REVIEW ARTICLE

Spatial Disorientation: Decades of Pilot Fatalities

Randall Gibb, Bill Ercoline, and Lauren Scharff

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Spatial disorientation (SD) has been a contributing factor in aviation mishaps for decades and efforts to mitigate SD have not been proportionate to the danger it poses to pilots. We argue that SD contributes to nearly 33% of all mishaps with a fatality rate of almost 100%. However, SD has not garnered the respect and awareness it requires from leadership and pilots because of historically inaccurate reporting within accident investigations and under-reporting of SD data in research. Over 30 research studies and 10 mishap case studies are presented to portray SD's role in aviation accidents since 1913. Research and training are recommended to improve pilot respect and awareness for SD-inducing scenarios that would include pilot recognition and successful recovery using SD-specific simulators. Consequently, funding is needed to further SD research, to fund SD training, as well as amend the current mishap investigation process to better articulate SD contributions in aviation accidents.

Keywords: aviation mishaps, aviation accidents, aviation spatial orientation, aviation safety, aviation training simulators.

"THE DAY THE MUSIC died…," as written and sung by Don McClean, referenced the February 1959 tragic airplane crash in which singers Buddy Holly, Ritchie Valens, and JP Richardson (aka, The Big Bopper) were killed. The cause of the crash is believed to have been spatial disorientation (SD) by the pilot during the dark night takeoff while attempting to interpret a newly designed attitude indicator display. Unfortunately, even such a high profile crash did not prompt a serious effort to reduce SD-related mishaps for several decades. In the fall of 1984, Col. (Dr.) Grant McNaughton, USAF Flight Safety Center, decided to produce a safety video for use in military flying squadrons. The video was titled "Spatial Disorientation—Still a Killer!" Col. McNaughton, a flight surgeon and private pilot, understood the problem of spatial disorientation in aviation and wanted to do something that would help USAF pilots be better prepared for SD.

Now, almost three decades later, the aviation community has still not substantially reduced the likelihood of SD-related mishaps; Col. McNaughton has long since retired, but the issue of SD remains a threat to all flying communities. Williams and Johnson in 2010 (52), also from the USAF Flight Safety Center, sum up their recent SD findings with a very poignant statement (and echo from the past), "the only way to save your life from a leading killer of fighter pilots is to prevent it" (p. 21). In six decades what have we learned? What are we doing about this "known killer"?

This paper summarizes current research and mishaps involving SD, an issue that cuts across the entire aviation community. Although we primarily address military aspects of SD, the problem also exists in both the commercial and general aviation sectors. The accurate perception of one's orientation in space is vital for safe aviation operations and, despite assumed improvements in training programs and technology, SD-related mishaps continues to occur and the most common types of SD experiences have not drastically changed over the decades.

SD is defined by Benson (6) as, "the pilot fails to sense correctly the position, motion, or attitude of his aircraft or of himself within the fixed coordinate system provided by the surface of the Earth and the gravitational vertical" (p. 277). The 2005 United States Air Force Manual of Instrument Flying Procedures, 11-217 Volume I (45), defined SD as "the erroneous percept of any of the parameters displayed by the aircraft control and performance instruments…regardless of a pilot's experience or proficiency, sensory illusion can lead to differences between instrument indications and what the pilot "feels" the aircraft is doing" (p. 355). It is important to note the multisensory contributions to SD. Both vision and equilibrium/vestibular perceptions contribute (interactively) to spatial orientation perception, with vision accounting for nearly 80% in the aerospace environment (35).

In contrast, for many years within the aviation community, SD was often thought of only within the context of vestibular illusions. It was not until Gillingham's 1992 landmark paper (19) published in the *Journal of Vestibular Research* that "tied the loose ends" of the complete SD problem together. However, there are still many examples where it is obvious that the role of SD is not being recognized, as noted in two 2009 SD mishaps presented below. Another example of the failure to understand the multisensory concept of SD is seen in the U.S. Naval Aviation Safety office (46) release of aeromedical causes in mishaps from 1990 to 2008. The #1 causal factor was SD and then listed at #4 were "visual illusions." Visual illusions should be considered a form of SD. The interplay between vision, proprioceptive, and vestibular

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From the USAF Academy, CO.

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Address correspondence and reprint requests to: Col. Randall Gibb, Behavioral Sciences & Leadership, USAF Academy, 2354 Fairchild Dr., Ste. 6L-166, USAF Academy, CO; randall.gibb@usafa.edu.

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systems is vital for accurate perception of a pilot's orientation; thus all play a key role in understanding the causes of and countermeasures for SD.

Perhaps the long history and commonness of SD have led the aviation community to become numb and desensitized to its threat, to the point of it being considered "the cost of doing business." For example, in 2000, Lessard (26) simply stated that SD "remains a problem for current pilots as it was for early aviators" (p. 27). We argue that SD contributes to at least 25–33% of all aircraft mishaps and it results in the highest number of fatalities. Other research reports generally do not credit (blame) SD to that high of a causal/contributing percentage. However, given the underreporting and inaccuracy of SD in mishap reports, and its correlation with controlled flight into terrain, loss of control, inadvertent flight into weather, and loss of situational awareness (47), SD's actual impact may even be higher than one-third.

We are not the only ones who are pushing for heightened awareness of SD. In a 2002 keynote address, Benson (7) clearly stated that SD has continued to plague pilots for 50 years and, despite improved understanding of its etiology and enhanced pilot displays, SD continues to kill pilots. He provided a historical perspective of SD and detailed aviator SD mishaps going back to 1913. Despite the fact that today's pilots have instruments/visual displays to help maintain orientation, it is apparent that aviation's extreme demands on pilots exceed human sensory-perceptual-cognitive capabilities, even with new technology. In fact, at times the new technology plays a contributing factor in SD (see below).

Despite warnings such as Benson's and others', SD-related mishaps are still occurring, and unfortunately, SD is often not formally recognized as a contributing factor in mishaps. For example, in 2009 (2), a $21M F-16 aircraft and pilot on a night training sortie wearing night vision goggles (NVGs) impacted the ground while accomplishing a high-altitude strafe. This aggressive maneuver requires the pilot to descend toward the ground at a steep angle, release ordinance, and then pull a high number of Gs to climb away from the ground. The Accident Investigation Board (AIB) determined that the mishap and fatality occurred because of the pilot's inability to properly recognize his altitude during the maneuver. The board found additional contributing factors, including limited aircraft experience, channelized attention, breakdown in visual scan, and an inability to distinguish terrain features because of low illumination and contrast. Recall the pilot was wearing NVGs, a night vision device that reduces contrast, reduces acuity, and has a limited field of view. Thus, any chance to visually perceive ambient cues vital for visual orientation, altitude estimation, and closure with the ground was degraded. Despite obvious links to SD, the AIB's executive summary failed to mention SD as causal or a substantial contributor to the mishap.

A similar mishap occurred 1 month later, this time resulting in two F-15E pilot fatalities and destroying a $55M aircraft (3). The pilots were on a night training flight accomplishing a high-altitude strafe while wearing NVGs. That night the illumination was defined as "low" and the pilots overestimated their height above the featureless terrain. The primary causal factor determined by the AIB was the incorrect calculation of the target elevation. Five contributing factors were also presented by the AIB: misperception of operational conditions, erroneous expectation of a typical night strafing attack, inexperience executing night strafing, channelized attention, and an improper crosscheck. Despite the investigation presenting many aspects of SD in terms of an extremely dark night, featureless terrain, and NVG visual limitations, SD again was not formally listed in the report. Are these really examples of 'pilot error' or might mission requirements simply be exceeding human physiological/perceptual capabilities?

In contrast to the two above mishaps and their lack of formal SD acknowledgment is a recognized SD mishap that occurred in 2008 involving an F-16, from which the pilot successfully ejected and survived (1). The experienced pilot was flying a nighttime NVG training mission off the coast of Florida. The AIB determined the cause of the accident was SD due to environmental conditions of a limited horizon over featureless terrain combined with excessive maneuvering. The pilot surviving this SD mishap certainly helped investigators determine the contributing causes to the accident compared with the two previously discussed mishaps. However, despite the fatalities in the other mishaps, sufficient information regarding aspects of SD was presented in the investigative report. The question becomes why SD did not make its way into the executive summary and official list of contributing causes.

Our objective in writing this paper is to highlight the continuing danger of SD and offer solutions. More importantly, we want to enlighten readers that lives and resources lost could have possibly been saved had a meaningful investment been made in treating SD as the serious aviation threat it truly is. For far too long, decade after decade, SD has claimed lives and too little has been done to mitigate the impact of SD.

Inaccuracy and Under-Reporting of SD

Two factors work together and contribute to the lack of respect and attention given to SD mishaps: 1) inaccurate reporting of SD within accident investigations and 2) under-reporting of SD data. Five reasons are presented that foster inaccuracy and under-reporting. The first has already been presented and that is the misapplication of the operational definition of SD; at times it is too vestibular-centric. The 2009 F-16 and F-15E mishaps both contained visual aspects of SD, yet SD was not formally presented in the report, although many degraded visual limitations were discussed as well as environmental factors contributing to the pilots' difficulties maintaining orientation.

Related to the definition of SD is the mishap investigative process itself and the subsequent classification of an accident's contributing factors (reasons two and three).

When an accident occurs, a team is established to determine its cause with the hope of learning what contributed to the mishap in terms of aircraft, human, and/or environmental factors. Depending upon the scope of the accident, different types of expertise are brought in to assist. Although attempts are made to standardize accident investigative teams, different accident teams will bring different perspectives to their analyses and conclusions. During creation of the final report, investigators use accident classification taxonomies, such as the Department of Defense Human Factors Accident Classification System (HFACS), which force investigators to choose specific, predetermined classification options. According to a 2008 North Atlantic Treaty Organization (NATO) report on SD (8), the database of SD accidents is obscured because of the differing manner in which one investigator may or may not code a factor as SD. Similarly, during a 2010 briefing on the U.S. Naval Aviation mishap data using the HFACS categories (at the annual conference of the Aerospace Medical Association), a U.S. Naval Aviation Safety Officer stated that the HFACS data were not accurate in terms of SD incidence rates (15). Overall, the confusing classification of mishaps and their contributions cloud data analysis for SD researchers (e.g., the F-16 and F-15E mishaps shared above).

The fourth reason for inaccuracy and under-reporting is the reality of perishable data (47). Because of the high fatality rate, it is often very difficult to determine what the pilot was thinking, feeling, sensing, and trying to do prior to the accident. Pilot behavior is based upon environmental perception, decision-making, and aircraft control input or the lack of input due to misperception. Teasing out the "causal" link in this sensory-perceptual-cognitive process is exceedingly difficult and open to various interpretations because of the high fatality rate.

The fifth and final factor contributing to inaccuracy and under-reporting of SD is the resistance to including human factors topics such as sensation-perception-cognition in the final report (47). This resistance might partially be due to the fact that human factors investigators often show an "inability to completely quantify and present the magnitude of SD effects in a particular individual, as compared to his or her adeptness at providing straightforward, traditional failure analysis of hardware systems" (p. 198). Thus, board presidents may not "buy into" pilot physiological and psychological contributing factors. There is also a possibility that liability concerns may influence final investigative reports and conclusions of mishap causality. In the military, safety investigation boards exist to determine causality without punishment and make safety recommendations to prevent future accidents, compared to accident investigation boards, which are more "blame"-oriented.

Inaccurate and under-reporting of SD create a death-spiral in terms of awareness and respect by pilots, as well as failing to inform the public of the real danger SD poses to aviation. Essentially, the absence of SD in the final reports equates to marginalizing the role of SD in aviation incidents/accidents. In Nuttall and Sanford's 1959 research (36), their survey revealed that most pilots did not believe SD was an issue. Yes, a dated reference, but unfortunately that mindset still exists in many flying organizations today. For example, a 2003 (23) study found that of 711 British aviators, 75% reported not experiencing/recognizing an SD episode or having only a minor SD experience. This majority group of aviators becomes a challenge to convince that SD is a problem, since in their experience it is not perceived as a danger. Consequently, pilots may not respect a near 100% fatal aviation threat.

SD Research

In 2010, the lead author presented an assessment of visual spatial disorientation at the annual Aerospace Medical Association conference and cited 25 studies dating from 1947 to the present declaring SD's role in mishaps as well as surveys of pilots anonymously sharing their SD experiences (17). Most striking across all the data from various countries and researchers was the consistency over the years—SD rates are not decreasing. For example, a 2008 NATO report showed that SD contribution to accidents in the UK from 1983 to 1992 was 25% and from 1993 to 2002 the percentage was 33% (8). Some countries are responding to the data: the UK has embarked on improved SD mitigation efforts involving SD-induced scenarios in simulator training for pilots (20). However, there has not been a similar response in the United States.

As an attempt to convince more people of the magnitude of the SD impact, the following list documents the role of SD in aviation. Keep in mind that these data under-represent SD's actual presence and represent a small sample of a larger international library of reports.

1947: U.S. Naval aviators, 67 total, reported on their illusionary experiences and categorized them into visual, non-visual, conflicting sensory cues, dissociative, and emotional (48). Of note within visual illusions categories were confusion with lights, depth perception, "black night," and judging height above the ground/water. Experienced pilots were still prone to illusions regardless of total flight time.

1959: USAF in Europe, 685 pilots were surveyed and it was determined that experience level was not a factor for SD; from 1954 to 1956, 4% of all mishaps were considered to be SD related, but they accounted for 14% of all fatalities (36).

1971: USAF mishaps between 1958 to 1968 were assessed and the authors summarized the likely SD pilot would be 30 yr old, with 10 yr and 1500 flight hours of experience, and flying fighter aircraft (5). They reported SD contributing to 6% of all mishaps and 11% of all fatalities.

1971: Worldwide turbo-jet transport operations from 1958 to 1967; there were 35 approach-and-landing accidents and of those, 27 (77%) had visual perception issues contributing to the mishap (21).

1995: USAF attributed 270 out of 356 mishaps (76%) from 1980 to 1989 to loss of situational awareness/SD, resulting in 437 fatalities and $2.05B in resources (22). The F-16 had a disproportionate number of those mishaps during the 1980s. Factors leading to the loss of situational awareness/SD were channelized attention (61%), visual restriction (30–40%), visual illusion (20–30%), and overconfidence (10–14%).

1998: U.S. Army helicopter data from 1987 to 1995 including all Class A, B, and C mishaps (970 total), showed that 30% had SD contributions and 62% of the SDs occurred at night (10).

2000: USAF accidents from 1994 to 1998 cited SD as a primary factor in 18 (12%) out of a possible 148 Class A mishaps (34). Data were re-examined with a broader definition of SD and the percentage of mishaps with SD jumped to 27%.

2002: USAF survey of 2582 pilots on their experiences with SD (28). The top seven most commonly experienced illusions were (% of pilots having experienced the illusion): leans, 76%; loss of horizon, 69%; sloping horizon, 66%; Coriolis, 61%; night approach–black hole, 58%; misleading altitude cues, 50%; and false sense of pitching up, 44%. The authors further justified the need for SD efforts based on USAF data from 1991 to 2000 that had SD costing the service $1.4B and 60 lives, and concluded that nothing has changed in three decades (28).

2002: The U.S. Navy in 2001 had 19 Class A mishaps, of which 26% were attributed to SD and accounted for 50% of the total number of fatalities (30).

2003: U.S. Navy Class A mishaps from 1990 to 2000 revealed 20% attributed to SD, of which 50% were at night, and accounted for 64% of all fatalities (51).

2004: U.S. Navy from 1997 to 2002 experienced 120 fixed-wing aircraft mishaps; 22 (18%) of those were SD-related, resulting in 23 fatalities and $475M in resources. Rotary-wing aircraft suffered 29% SD mishaps, resulting in 35 fatalities costing $118M (50).

2006: USAF mishaps between 1990 and 2004 had 11% of all mishaps attributed to SD and 23% of all night mishaps having SD contributing factors (27). Findings in terms of percentage of fatalities are more striking as SD accounted for 57% of all mishaps and 81% fatalities at night.

2007: an Australian SD safety investigation report stated that the probability of pilots experiencing SD in their aviation career was 90–100% (35); further, the rate of SD in mishaps was between 6–32% and accounted for 15–26% of all aviation fatalities. The author concluded that the "true prevalence of SD events is almost certainly underestimated" (p. vii).

2009: U.S. Navy data between 2000 and 2007 revealed 10% of all mishaps were SD-related and accounted for 40% of all fatalities; 13 of 18 were at night (46).

2009: USAF mishaps from 1991 to 2002 cost 82 lives and $1.9B in resources because of pilot unrecognized SD, costing the USAF $100M annually (Knight & Ercoline, Foreign Comparison Testing Office, evaluation of spatial disorientation trainers for Air Education and Training Command, February 2009).

2010: USAF data analyzed from 1999 to 2009 found that SD played a major role in 11% of all mishaps and 42% of all fatalities (52). Fighter aircraft accounted for 65% of fatal SD mishaps. Similar to the Barnum and Bonner's 1971 (5) description of the typical SD pilot, the authors, Williams and Johnson, characterized today's typical SD pilot as most likely flying an F-16, F-15, or A-10 with 2500 flying hours, at night on a low level, and during low to moderate Gs in a slight bank.

2010: SD mishap rate reported as not changing significantly in the last 20 yr for the USAF; 1990 to 1999 SD accounted for 14% of all mishaps and 30% of all fatalities compared with SD data from 2000 to 2009 in which SD was attributed in11% of all mishaps and 26% of all fatalities (43).

Approximately 10 years ago there was a surge in SD research within military aviation. Numerous articles were written (e.g., *Institute of Electronics and Electrical Engineers (IEEE) Engineering in Medicine and Biology* in 2000 dedicated an entire issue to SD as did Navy's *Approach* magazine in 2004), statistics were shared in journals as evidence of the many research papers during the 2000s, and an international conference on SD was held in 2002. U.S. Naval Aviation safety advocates Wechgelaer et al. (51) found that in assessing U.S. Naval Aviation mishap data the common themes were: 1) SD was underreported, 2) SD mishaps are more likely fatal, 3) SD mishaps were not decreasing in occurrence, 4) SD accidents/incidents were not related to pilot experience—all pilots are susceptible, 5) SD mishaps cost billions in resources, and 6) SD spending and attention were disproportionately lower than the magnitude of the problem (Wechgelaer P.; personal communication, 2010).

In 2003, the Secretary of the Defense, Donald Rumsfeld, initiated a safety effort to mitigate preventable accidents and cut mishaps by 50% (39). Although many in the safety community, especially those doing SD research, were hopeful that this proactive leadership directive could build momentum toward finally defeating SD, even it unfortunately failed to create organizational change. In a pointed 2009 USAF report, Knight and Ercoline introduced their SD paper (Knight and Ercoline, unpublished report, February 2009) by stating that SD training at that time was no different than it was seven decades ago, and that current training does not address SD proportionally to the cost.

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Thus, despite the effort of many researchers, SD continues to kill pilots. Why? SD continues to kill pilots because not only did that information fail to reach the pilots, but more importantly it failed to make an impression on the senior leadership to sway funding toward improved SD prevention measures.

SD Mishaps and Link to Advanced Technology

Unlike the aggregated SD research statistics and survey results that impersonalize the impact, specific mishap details highlight the cost in terms of humanity. Granted, mishaps have many contributing factors and whether or not the investigation board deemed SD as the primary causal factor or only as a contributing factor, the following mishaps are highlighted because of the SD factors involved as well as the timeframe depicting differing decades, phase of flight, and aviation communities. The bottom line is that no pilot has ever been nor will be immune to SD.

SD in a water environment: In 1941 while attempting to perform a twilight water landing in San Juan Harbor, the pilot of a Pan American Airways "flying boat" impacted the water with too low of a nose attitude; two people were killed and the airplane destroyed (12). The pilot had 11,284 flying hours, yet still misperceived his environment during a critical phase of flight. Possibly the pilot experienced a false sensation of being too high above the smooth water surface and was induced into initiating an unwarranted descent. In 2006 an experienced helicopter crew and five passengers were killed while attempting to land on an oil platform during a dark night approach over the water (42). The pilots struggled with their visual perception and orientation during a challenging visual approach in an environment with no horizon or terrain features. This tragic accident and other North Sea helicopter mishaps have prompted research into improving the helipad lighting configuration display to visually assist pilots during challenging visual landings in degraded conditions (14).

Degraded visual environment and confusing vestibular input: The 2008 F-16 mishap presented above (1) has commonalities with the tragic and well-publicized mishap in 1999 of John F Kennedy, Jr., his wife, and sister-in-law. JFK, Jr., was not instrument qualified, but had flown night visual flight rules (VFR) previously on a similar route; however, on the night of the mishap, no horizon was present and meteorological conditions greatly restricted visibility (33). Consequently, he was unable to use visual cues to help him override the confusing vestibular sensations, resulting in SD-induced water impact off the East Coast. This mishap highlighted the oxymoron of "night VFR" (25) and general aviation pilots became more aware of the hazards/risks/dangers of night flying without being instrument rated (38).

Black hole illusion: In 1974 the black hole illusion contributed to a Pan American World Airways, Boeing 707 crash short of the runway at Pago Pago International Airport, American Samoa (31). Only 5 of the 101 on board survived. The pilot in command, an experienced pilot with 17,414 flying hours, transitioned from instruments to visual conditions; however, he failed to correct his excessive descent rate because of limited visibility, the "black hole" illusion, inadequate monitoring of instruments, and failure of the flight crew to call out his descent rate. In 1997, a Korean Air Boeing 747 accomplishing a night landing at A. B. Won Guam International Airport impacted terrain 6.1 km (3.3 nm) short of the runway, killing 228 on board (32). The $60M aircraft was piloted by an experienced aviator, with nearly 9000 flying hours, who had made the flight from Seoul, Korea, to Guam eight times previously flying a Boeing 727 and had just made the same flight on the 747 a month prior. The National Transportation and Safety Board cited the mishap on an improperly briefed and flown instrument procedure; however, the pilot expected to fly a visual approach and on that dark, rainy night flew over the water and mountainous terrain into an area known as a "black hole" (37). The long, thin runway was slightly up-sloped and, given the dark night, if the pilot attempted a visual straight-in, the combined environment and runway conditions were conducive to a shallow approach illusion that results in landing short of the runway.

Somatogravic illusion or black night takeoff illusion: In 1958, a Northwest Airlines flight, Douglas DC-6B, crashed shortly after takeoff from the Minneapolis airport, destroying the aircraft; thankfully no fatalities occurred (13). The visual night takeoff induced the false sensation of pitching up excessively, thus the pilot pushed over into the ground. This somatogravic illusion is a vestibular misperception of acceleration confused with a climb, amplified when visual cues are absent. Essentially the pilot was flying a perfectly safe climb angle in taking off, but the vestibular illusion and lack of visual cues induced him into an unwarranted pitch-over into the ground. In 2001, a Navy F/A-18 Hornet high-performance jet fighter impacted the water shortly after a catapult launch off an aircraft carrier (30). It was an extremely dark night, with low clouds, and after becoming airborne beyond the ship 224 ft above the water's surface, the pilot applied forward pressure on the stick during climb-out and the aircraft accelerated on a downward vector into the water. The aircraft was destroyed and the pilot's ejection attempt was unsuccessful.

It is important to note that new technology has not mitigated the SD threat. As pointed out in numerous studies and substantiated by recent SD mishaps, improved avionics, helmet/head-mounted displays and glass cockpits have not reduced the incidence of SD. In fact Rupert (40) stated, "Technology has, in part, become part of the problem contributing to SD in aircraft" (p. 72). New sensation-perception technology has not eliminated SD, and has simply changed the types of errors that occur (18). One such advancement for example, are NVGs; however, the technology cannot completely turn "night into day" and it comes with the cost of severely reducing peripheral vision. Quite possibly, technology has wrongly inflated pilot confidence in degraded visual conditions.

Research and Training

Nuttall and Sanford (36) 50 yr ago noted that prevention measures must address two primary areas, research and training. Research is needed so that we can better understand, explain, and document the visual and vestibular SD interactions in a variety of flying conditions and how current technology/displays influence SD in those conditions. Additional research should investigate alternate means (e.g., non-visual) by which to present spatial orientation information to the pilot (7), the human–system interface. It has been well documented that vision, which supplies 80% of our reliable aerospace orientation perception, is already maximized (18). The tactile modality has shown much promise for "grabbing attention" of the pilot. For example, a tactile vest worn by a pilot provides a "tapping" pressure to the pilot that indicates orientation (29,40). Unfortunately, politics and funding has blocked its implementation for U.S. military pilots (Rupert AH, personal communication, 2010).

Research should also investigate means by which we can improve the man-made aspects of the environment, such as runway markings and lighting. For example, research was initiated due to the high number of North Sea helicopter accidents that occurred in challenging, degraded visual conditions. Through a series of helipad lighting configuration studies, different colors and shapes were found that helped pilots maintain distance and depth perception while landing on the platforms (14).

Finally, research support is needed to further develop simulator training experiences and general training protocols because it is through training/education that we will reach the pilots. Research supporting the effectiveness of SD training comes from several previous studies. In 1997 (9), Braithwaite published work on in-flight SD demonstrations for British helicopter pilots, its cost effectiveness, and pilot acceptance. Braithwaite led another report (11) in 1998, in which U.S. Army helicopter pilots were exposed to the British in-flight training program. More recently, Ercoline authored the "SD Countermeasures Research Program: Summary Report" (Air Force Research Laboratory, unpublished report, December 2005) that captured all of the SD prevention efforts in the previous 5 years. He concluded that SD countermeasures resulted in the saving of 12 aircraft, 20 aircrew members, and nearly $500M. Thus, sufficient evidence exists for the effectiveness of training programs.

Within training, three paths are possible: 1) SD-specific simulators, 2) use of in-service flight simulators for SD-producing scenario training, and 3) in-flight SD demonstrations. We will center our discussion on SD simulators, training devices with the capability to teach SD-specific scenarios as well as traditional instrument and emergency training. An SD simulator is capable of producing the known motion cueing and/or the degraded visual environments found in SD illusions while simultaneously creating a workload environment similar to that found in the operational mission of the aircraft. The sophisticated software in these simulators allows pilots to truly experience SD-inducing scenarios such as the nighttime, low-level scenario that commonly leads to SD.

The USAF has researched SD-specific simulators extensively and efforts have quantified the need for and effectiveness of such devices. In 1996 (53), in 2005 (16), and again in 2009 (Knight & Ercoline, unpublished report, February 2009), experienced pilots participated in SD-specific simulator studies and the results were favorable regarding pilots' impressions regarding how these simulators helped them learn, recognize, and recover from SD situations. Unfortunately, efforts to purchase and install these new devices into the flight training programs have been completely unsuccessful. For the past 5 years the purchasing of an SD trainer has missed the funding line due to other "more important operational" requirements. The request for a new SD trainer has been "on the books" in the USAF for the past three decades. In contrast, the Indian AF has acquired and assessed an SD-specific trainer in 2004; Baijal et al. (4) reported that 90–97% of pilots surveyed found their training as "good to excellent" in emphasizing "trust in instruments" and ability to recover from SD situations.

Current existing flight simulators, although capable of some SD-inducing scenarios, are incapable of truly creating realistic SD experiences for pilots due to both hardware and software limitations. The cost of retrofitting the hardware and the necessary software development for the current flight simulators may actually be greater than the cost of the more sophisticated SD-capable simulators. However, despite the limitations of existing simulators, there is some research suggesting that they can help increase appreciation for the effects of SD. Bles (8) provided examples in their report of ground-based training using current in-service simulators with scenarios developed by an SD training team. These engineered scenarios induced pilots to fly themselves into an unrecognized SD situation. Grimshaw in 2010 (20) summarized the UK's Royal Air Force efforts to incorporate SD scenarios into their rotary wing refresher training using current in-service simulators (Grimshaw T, personal communication, 2010). Her study revealed that unrecognized SD often occurs during certain mission phases and simulated conditions (any cognitive activity drawing from the limited pool attention such as high workload, cockpit distractions, unexpected/deteriorating weather, or unusual landing environments) can induce SD in pilots. Specifically, her assessment included 72 simulator sorties with instructors rating the severity of SD within each. The majority of the pilots, 65%, found themselves in 'significant' SD situations and 14% resulted in controlled flight into terrain.

A 2009 survey of subject matter experts by Walker, Owens, and Muth (49) found that visual-only simulators (i.e., existing in-service flight simulators) could be effective for SD prevention via scenario-based training. Consequently, current in-service simulators that exist at every operational flying location could be used for some SD-specific, scenario-driven training at relatively minimal cost. However, we question if this limited SD-producing effort would have the fidelity to counter SD to the level required for significant improvement of aviation operations, especially with increasing demands placed on pilots due to new technologies. Pilots need to experience multiple, realistic (vision and motion) SD illusions in a safe, simulated world. That would be far better than experiencing them for the first time in an airplane, which is the way it most often occurs now.

The experience of multiple training scenarios is also key, allowing pilots to develop recognition-primed decision making (24), which speeds recognition and recovery when a pilot enters SD-inducing conditions. Again going back to the F-16 and F-15E mishaps that occurred in 2009, training possibly could have instilled recognition of the conditions that led to SD. These mishaps involved low illumination and low contrast combined with NVGs and fatigue while flying a demanding sortie, which can be presented by the high-fidelity SD simulators. If these dangerous scenarios were repeatedly experienced in a simulated environment prior to the actual aircraft mission, pilot risk could be greatly mitigated. Unfortunately, current SD training typically consists only of simple classroom discussions. We are not preparing our pilots adequately for what they will actually experience. This is even more alarming considering the increased amount of night flying occurring and the new cockpit head/helmet technologies with which the pilot must cope. Recall the opening quote, "the only way to save your life is to prevent SD." Therefore, during both initial training and refresher training, having pilots fly multiple scenarios and experience the effects of SD may be an effective way to train and educate pilots.

Summary and Recommendations

Convincing large organizations of funding changes in the name of safety are often considered an "altruistic effort" with no return on investment (41). This, however, is not the case with SD. For example, in the USAF (44), the 10-year average mishap rate is 1.29 out of 100,000 flying hours or one mishap every 77,519 flying hours (time-between failures). The mishap rate for this past fiscal year, 2009, was 0.8. However, included in that "lower" 0.8 mishap rate were the F-16 and F-15E SD-related mishaps that were not officially classified as SD and which accounted for 3 of the 6 FY2009 aviation-related fatalities. Given the decades of statistics, the odds are fairly high, near one-third or greater, that the next "failure" will be an SD mishap and the probability of that mishap being a fatality near 100%. Thus, funding SD prevention is far from altruistic.

The argument that new display technologies will in themselves reduce mishaps is ill founded with respect to SD. Advanced fighter cockpits and helmet displays have significantly increased perceptual/cognitive demands on pilots, leading to increased likelihood of SD. For example, threats such as visual clutter, visual capture, cognitive tunneling, and task saturation all help induce SD. As helmet-mounted displays increase viewing opportunities, a pilot's orientation system can become overwhelmed with sensory-perception-cognition mismatches between visual, proprioceptive, and vestibular inputs. Should we simply consider the result to be "pilot error" or should we explicitly acknowledge the human physiological and psychological limitations and work to reduce the potential likelihood of a mishap?

Based on the overwhelming data and prior research, we present three recommendations, two of which focus on funding resources related to training:

1. Fund SD research regarding advanced aviation technology and simulator training.
2. Fund SD training, including the purchase of SD-specific simulators, further hardware and software development, and training program syllabus development (so that SD training is systematically incorporated in both initial as well as refresher training).
3. Amend the mishap investigation process to better articulate SD as a contributing factor and not allow classification systems to separate visual and vestibular disorientation; educate investigators on the operational definition of SD.

Unless the Department of Defense leadership prioritizes SD from the "unfunded" to the "funded" category of budget spending, SD mishaps will continue at unacceptably high rates and result in pilot fatalities. Committed funding is needed to create change for our aviation future; a relatively small investment (compared to the cost of the mishaps) could reduce the percentage of SD-related mishaps. Other countries are already making the commitment; the second author attended an international SD training conference in December of 2010. It was clear from the presentations that aviation organizations in Europe consider SD a serious threat and are actively taking steps toward mitigating SD mishaps.

The United States should follow Europe's lead and also draw on the success of an analogous training effort in the late 1980s and early 1990s. During this time period, aircrew coordination training grew into crew resource management training to curb the high number of mishaps, both military and commercial, that were occurring due to pilots failing to work together as effectively as possible. This effort was successful only because leadership and funding made it a priority. Pilots received the required training via the current in-service simulators as well as it becoming an area for in-flight training focus. The hope is that SD mitigation efforts will achieve the same level of research, awareness, leadership focus, and funding implementation as crew resource management has and still is receiving today. After decades of pilot fatalities as well as mishap statistics and investigative reports demonstrating the danger of SD, the evidence is clear and the solutions are known—it is time to stop SD.

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Authors and affiliation: Randall Gibb, MSE, Ph.D., Bill Ercoline, M.S., Ph.D., and Lauren Scharff, M.A., Ph.D., USAF Academy, CO.

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