impact of virtual and augmented reality on aviation in contexts such as procedural task training and efficacy (Birdsong & Reesman, 2024; Fussell, 2023, 2024; Fussell & Hight, 2021; Fussell & Truong, 2022; Hancock et al., 2022; Harris et al., 2023; Hight et al., 2020; Song et al., 2021; Wang et al., 2023). Additionally, while researchers have recently focused more on virtual reality, the technology has lacked the use of motion, often involving only a virtual reality headset (Birdsong & Reesman, 2024; Fussell, 2023, 2024; Fussell & Hight, 2021; Hancock et al., 2020; Hight et al., 2022). This approach offers a wealth of options for training, and several studies and a meta-analysis have discussed the effectiveness and acceptability of virtual reality in procedural task training (Fussell, 2023, 2024; Fussell & Hight, 2021; Fussell & Truong, 2021, 2022; Hancock et al., 2020; Hight et al., 2022). For example, researchers have noted challenges relating to the costs and availability of simulators and have utilized more accessible—in other words, lower-end—simulators (Neal et al., 2020). Additionally, Neal et al. (2020) established that, on average, fewer than two articles per year on the subject had appeared in the preceding 15 years and suggested that more attention to the issue was needed. Their review also emphasized the continued use of and research into the traditional simulator approach without diminishing the increased options.

The objective of this article was to analyze past research and identify and compare the specific transfer-of-training benefits offered by non-motion and motion simulators. Simulators have been viewed as less beneficial than actual aircraft for training, whether a simulator is high-fidelity with full motion or a scaled-down version (including no-motion).

Definition of Terms

A flight simulator is any simulated flight experience designed for use by pilots on the ground.

Fidelity refers in part to a simulator's realism, such as the visual range and handling characteristics offered by motion.

Transfer of training refers to the carryover of a skill learned in one context to another context. In this case, a skill learned in a simulator, if transferable, would be demonstrated in an aircraft with a similar level of accuracy and success.

Negative transfer refers to a reduction in a skill when moving from one environment to another, such as from a simulator to aircraft.

Virtual reality is a simulated environment that allows for real-time interaction with that environment. In the context of this article, the discussion of virtual reality is limited to a headset with a handheld or responsive controller.

A ***full-flight simulator*** (FFS) has full motion with a hexapod-motion system (Sparko et al., 2010).

A ***full-flight trainer*** is an alternative to an FFS with simulated motion in place of the hexapod-motion systems used in FFSs and featuring a dynamic seat and vibration cues (Sparko et al., 2010).

Flight training devices (FTDs) or flight simulation training devices are simulators that are not full-flight or motion-based, such as desktop computer-based devices or larger units that do not simulate motion.

Research Questions

Hypothesis

When simulators are used to introduce and teach a skill, and the skill is applied in an actual aircraft, the transfer of training is nearly the same as when the skill is taught using an aircraft. Overall, simulators offer benefits nearly equal to the use of actual aircraft (based on existing research).

Thus, the hypothesis tested in this review is that full-motion simulators do not differ significantly from no-motion simulators in terms of the transfer of training. Put differently, no-motion simulators provide transfer-of-training benefits nearly equal to the benefits provided by full-motion simulators. Accordingly, the following research questions served to guide the study.

RQ1: What are the findings of the existing literature regarding the transfer of training when simulators are used?

RQ2: Does the existing literature indicate that the transfer of training differs based on the fidelity of simulators?

RQ3: Does the existing literature indicate that the transfer of training differs between no-motion and full-motion simulators?

Problem Statement

There are two main concerns regarding the use of aviation simulators for training. The first concern is that simulators are less effective than training involving aircraft (Ross, Slotten, & Yeazel, 1990). The second concern is whether full-motion and/or high-fidelity simulators are substantially better than limited or no-motion and low-fidelity simulators. The conclusion that full-motion and/or high-fidelity simulators are better is often supported with reference to the FAA's requirement that Part 135 and 121 operators need full-motion and high-fidelity simulators for training, but there is no corresponding support for this conclusion beyond longstanding popular opinion (Bürki-Cohen et al., 1998; Caro, 1979; Grant et al., 2006).

Significance of the Study

This article addresses two overarching areas regarding simulator use in aviation training. The first is safety, specifically, the ability to train in a simulator without neglecting aspects of training in a manner that would later result in a direct or indirect safety issue in real-world aircraft operation as well as reincorporating complex training that would otherwise be omitted because of safety concerns. The second overarching area is the need for an affordable and accessible training method, especially given the ever-increasing costs of flight training. The existing research has provided considerable support for transfer of training when simulators are used. However, there has been less of this type of research in recent years, and, while the evidence is in favor of simulator use, the regulations and usage in general aviation have not caught up (Boril et al., 2017; Bürki-Cohen et al., 1998; Dahlström, 2008; de Winter et al., 2012; Dyre et al., 2016; Gheorghiu, 2013; Neal et al., 2020; Preudhomme et al., 2012; Stewart, 1994; Wang et al., 2023).

The significance of the present study is in clarifying the benefits of simulators as a training tool compared with aircraft training and whether motion is important. If these benefits are confirmed, simulators offer pilots a means to reduce the cost of and gain easy access to training and increase schedule flexibility. The findings can also contribute to a framework for industry and regulatory changes relating to the acceptance of simulators for training, potentially allowing for lower-cost simulator options if, in fact, full motion is not necessary, and a framework for future research. Ideally, such research may increase the use of simulators, including in the early stages of training.

Methodology

The purpose of this research was to demonstrate the general transfer-of-training benefits by synthesizing the results of previous studies through a structured literature review. First, an in-depth literature review was conducted. The following search terms were used with Boolean modifiers: “flight simulators,” “aviation simulators," "transfer of training," "high-fidelity simulation," "low-fidelity simulation," "simulator fidelity," "simulation fidelity," "motion simulators," "no motion versus motion simulators," "simulator transfer of training," "simulation transfer of training," and "aviation simulation."

The search strategy involved the use of indexed journals through an academic journal search engine in the EBSCOhost Databases. When the search was conducted, databases and journals unrelated to the subject, such as medical journals, were initially excluded. The academic journal search was further restricted to exclude conference materials. The databases included were Academic Search Premier, Academic Search Ultimate, ERIC, Library, Information Science & Technology Abstracts, MasterFILE Premier, Military & Government Collection, Primary Search, and Applied Science & Technology Source.

The search was done with all fields inclusive of titles, abstracts, all text, author, subject, and search terms. There was no time frame restriction on the search. Only peer-reviewed articles were included except for topics relating to reports, costs, or regulations—for example, obtaining airplane rental costs directly from a flight training center—which were restricted to direct sources. Only English-language studies were included, among them international studies presented in English. Further inclusion criteria were civil, commercial, and military aviation with adult subjects for experimental designs and some form of simulator usage. The exclusion criteria included research unrelated to airplanes, non-empirical research, and research not directly related to the transfer or effectiveness of training relating to simulation.

This search generated 556 results. After duplicates were eliminated, 194 results remained. Of these results, a cursory review resulted in the further elimination of unrelated articles, such as engineering simulations and other non-training type simulations. A full review of the remaining 45 results identified 39 studies matching the inclusion and exclusion criteria outlined above.

The studies were compared thematically rather than by design type because of the nature of this study. The study took the form of a narrative literature review given the summation and synthesis of the body of literature on simulator transfer-of-training within aviation (Baumeister & Leary, 1997; Green et al., 2006). In addition, some other research related to the topic was considered, such as virtual reality, helicopter simulation, and medical simulation; this research is not included in the literature results described above but, rather, served a supplementary purpose.

Aviation simulation research can involve two approaches. First, simulations can facilitate the analysis of potential risks or the identification of the factors that led to an accident or incident. Second, simulations can supplement training and address—and thereby reduce—known safety issues. Both approaches were considered in this study in order to show the benefits of simulation as a training tool.

Conceptual Framework

Amid the constant need and push for safety and, thus, for quality training in aviation, Reason's Swiss cheese model offers guidance for the importance of the topic and broader inclusion criteria (Reason, 1990; Reason et al., 2006). According to Reason's model, safety issues occur when something slips through cracks in the multiple layers of a system, allowing small things to pass through and worsen as the system progresses, whether because of active failures or latent conditions (Reason, 1990; Reason et al., 2006; Wiegmann et al., 2022). When the cracks line up, accidents can occur. This approach exposes weaknesses in a system and can be used to analyze small and large issues as well as potential problems, thus allowing for a better understanding of how or why an incident may have occurred. Some researchers have argued that this model oversimplifies the review of accidents and is overly general (Larouzee & Le Coze, 2020). While accurate, this approach is nuanced in that it takes into account every layer of a system rather than focusing on the largest breakdown first, thus making available better information to address or prevent problems (Larouzee & Le Coze, 2020).

Review of Relevant Literature

Supporters and critics of aviation simulators alike have long questioned the effectiveness and benefits of the transfer of training from simulators to aircraft (Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Gheorghiu, 2013; Micheli, 1972). Even when pure opinion is removed from consideration, it is critical to know what will and will not work in a simulator for the purpose of training so that safety can be maintained in real-world aviation. Arguably, any transfer benefit, even partial, is worthwhile given the reduction in training and/or operation costs along with the risk reduction (Boril et al., 2017; de Winter et al., 2012; Dyre et al., 2016; Gheorghiu, 2013; Micheli, 1972; Preudhomme et al., 2012; Vishnyakova & Obukhov, 2018; Wang et al., 2023). However, debate persists regarding where the perfect transfer point lies, so there is a need for further study. While not aircraft-related, NASA's Apollo Program is a good relatable case for simulators because the training for this program was completed entirely in simulators (Micheli, 1972).

Skills can be learned more quickly in a simulator than in an aircraft primarily because of the removal of extraneous tasks such as pre-flight and takeoff/landing. Thus, at least, training time should be equal in most cases (Gheorghiu, 2013; Micheli, 1972; Rantanen & Talleur, 2005). Conservatively, one study showed that, compared with the control group of those using an aircraft, the simulator group for one portion spent an additional 1.6 hours in a simulator but also saved 4.7 total hours, resulting in 55% flight-time savings (Micheli, 1972). Another study showed that, depending on what was included in the training, 11 hours in a simulator could save 9 to 11 hours in an aircraft (Gheorghiu, 2013).

Another study looked at several maneuvers, including takeoff, heading standard deviation, the yaw rate, exceeding airspeed, deviation in pitch, localizer, glideslope, and roll (Sparko et al., 2010). These researchers found no statistically significant difference between the no-motion and the motion simulator-trained groups when tested in a full motion simulator, and the differences noticed in the no-motion group disappeared when the members of this group were tested in the full-motion simulator.

Transfer-of-training studies vary in terms of what the researchers consider and how they approach the topic. Dahlstrom and Nahlinder (2009) studied psychophysiological reactions in basic pilot training to explore the link between simulators and aircraft because of the general lack of comprehensive transfer-of-training studies. While they found a clear need for cost-effective training to produce safe pilots, their focus was on heart rates during various phases of flight, with lower rates corresponding to higher mental workloads. Their findings were unexpected regarding anticipatory responses. For example, they observed increased heart rates prior to simulation events such as engine failure, which showed the pre-response to expected occurrences. While their study has limitations in terms of the lack of statistical significance between aircraft and simulators in other areas of research, a combination of their findings with their earlier work indicates a transfer-of-training benefit in some cases. They also emphasized the need for more research on mental workloads but cautioned about simulating unexpected events and the benefits of transfer. Their findings support the use of heart rate measures to assess mental workload in transfer-of-training assessments and show promise for further application. Their study is just one example of the research available, and the discussion below shows the variety of research available on the topic and the particulars of motion and non-motion simulator studies.

Limitations of Simulator Use

While studies have been conducted regarding the transfer of training from simulators to aircraft, the use of simulators as training and testing units, the importance of fidelity, and the need for motion, several researchers have pointed out a general lack of research and specific issues raised in previous research that remain to be addressed (Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Huet et al., 2009; Myers et al., 2018; Zaal et al., 2010). One general issue emphasized in the existing research is the lumping together of pilots' behaviors in simulators and real aircraft, particularly in relation to what Zaal et al. (2010) described as "skill-based control tasks" (p. 1). These researchers asserted that, as a consequence, there are significant challenges to identifying the issues and distinguishing factors that are not responsible for adverse effects. While still somewhat limited and requiring more precise techniques, their study is instructive because of the use of view-limiting masks so that the participants only received visual cues for error signals and their visual and vestibular systems could be studied separately.

Another limitation of previous research on simulator use and cognitive processing is the technology, at least from the standpoint of computer performance. Audio and visual effects need to be synchronized in time and avoid processing delays (Holzapfel et al., 2009; Meyer et al., 2012; Zeyada & Hess, 2003). Computer processing delays cause problems with pilot cues, and given that the cues are quick for pilots, a delay by the simulator, especially in time-sensitive tasks such as emergencies, can result in negligible or even negative transfer-of-training effects (Holzapfel et al., 2009; Pavel et al., 2015). The aspects to be considered include visuals, motion cueing, and control loading, among other things, which seem to add about 100 milliseconds when combined, a period longer than recommended for a delay since it is detectable by humans (Pavel et al., 2015). Acceleration forces and the lack of replication in motion simulation are another concern for simulators (de Winter et al., 2012) that developers will have to continue to address.

Tools of Training

Simulators have long been used for training and research purposes (Boling & Hardin-Pierce, 2016; Boril et al., 2017; Dahlström et al., 2009; de Winter et al., 2012; Dyre et al., 2016; Harris et al., 2023; Hontvedt & Arnseth, 2013; Huet et al., 2009; Micheli, 1972; Neal et al., 2020; Song et al., 2021; Wang et al., 2023). Simulation enables the safe testing of new and high-risk techniques (Dahlström, 2008; Huet et al., 2009; Vishnyakova & Obukhov, 2018). In safety training and investigation, fidelity may be helpful, especially when investigating pilots' perspectives and actions.

Simulators have been and continue to be viewed as poor training devices by some and as necessary by others (Bürki-Cohen et al., 1998; Dahlström, 2008; Dahlström et al., 2009; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Fussell & Truong, 2022; Fussell & Truong, 2021; Huet et al., 2009; Neal et al., 2020; Salas et al., 1998; White et al., 2013). While opinion may continue to drive both the use and the regulation of simulators, continued research is necessary, and the research so far has shown the overall benefits of simulator use for training at all levels (Boril et al., 2017; Bürki-Cohen et al., 1998; Dahlström, 2008; de Winter et al., 2012; Dyre et al., 2016; Gheorghiu, 2013; Preudhomme et al., 2012; Stewart, 1994; Wang et al., 2023). Pilots find themselves using simulators more often as they progress through training, especially at the professional level (Bürki-Cohen et al., 1998; Dahlström, 2008; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Salas et al., 1998). A comprehensive review found no difference between pilots who trained on high- or low-fidelity simulators, with "high fidelity" defined as involving motion and better scenes (Salas et al., 1998). Task requirements using cognition and/or relating to behavior may be among the small set of things that require differing fidelity needs (Meyer et al., 2012). Other researchers have gone so far as to say that higher fidelity may hinder certain types of training, especially non-procedural skills such as handling emergencies (Dahlström et al., 2009; Zaal et al., 2015). For instance, varying the scenes on the screen does not seem to help, especially during the first 24 training sessions (Salas et al., 1998).

Additionally, most low-fidelity simulators, including basic home computer setups, offer performance measurements while, typically, high-fidelity simulators do not (Salas et al., 1998). Coupled with difficulties in overall evaluation and poorly defined objectives, high fidelity can negatively impact both the research and the actual instruction (Salas et al., 1998). In other words, basic instruction and instructional design must be improved first. Improved instruction will lead to better training in simulators and better research on the transfer of training and the needs associated with it. New research on the use of virtual reality in training has focused on procedural tasks and understanding the benefits while controlling for newer technologies that have considerable potential in the coming years (Birdsong & Reesman, 2024; Fussell, 2023, 2024; Fussell & Hight, 2021; Harris et al., 2023; Hight et al., 2022; Song et al., 2021; Wang et al., 2023). Fundamentally, the purpose of training should dictate the need for fidelity (Dahlström, 2008).

Members of the new generation of pilots want to utilize more technology, and those involved in commercial aviation will inevitably encounter simulators (Birdsong & Reesman, 2024; Dahlström, 2008; Micheli, 1972). Other research has supported early training in simulators, though, on average, such training seems to have been limited to 5 to 10 hours of effectiveness in transfer before additional time would provide much benefit (Micheli, 1972; Rantanen & Talleur, 2005). While researchers mention skill development, the best use of simulators seems to be to develop cognitive and collaborative abilities, including emergency procedures and multi-crew environments (Dahlström, 2008; Micheli, 1972).

The benefits of inexperienced pilots using simulators are increasingly evident as well, even when visual flight training is involved (Dyre et al., 2016; Huet et al., 2009; Rantanen & Talleur, 2005; Sparko et al., 2010). Likewise, as further described in subsequent sections, task and procedural skills seem to benefit most from simulator transfer of training, and scenario-based training also appears to be successful, especially given the associations of the tasks and procedures involved (Dyre et al., 2016; Micheli, 1972; Rantanen & Talleur, 2005). The title of a study by Dyre et al. (2016), "Imperfect Practice Makes Perfect," emphasizes this point.

Safety

As mentioned, simulators provide a safe means to try out new techniques, determine what went wrong in accidents, and investigate variables that affect planes and pilots (Dahlström, 2008; Huet et al., 2009; Vishnyakova & Obukhov, 2018). In safety training and investigations, fidelity may be helpful, especially when considering pilots' perspectives and actions. While studying accidents in the commercial sector can help identify training issues, including the possibility that problems have resulted from the use of simulators rather than aircraft, such accidents are rare (Causse et al., 2011). Thus, while the use of simulators may not be the only factor contributing to the rarity of accidents, it does not seem that simulators are problematic or related to any accidents that have occurred. In fact, the National Transportation Safety Board reported that, between 2013 and 2019, fatigue was a contributing factor in 28% of aviation accidents (Parenteau et al., 2023). As discussed, simulators enable pilots to practice high-risk maneuvers in training that considerations of safety and cost would otherwise preclude (Micheli, 1972). Given that pilot error plays a role in 85% of general aviation accidents and 38% of commercial aviation accidents, there is both room for improvement in human factors and emergency procedures through the use of simulators (Causse et al., 2011; Neal et al., 2020; Vishnyakova & Obukhov, 2018; Wang et al., 2023).

Costs of Training

Dahlström (2008) argued that members of the current generation of pilots want to access and use new technology. Simulators provide a unique combination of training benefits, such as cost and convenience, along with the technology. Private pilot training costs often exceed $10,000 USD, and, for commercial pilot training resulting in airline transport pilot (ATP) certification, trainees not uncommonly spend $100,000, with a range $60,000 to $120,000 on average (Aerosim, n.d.; "Tuition and Estimated Costs," n.d.; "Getting your ATP certificate," 2015; Utah Valley University, 2017, 2024). These figures do not include the cost of a college degree, which is typically expected from airlines (ATP Flight School, n.d.). Accordingly, it is critical to reduce these costs without diminishing the effectiveness and safety of the training for pilots.

In 2017, the use of a basic simulator found in flight schools cost about $54 per hour, whereas the cost of flying a Cessna 172 S or R model was about $150 per hour, and instructors charged $60-65 per hour (Aerosim, n.d.; Frederick Flight Center, n.d.). In 2025, the costs are around $60 per hour for the basic simulator, $175 per hour for the aircraft, and $70 or more for instructors—an increase of roughly $40 for the aircraft and instruction in less than eight years ("Aircraft Rates," 2024). The minimal marginal increase in the simulator cost offers some hope. The cost in some locations, however, can be even higher, exceeding $200 per hour for plane rentals or basic simulators (Embry-Riddle Aeronautical University Prescott, n.d.).

Although some argue that pilots, especially new pilots, should experience "real flying," it is also important to realize the cost savings if the transfer of training is relatively equal (Dahlstrom & Nahlinder, 2009; Micheli, 1972; Rantanen & Talleur, 2005). Additionally, research over the past two decades has shown that novice pilots may benefit the most from simulator training (Dahlström, 2008; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012).

Fidelity

Fidelity in flight simulators has been studied for many decades, though substantial research on the topic has been rare (Boril et al., 2017; Bürki-Cohen et al., 1998; Dahlström, 2009; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Harris et al., 2023; Hess & Malsbury, 1991; Neal et al., 2020; Salas et al., 1998; Zeyada & Hess, 2000). While more research is needed, the findings of older and newer research have been consistent (Bürki-Cohen et al., 1998; Caro, 1979; Dahlström, 2008; Dahlström et al., 2009; de Winter et al., 2012; Myers et al., 2018). Notably, fidelity and realism are distinct concepts, although they do have similarities in simulators. In understanding simulator fidelity, it is important first to understand what is necessary for the particular use(s) in training (Dahlström, 2008; Dahlström et al., 2009; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Grant et al., 2006; Meyer et al., 2012; Pavel et al., 2015; Salas et al., 1998; Vaden & Hall, 2005; Zaal et al., 2010). For example, if the focus of training is on upset recovery, then motion to simulate handling is likely necessary. Simulators can provide kinesthetic feedback in partial or full-motion versions, a feature about which many experts are concerned (Bürki-Cohen et al., 1998; de Winter et al., 2012). The constraints on simulator fidelity are either general, such as physical and computational limitations, or on individuals, such as limited financial resources (Meyer et al., 2012). Accordingly, there are many affordable options for students and instructors to focus on what is needed. Likewise, the role of the instructor cannot be understated (Myers et al., 2018).

Studies involving the simulation of assembly tasks also provide insight into cognitive fidelity. In one such study, while cognitive fidelity took longer at training and test time, compared with the virtual-physical simulation group, the cognitive group did better in error-correction tasks and had complementary advantages (Hochmitz & Yuviler-Gavish, 2011). These findings serve as a reminder that alternatives to real-world training are important, especially with respect to cost and safety (Borden et al., 2024; Dyre et al., 2016; Hochmitz & Yuviler-Gavish, 2011; Wang et al., 2023).

Ross et al. (1990) found that visuals only accounted for a slight difference in the benefits of using a simulator, although much research since then has found visual quality to be of increasing importance (Çetin et al., 2012; Harris et al., 2023; Hess et al., 1993; Hess & Marchesi, 2009; Hess & Siwakosit, 2001; Meyer et al., 2012; Pavel et al., 2015; Salas et al., 1998; Stewart, 1994; White et al., 2013; Zaal et al., 2010; Zeyada & Hess, 2000, 2003). Previous research has also shown the need for some realism to allow learning to transfer based on particular tasks (Meyer et al., 2012; White et al., 2013). If a pilot needs visual references, then the image in the simulator must be realistic. One study of visual necessity found that, during a roll-step maneuver in a helicopter, pilots went lower in the simulator to obtain necessary cues to perform the maneuver (White et al., 2013). Another study showed that a lack of texture or an adequate field of view was detrimental to lateral maneuvers (Hess & Malsbury, 1991).

Another study demonstrated the stability of a helicopter to be inversely proportional to the motion necessary in a simulator (Hess & Marchesi, 2009). Simulators seem to support hover tasks in helicopters that require especially accurate visuals and dense scenes, and pilots responded negatively to limited visuals (Çetin et al., 2012; Hess & Malsbury, 1991; Stewart, 1994; White et al., 2013). These findings reaffirm the importance of visual as well as vestibular and proprioceptive feedback, although, ultimately, these forms of feedback together provide "redundant information," and, given that proprioception has less "bandwidth," it may be less useful (Hess & Marchesi, 2009; Zeyada & Hess, 2000). In any case, visual cues may be the most critical, indeed, the key to fidelity strength (Hess & Siwakosit, 2001; Meyer et al., 2012; White et al., 2013; Zeyada & Hess, 2000). That said, since pilots have multiaxis tasks and proprioception, vestibular and visual cues need to be considered comprehensively (Harris et al., 2023; Hess & Siwakosit, 2001).

Visual cues must also be synchronous with any motion (Harris et al., 2023; Hess et al., 1993; Hess & Siwakosit, 2001; Meyer et al., 2012). The finding that the lack of overall simulator fidelity has proved problematic in low-altitude maneuvers further demonstrates the need for improved visuals and reduced time delays connected with the motion system (Hess et al., 1993; Hess & Siwakosit, 2001; Meyer et al., 2012). While timing may be important, the combination of visuals and motion does not seem to offer additional benefits beyond what each feature provides separately, at least from the perspective of post-training sessions and pilot performance (Meyer et al., 2012). In other words, utilizing either visual or motion alone is sufficient and effective, and using both does not confer an additional benefit or reduce the benefit as long as both types of cues are synchronized.

However, physical fidelity, while popular and believed to be particularly important, is likely overemphasized and without significant benefits (Bürki-Cohen et al., 1998; Meyer et al., 2012; Meyers et al., 2018; Vaden & Hall, 2005; Sparko et al., 2010). Low-fidelity simulators are useful, providing a large benefit to aviation, especially considering the cost and operational savings (Bürki-Cohen et al., 1998; Dahlström et al., 2009; de Winter et al., 2012; Dyre et al., 2016; Hess & Marchesi, 2009; Meyer et al., 2012; Myers et al., 2018; Preudhomme et al., 2012; Salas et al., 1998; Sparko et al., 2010). It seems reasonable to conclude that the amount of movement involved in operating an aircraft should correspond to the amount of movement in a simulator session (Hess & Marchesi, 2009). While there is some disagreement on this point, and motion may be useful, the suggestion that a negative transfer-of-training effect would occur is not well supported (Hess & Marchesi, 2009; Meyer et al., 2012; Zaal et al., 2015). In essence, lower-fidelity simulators offer opportunities to develop needed skills, such as problem-solving and skills that require extensive knowledge, and reduce computational and physical needs (Dahlström, 2008; Dahlström et al., 2009; Holzapfel et al., 2009). While some researchers have suggested a more direct overall positive benefit, they have also urged caution given the limited number of studies (Bürki-Cohen et al., 1998; Vaden & Hall, 2005).

When looking at less-researched areas, backwards transfer analysis can be useful. In this situation, a pilot receives training in an aircraft, carries out the same or similar tasks in a simulator, and then provides an opinion about handling and is evaluated on the skills involved. In one such study, 88% of the tasks were completed to standard, and the pilots reported that the handling characteristics in the simulator were similar to those they experienced in aircraft (Stewart, 1994). While skill development is important and can be achieved in simulators, the use of simulators seems to be consistently supported for cognitive and collaborative abilities, behavior, and, especially, task-specific procedures (Dahlström, 2008; Fussell, 2023, 2024; Hess & Malsbury, 1991; Holzapfel et al., 2009; Meyer et al., 2012; Micheli, 1972; Myers et al., 2018; Salas et al., 1998; Zaal et al., 2015). Fundamentally, the need for and the effect of fidelity, if any, are based on the purpose of training (Dahlström, 2008).

While the findings have typically been consistent, disagreement persists regarding the effects of simulators and the need for high fidelity (Bürki-Cohen et al., 1998; de Winter et al., 2012; Dyre et al., 2016; Hess & Marchesi, 2009; Zaal et al., 2010; Zeyada & Hess, 2000). Additionally, psychological fidelity has received relatively little attention. While this type of fidelity was mentioned in the context of mental workload and heart rate in the study by Dahlstrom and Nahlinder (2009) discussed above, it also covers experiences such as feeling self-efficacious prior to simulations and then anxious and stressed afterward, as is often observed in law enforcement simulations (Holbrook & Cennamo, 2014). While emotional arousal is not necessarily negative and can increase the "realism" of experiences, researchers need to continue to pay attention to it (Holbrook & Cennamo, 2014).

Lastly, some researchers have developed aircraft simulations based on designing or redesigning small aircraft to mimic larger aircraft (Sato & Satoh, 2011). While this approach may not offer all of the features of a ground simulator, it represents an evolution of sorts that could be better utilized for training purposes, especially at higher levels.

Motion Simulators Compared with No-Motion Simulators

Multiple studies, including meta-analyses, have found no significant difference between the training benefits of motion and no-motion simulators (Bürki-Cohen et al., 1998; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Grant et al., 2006; Huet et al., 2009; Meyer et al., 2012; Salas et al., 1998; Sparko et al., 2010). However, this topic continues to be vigorously debated, and, regardless of the actual need, the regulatory requirements include motion for commercial pilots to achieve certification and re-currency (Bürki-Cohen et al., 1998; Dahlström, 2008; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Hess & Marchesi, 2009; Meyer et al., 2012; Preudhomme et al., 2012; Salas et al., 1998; Zeyada & Hess, 2000).

Recapping the discussion of fidelity, physical fidelity, which includes motion, is often overemphasized given the lack of significant benefits, so researchers and the field as a whole should focus on tasks and competence (Grant et al., 2006; Meyer et al., 2012; Micheli, 1972; Sparko et al., 2010; Vaden & Hall, 2005; Zaal et al., 2015). If motion is utilized, improvement is needed in terms of processing delays and synchronization (Hess et al., 1993; Hess & Siwakosit, 2001; Meyer et al., 2012). Additionally, specific maneuvers need to be considered, with motion being of greater need for low-altitude maneuvers and those that normally would involve a great deal of motion (Hess et al., 1993; Hess & Marchesi, 2009; Hess & Siwakosit, 2001; Meyer et al., 2012)—though some research shows that motion is not important even in this context (Sparko et al., 2010).

It appears that motion is most useful for simulations based on disturbances that would incur movement, such as engine failures, though these may not be effectively programmed given their random nature (de Winter et al., 2012). Oddly, full motion seemed to impair touchdown accuracy compared with no motion or partial motion, such as in a small hexapod simulator (Zaal et al., 2015), consistent with the previously mentioned skill-specific use of motion in simulators (de Winter et al., 2012; Grant et al., 2006; Vaden & Hall, 2005; Zaal et al., 2015). Other strong evidence supporting the use of motion in simulations appears to be for "flight-naïve" individuals and those in early training and transfer sessions, though possibly only for a short time in the early parts of simulator training (de Winter et al., 2012; Causse et al., 2011; Dahlstrom & Nahlinder, 2009; Rantanen & Talleur, 2005; Sparko et al., 2010). Skill-specific use may be the easiest and most generalizable recommendation (de Winter et al., 2012; Grant et al., 2006; Vaden & Hall, 2005; Zaal et al., 2015; Wang et al., 2023). Some research has shown that, for overall transfer-of-training benefits, motion is favored, though only quasi-transfer studies in which the participants moved from a non-motion simulator to a full-motion simulator (de Winter et al., 2012). Indeed, even then, not all studies in the quasi-transfer group found a sizable benefit (Sparko et al., 2010). A few studies found a small positive benefit, though the researchers cautioned against generalizing the findings given the limited number of studies available (Vaden & Hall, 2005). In true transfer studies, the participants who moved from simulators to aircraft did not derive any benefit from using motion (de Winter et al., 2012). While some aspects of training may benefit from motion, it does not appear to be critical, especially given the studies showing that it often has several exclusions (Bürki-Cohen et al., 1998; de Winter et al., 2012; Zaal et al., 2015).

As mentioned regarding the limitations, delays in feedback and visual cues cause especially negative effects (Zeyada & Hess, 2003). Again, motion may have no positive effect, or even a negative effect (Meyer et al., 2012; Pavel et al., 2015; Zeyada & Hess, 2003; Zeyada & Hess, 2003). Nevertheless, any practice in a simulator may prove to be worthwhile and facilitate skill development (Dyre et al., 2016).

Conclusion

While more research on the transfer of training from simulators to aircraft is necessary, the available research provides abundant support for the use of simulators (Birdsong & Reesman, 2024; Bürki-Cohen et al., 1998; Dahlström, 2008; Dahlström et al., 2009; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Gheorghiu, 2013; Huet et al., 2009; Myers et al., 2018; Neal et al., 2020; Preudhomme et al., 2012; Salas et al., 1998; Stewart, 1994; White et al., 2013). It has been suggested that researchers conduct more quasi-transfer studies, such as from no-motion to full-motion simulators, to identify ways to cut costs and hazards, especially for dangerous testing in real aircraft (de Winter et al., 2012; Huet et al., 2009; Preudhomme et al., 2012; Vishnyakova & Obukhov, 2018; Wang et al., 2023). Motion does not seem to be necessary except in a few cases (Bürki-Cohen et al., 1998; Dahlström, 2008; Dahlstrom & Nahlinder, 2009; de Winter et al., 2012; Grant et al., 2006; Hess et al., 1993; Hess & Marchesi, 2009; Hess & Siwakosit, 2001; Huet et al., 2009; Meyer et al., 2012; Micheli, 1972; Preudhomme et al., 2012; Salas et al., 1998; Sparko et al., 2010; Vaden & Hall, 2005; Zaal et al., 2015; Zeyada & Hess, 2000). One analysis found no statistically significant difference between no-motion and motion simulators, further supporting the conclusion that the two types confer similar transfer-of-training benefits (Sparko et al., 2010). These findings support not only the use of no-motion simulators but also the conclusion that simulator training is beneficial for pilots at all levels regardless of experience.

In the context of regulatory changes, the research provides another data point indicating that some requirements for simulators may be unnecessary and cumbersome and, in a few instances, may result in negative transfer (Meyer et al., 2012; Myers et al., 2018; Pavel et al., 2015; Zeyada & Hess, 2003; Zeyada & Hess, 2003). For general and commercial aviation, both in the United States and globally, given the high cost of flight training, the use of simulators can reduce costs without sacrificing training and, indeed, improve training in emergency and recovery procedures that is presently limited. However, even without regulatory changes, flight instructors, flight centers and schools, and student pilots can themselves plan some of the initial training in a simulator—for instance, working on particular skills and tasks, procedural flow, and familiarization. If nothing else, the use of simulators can reduce the cost of learning procedures, but it is likely to assist in many other ways.

Recommendation

Based on the research reviewed for this study, a more programmatic approach to the use of simulators should be taken, such as following student pilots who use simulators and those who do not through early training in a cohort study. This type of research can provide a better idea of the benefits of simulators in general. Likewise, additional research focused on particular maneuvers and comparing them between simulators and aircraft would be helpful, though the focus should be on FAA testing standards, which are more easily understood and adopted. As Stewart (1994) suggested, backwards transfer studies may provide additional support to the field and regulators and help improve simulator design from a practical use standpoint. With these recommendations in mind, studies such as Stewart's could be repeated with more in-flight maneuvers for testing and analysis.

Additionally, overall instructional design (i.e., flight instruction) should continue to be evaluated and improved. As an example, the support for task- and skill-specific training in simulators is strong and should be measured and presented (de Winter et al., 2012; Holzapfel et al., 2009; Vaden & Hall, 2005; Zaal et al., 2015). Likewise, the fidelity levels of simulators should be based on the task being taught or evaluated, and more research should be conducted into the current requirements for fidelity, which may be unnecessary (Hess & Malsbury, 1991; Neal et al., 2020; White et al., 2013). Additional research should be conducted to determine whether visuals are, indeed, more important than motion, and developers should focus on improving realism and definition as well as reducing time delays.

This topic as a whole—including costs, fidelity, and transfer of training—is important in terms of finding the best combination and utilizing it to facilitate learning and improve training and, thereby, stop preventable accidents and incidents from occurring. Training requirements have evolved over the years, for instance, focusing more on stall recovery and spin awareness. If the increased use of simulators, especially early on, can reduce accidents, it can likely also help address other problems that pilots face. Therefore, finding a safe means to conduct emergency training is arguably an even more important topic. The importance of fidelity in transfer of training is critical here. A simulator must serve a defined purpose and result in quality transfer of training to be effective. The research on these issues will help determine the proper use and timing of such tools and, ideally, improve training and reduce errors and costs.

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