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Spatial Disorientation in Fatal General Aviation Accidents (2003 – 2021)

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12. Abstract

The incidence of spatial disorientation (SD) during flight poses a distinct threat in general aviation (GA) due to the high fatality risk associated with its occurrence. While historical analyses have examined the incidence of SD in GA accidents, little current research exists. This research examines fatal GA accidents associated with SD from 2003 to 2021 and investigates the pilot demographics, flight characteristics, and environment conditions associated with these accidents to identify potential risk factors and compares these findings with previous historical analyses. Overall, 367 fatal accident reports from the National Transportation Safety Board (NTSB) that were GA associated with SD were analyzed. These accidents showed a strong correlation to pilots with less than 500 hours of flight experience. Additionally, instrument meteorological conditions (IMC) were likely to involve flights into IMC despite intentions to fly using visual flight rules (VFR). While the number of fatal SD GA accidents has decreased in comparison to previous analyses, the fatality rate associated with SD is still high (94%) and involves high fatality numbers for pilots, passengers, and even ground bystanders. Further, the number of fatal SD GA accidents associated with positive toxicology findings has increased over time, particularly for drugs that pose potentially impairing effects. This research highlights the necessity for continued education and awareness efforts for SD within GA.

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List of Abbreviations

Abbreviation	Definition
CAMI	Civil Aerospace Medical Institute
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
GA	General aviation
IMC	Instrument meteorological conditions
NTSB	National Transportation Safety Board
SA	Situation awareness
SD	Spatial disorientation
THC	Tetrahydrocannabinol
VFR	Visual flight rules
VMC	Visual meteorological conditions

Abstract

The incidence of spatial disorientation (SD) during flight poses a distinct threat in general aviation (GA) due to the high fatality risk associated with its occurrence. While historical analyses have examined the incidence of SD in GA accidents, little current research exists. This research examines fatal GA accidents related to SD from 2003 to 2021 and investigates the pilot demographics, flight characteristics, and environment conditions associated with these accidents to identify potential risk factors and compares these findings with previous historical analyses. Overall, 367 fatal accident reports from the National Transportation Safety Board (NTSB) that were GA involving SD were analyzed. These accidents showed a strong correlation with pilots with less than 500 hours of flight experience and instrument meteorological conditions (IMC) and were likely to involve flights into IMC despite intentions to fly using visual flight rules (VFR). While the number of fatal SD GA accidents has decreased in comparison to previous analyses, the fatality rate associated with SD is still high (94%) and involves high fatality numbers for pilots, passengers, and even ground bystanders. Further, the number of fatal SD GA accidents associated with positive toxicology findings has increased over time, particularly for drugs that pose potentially impairing effects. This research highlights the necessity for continued education and awareness efforts for SD within GA, particularly in regard to the association between substance use and SD.

Introduction

Spatial disorientation (SD) can be characterized as an “erroneous sense of one's position and motion relative to the plane of the earth's surface” (Gillingham & Previc, 1993), and is a widely known aviation safety risk. SD research in aviation has predominantly focused on military operations due to the capabilities of high-performance aircraft (Barnum & Bonner, 1958; Gillingham, 1992; Matthews et al., 2002). However, SD is similarly a risk in civil aviation, where it is often linked to loss of control outcomes (Newman & Rupert, 2020). While the risks for SD are ubiquitous to civil aviation, general aviation (GA) operations may be most at risk (Kirkman et al., 1978).

While SD can occur during any aviation operation, there are risk factors that may increase the probability of losing situation awareness and experiencing SD. For example, SD is a particular risk in reduced visibility environments due to the complex cognitive, psychomotor, and sensory challenges that such environments present to a pilot (Mortimer, 1995; Gibb et al., 2011). Any factors that influence pilot perception, such as drug or alcohol use, can increase the risk for SD (Gibbons, 1988; Collins, 1972; Mortimer, 1995). Further, the National Transportation Safety Board (NTSB) has identified an increase in positive toxicology findings in pilots for potentially impairing substances from 1990 to 2017 (NTSB, 2020), highlighting the importance of understanding the relationship between drug use and SD.

Previous research at the Civil Aerospace Medical Institute (CAMI) has worked to categorize the incidence of fatal SD accidents within general aviation (Kirkman et al., 1978; Collins & Dollar, 1996). However, it has been nearly 30 years since the last comprehensive CAMI accident analysis on this topic, and research within the wider scientific community on civil aviation rates is similarly dated (Gibb et al., 2011; Mortimer, 1995). To understand the current state of SD accidents in GA and to better evaluate the effectiveness of current SD training and awareness programs, an updated baseline of SD fatal accidents is necessary.

The current report describes an analysis of SD-related accident reports from the NTSB aviation accident database (CAROL) for accidents between 2003 and 2021. Characteristics of these accidents, fatality rates, and demographics of the pilots involved were evaluated to better understand the current incidence of SD fatal accidents in GA. Toxicology findings were also evaluated in SD accidents, including previously unexplored ethanol findings.

Methods

CAROL was queried for fatal GA accidents in fixed-wing aircraft between 2003 and 2021. Reports were filtered to only include those referencing the term “spatial disorientation” in the factual narrative, probable cause, or finding text. Final reports and associated dockets from completed investigations were reviewed. The findings and analyses were evaluated for overall trends across accidents, and factual information was documented for each accident (e.g., fatalities, pilot experience, visual conditions).

To evaluate the incidence of positive toxicology findings for potentially impairing drugs, data from the CAROL were matched with available test results from CAMI’s Forensic Sciences toxicology database. The current analysis of toxicology results adopted drug categories and definitions used in the 2014 and 2020 NTSB reports on aviation drug use (NTSB, 2014; 2020). Similarly, the potentially impairing drug definitions utilized in the NTSB reports were employed. Specifically, these were defined as drugs that carry a Food and Drug Administration (FDA) warning regarding effects associated with routine therapeutic usage that could impair a pilot’s judgment, decision-making, or reaction time, or those that carry a warning regarding driving or operating machinery. Unlike the 2014 and 2020 NTSB reports, the current study included ethanol results. All ethanol results were scrutinized to exclude cases where ethanol was likely or possibly due to postmortem microbial formation.

Results

Incidence of SD GA Accidents

A total of 367 fatal GA accidents from 2003 to 2021 included SD in the factual narrative, probable cause, or finding text. The number of accidents each year varied across this 19-year span, from a minimum of 9 in 2016 to a maximum of 29 accidents in 2019 (Table 1). Across this same span, there were a total of 26,535 GA accidents, with 4944 being fatal. The overall percentage of fatal GA accidents that involved SD was 7.4%. In comparison to CAMI’s 1996 review of similar accidents, where there was a trending decrease in the percent of fatal SD GA accidents over time, the current review found a slight trending increase (Pearson’s correlation coefficient (r) = 0.65) over the 19-year span (Figure 1).

Table 1

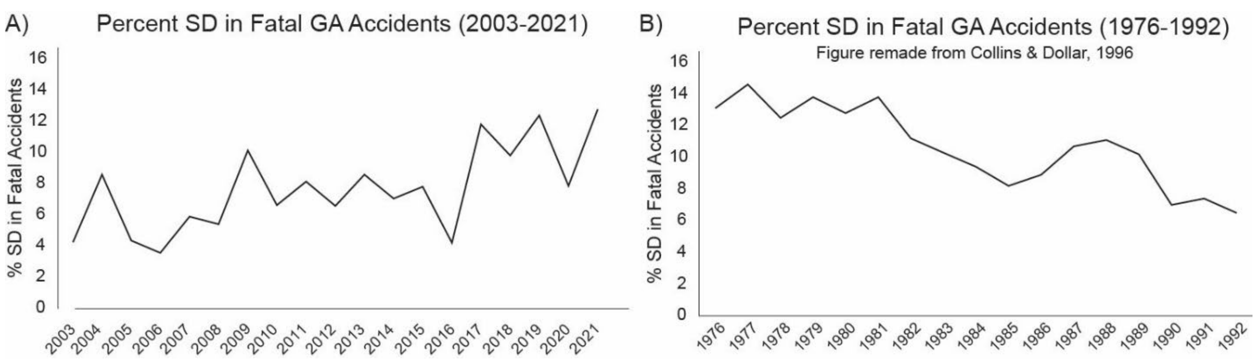
Fatalities Related to Spatial Disorientation (SD) in General Aviation (GA)

Year	Total GA Accidents*	Fatal GA Accidents*	Fatal GA Accidents with SD	% Fatal GA Accidents with SD
2003	1,741	352	15	4.3
2004	1,619	314	27	8.6
2005	1,671	321	14	4.4
2006	1,523	308	11	3.6
2007	1,654	288	17	5.9
2008	1,569	277	15	5.4
2009	1,481	276	28	10.1
2010	1,441	271	18	6.6
2011	1,471	270	22	8.1
2012	1,471	273	18	6.6
2013	1,223	221	19	8.6
2014	1,222	255	18	7.1
2015	1,211	230	18	7.8
2016	1,268	213	9	4.2
2017	1,234	203	24	11.8
2018	1,275	224	22	9.8
2019	1,221	234	29	12.4
2020	1,086	203	16	7.9
2021	1,154	211	27	12.8
Total	26,535	4944	367	7.4

*Data from NTSB U.S. Civil Aviation Accident Statistical Review.

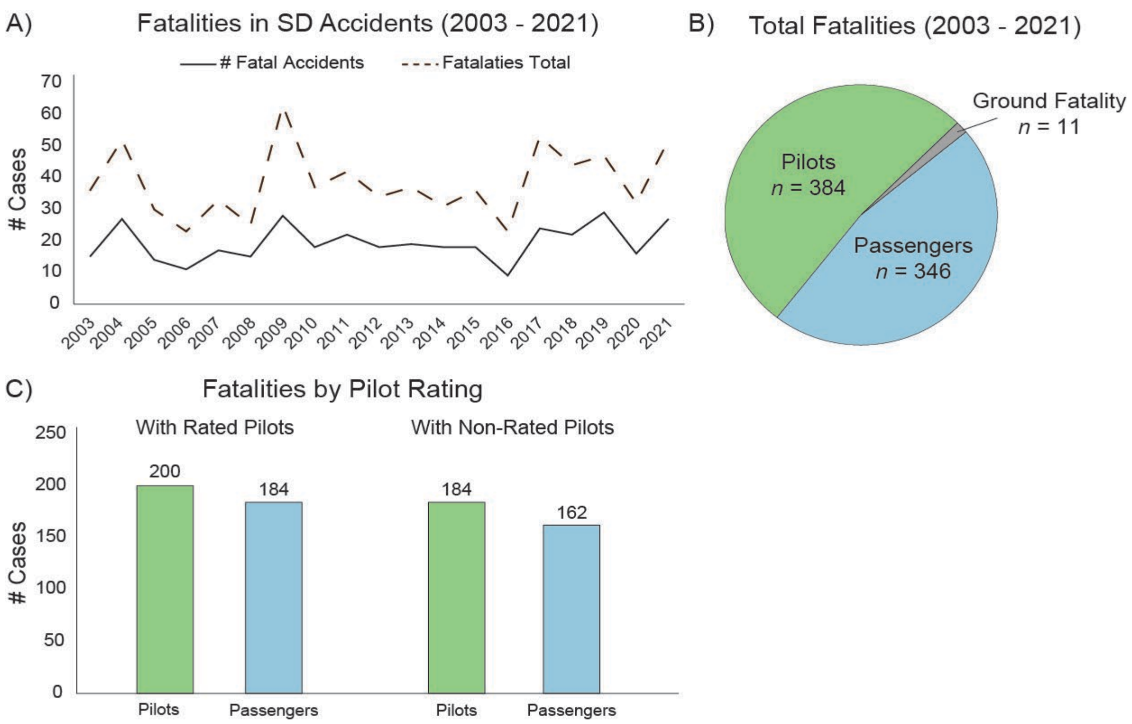
Figure 1

Comparison of SD in Fatal GA Accidents Across Years



These 367 fatal SD accidents were associated with a total of 741 fatalities, which included 384 pilots (51.8%), 346 passengers (46.7%), and 11 ground fatalities (1.5%; Figure 2). The number of fatalities varied across the years along with accident frequency, with a maximum of 63 fatalities in 2009. There was no difference in the number of fatalities for either pilots (twotailed t-test: $t(364) = 0.810$, $p = 0.419$) or passengers ($t(210) = 0.166$, $p = 868$) depending on whether the pilot was instrument-rated or not (Figure 2C).

Figure 2
Fatalities in Spatial Disorientation Accidents (2003 - 2021)



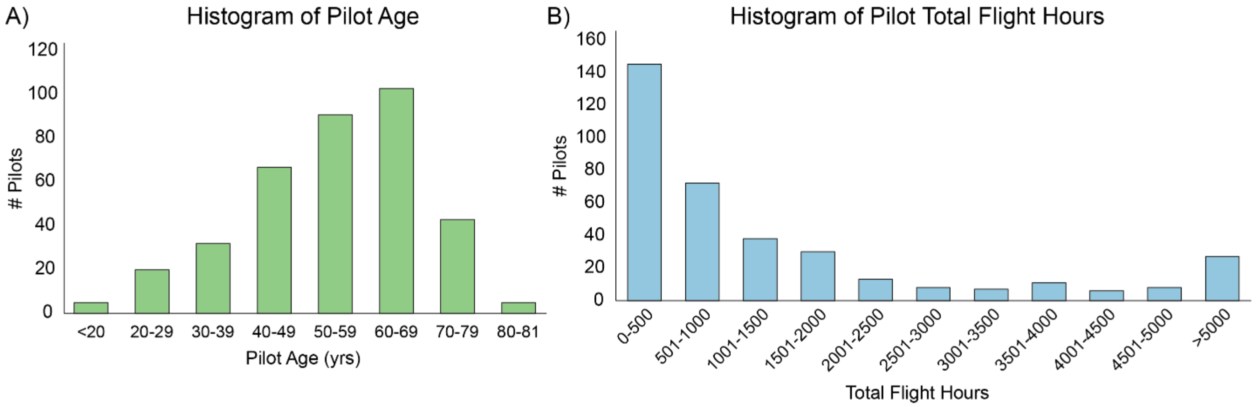
To better understand the likelihood of fatality in SD GA accidents, the same search of CAROL was performed, except the criterion for fatal accidents was removed. This returned 390 total GA accidents in fixed-wing aircraft related to SD, indicating that the fatality rate for SD accidents in GA is 94%, compared to the fatality rate for all GA accidents, which is 19%.

Pilot Demographics and Flight Characteristics

The pilots involved in these fatal SD accidents represented a wide spectrum of ages and levels of experience. Histograms in Figure 3 demonstrate these ranges. The average age for these pilots was 54.4 (standard error of the mean [SEM]: ± 0.7 years), and the average flight time experience was 1799 total flight hours (SEM: ± 164.1 hours). Over half of all pilots ($n = 194$ of 367) were between 50 and 69 years old. However, total flight hour experience tended to cluster in the <500 hours of total flight time group ($n = 145$ of 367; Figure 3B).

Figure 3

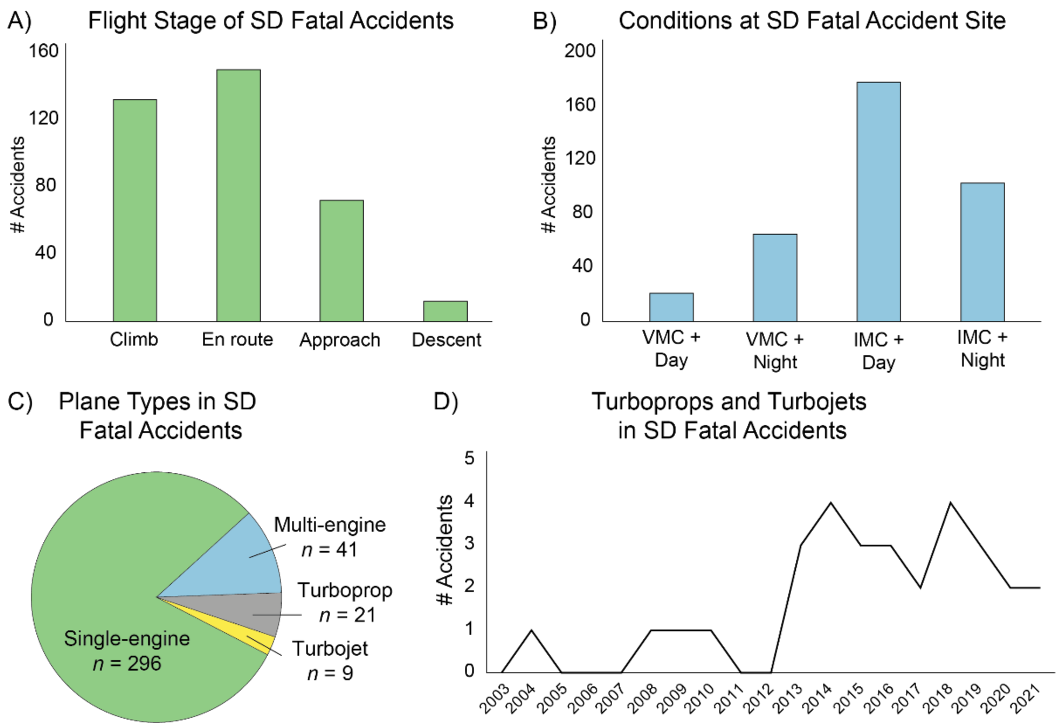
Demographics of Pilots in Fatal Spatial Disorientation Accidents



The flight characteristics of these fatal SD GA accidents showed potential environmental and situational risk factors for SD. The majority of accidents occurred either during the climb (*n* = 132) or en route (*n* = 150) portions of the flight (Figure 4A). According to NTSB meteorological findings, most accidents occurred during instrument meteorological conditions (IMC; *n* = 281 of 367) and during daytime (*n* = 199 of 367; Figure 4B). Most accidents occurred in single-engine planes (*n* = 296), with a smaller amount occurring in multi-engine planes (*n* = 41), turboprops (*n* = 21), and turbojets (*n* = 9; Figure 4C). Interestingly, there was a slight increase in the incidence of turboprop- and turbojet-related accidents over time, beginning in 2013 (Figure 4D), though the small number of aircraft in this category makes it difficult to interpret these findings.

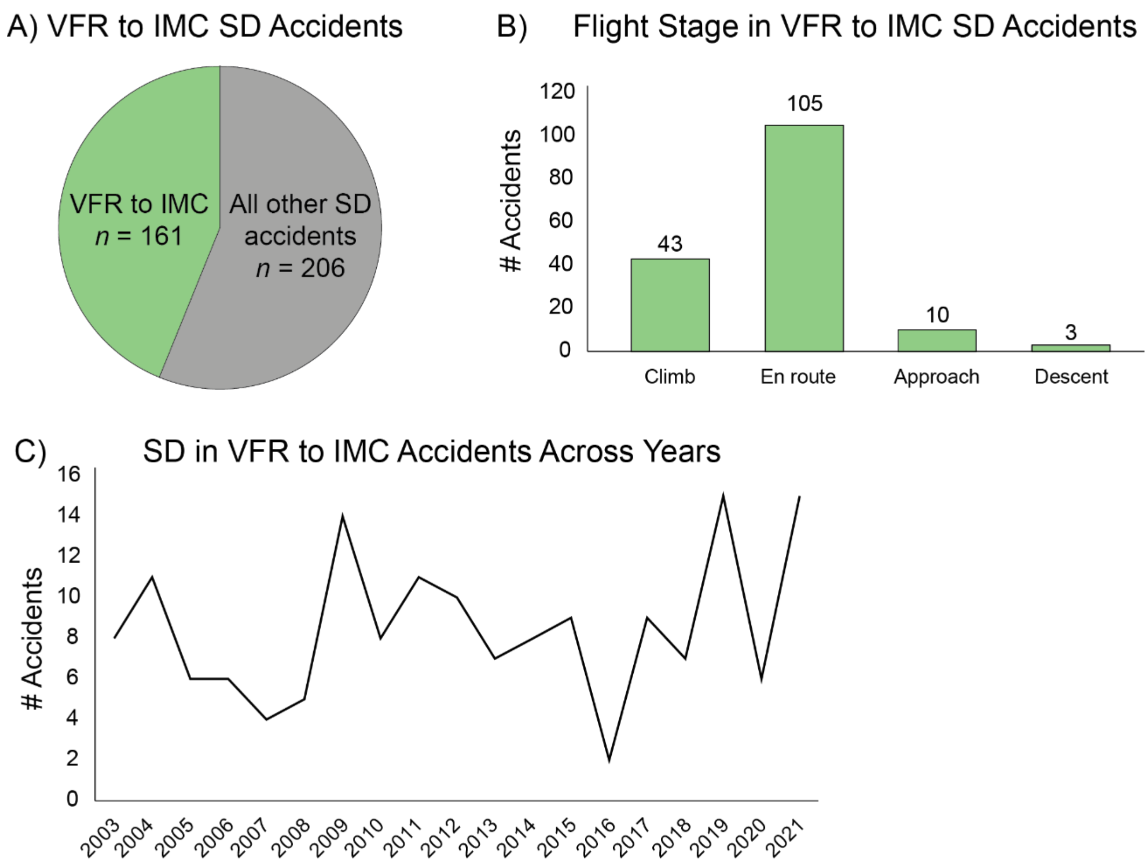
Figure 4

Flight Conditions and Plane Types in SD Fatal GA Accidents



Based on meteorological information in the final NTSB reports, flights were evaluated for cases where a pilot entered IMC while intending to operate under visual flight rules (VFR). VFR to IMC flights made up nearly half of all fatal SD GA accidents in the current dataset (43.9%; *n* = 161; Figure 5A). Further, the majority of VFR to IMC accidents occurred during the en route portion of the flight (*n* = 105; Figure 5B). Most pilots involved in these VFR-IMC accidents did not hold instrument rating (*n* = 127), and the incidence of these accidents was relatively consistent across the 19-year span (Figure 5C).

***Figure* 5**
VFR to IMC in SD Fatal GA Accidents

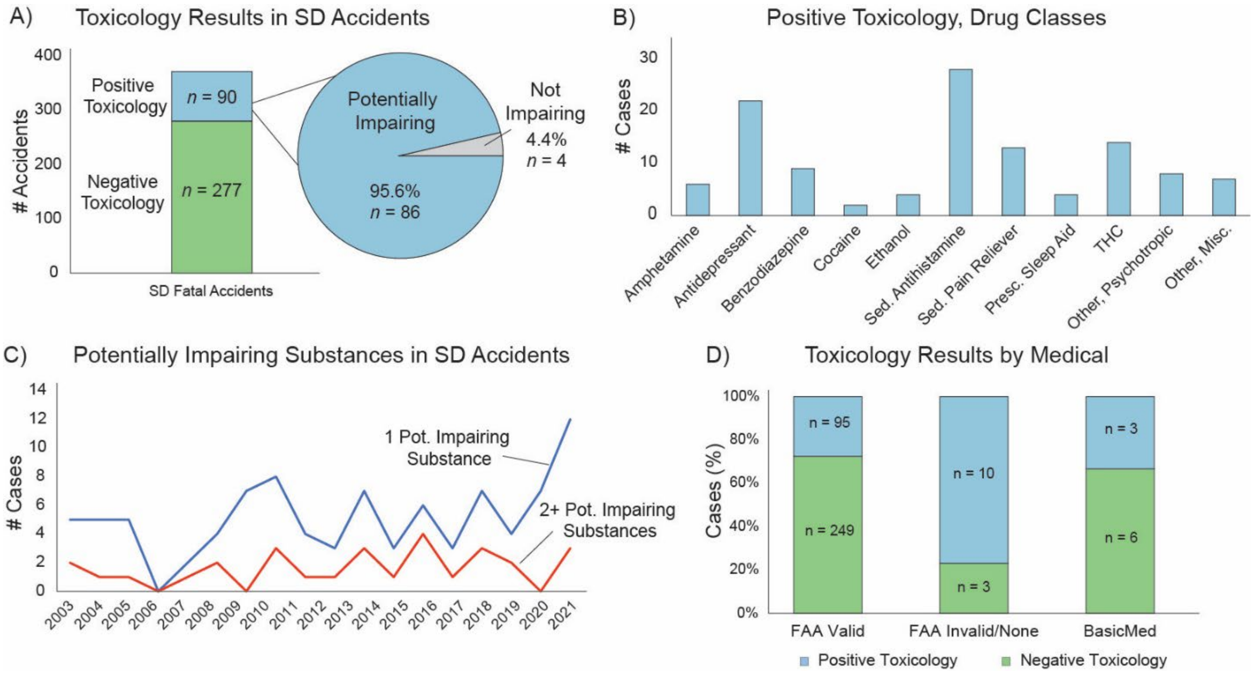


Toxicology Results

To evaluate the incidence of potentially impairing drugs, data from CAROL were matched with available test results from CAMI's Forensic Sciences toxicology database. A total of 90 out of 367 (24.5%) fatal pilots had a positive toxicology result, with 86 of those 90 cases including at least 1 potentially impairing drug (Figure 6A). The drug classes identified in drug-positive cases are included in Figure 6B. The most frequently identified substances included sedating antihistamines (*n* = 28), antidepressants (*n* = 22), tetrahydrocannabinol or its metabolites (THC, *n* = 14), and sedating pain relievers (*n* = 13). While 31 were positive for ethanol, only 4 of these cases were conclusively attributable to antemortem alcohol consumption. These alcohol consumption cases included one with an ethanol blood concentration between 20 and 39 mg/dL (0.02-0.039%) and three with ethanol blood concentrations over 40 mg/dL (0.04%). Of note, blood concentrations over 0.04% are in violation of Federal Aviation Administration (FAA) ethanol regulations (14 CFR § 120.37). For the other 27 ethanol-positive cases, 7 cases included findings that supported postmortem microbial ethanol formation, 11 cases had indications of postmortem microbial ethanol formation, but some antemortem consumption could not be ruled out, and in 9 cases, the origin of the ethanol is unclear. Therefore, only four cases consistent with antemortem consumption were included in the current analyses.

Overall, 27 accidents included positive toxicology findings for two or more potentially impairing substances (Figure 6C), and 14 pilots tested positive for an illicit substance. While a majority of the pilots included in this study had valid FAA medicals on file (*n* = 344) or met BasicMed requirements (*n* = 9), most pilots without valid FAA medicals had positive toxicology results (*n* = 10 of 13; Figure 6D). Pilot demographics in cases with positive toxicology results were similar to those of all fatal SD GA accidents, with an average pilot age of 54.0 (SEM: ± 1.4 years) and 2395.6 total flight hours (SEM: ± 438.4 hours).

***Figure* 6**
Positive Toxicology Results in SD Accidents



Discussion

Spatial Disorientation Leads to Fatal Accidents in GA

Overall, the incidence of fatal GA accidents related to SD has decreased since the initial CAMI analysis in 1978, likely associated with increased education and awareness efforts. From 1970 to 1975, 15.6% of fatal GA accidents were related to SD (Kirkham et al., 1978). From 1976 to 1992, this percentage dropped to 13.2% (Collins & Dollar, 1996), with a clear downward trend that culminated in 9.7% in 1992 (Figure 1). By 2003, the average incidence of fatal GA accidents related to SD had dropped to 7.4%, and there had been an overall decrease in the total number of fatal GA accidents from previous analyses. However, while the average for the 2003 to 2021 study was lower than previous studies, there was an upward trend across the 2003 – 2021 period, with a maximum of 12.8% SD GA fatal accidents in 2021. This highlights the need for continued education efforts.

Despite the improvements in SD accident incidence from initial CAMI analyses, the relationship between SD and fatal GA accidents warrants increased attention to these accidents. In the current analysis, 94% of GA fixed-wing accidents that involved SD were fatal. According to data from the NTSB U.S. Civil Aviation Accident Statistical Review, the overall fatality rate of GA accidents from 2003 to 2021 was only 19%. Further, these 367 fatal SD accidents included a total of 741 fatalities, including pilots, passengers, and even bystanders on the ground. The high cost of life and the high likelihood of fatality underscore the seriousness of experiencing SD in flight.

Risk Factors for SD Accidents

Understanding common characteristics of pilots who were involved in these accidents is important in determining potential risk factors for SD in flight. In comparison to previous analyses, the current analysis of fatal SD GA accidents more frequently involved an older generation of pilots. The most commonly identified age range for pilots in this study was age 60 – 69 (28%), while previous analyses most often identified pilots aged 40 – 49 years old (Kirkham et al., 1978; Collins & Dollar, 1996). Indeed, over half of all pilots involved in these accidents were aged 50 – 69 in the current sample, indicating that this is a particular age range to target for awareness. Similar to previous findings (Kirkham et al., 1978; Collins & Dollar, 1996), about half of the pilots involved in these accidents tended to have under 500 flight hours, indicating that experience may be a risk factor for SD.

Along with understanding pilot demographics of SD accidents, understanding the flight and environmental conditions associated with the accidents is useful in identifying potential risk factors for future accidents. The majority of these cases occurred during the climb or en route stage of flight and, similar to the previous analyses, IMC was a frequently reported finding (Kirkham et al., 1978; Collins & Dollar, 1996). Over 75% of fatal SD GA accidents in this study involved IMC. Further, 46% of accidents occurred in night conditions, while 44% of accidents involved a pilot entering IMC while intending to fly under VFR, a finding that is consistent with the previous accident analyses (Kirkham et al., 1978; Collins & Dollar, 1996). Importantly, many of these pilots were briefed or were aware of the weather conditions before the flight and still chose to operate under VFR, regardless, indicating that these accidents were not due to oversights or sudden changes in weather. This is an important area for potential outreach and education within the pilot community that could potentially minimize future SD accidents.

Finally, the type of aircraft involved in these accidents is also an important consideration. The current analysis identified that most accidents involved single-engine aircraft. However, a growing number of accidents involving turboprop or turbojet aircraft occurred over the 19-year span, beginning largely around 2013 (Figure 4D). These complex aircraft are highly automated to accommodate single-pilot operations, which may lead to more reliance on autopilot (FAA, 2013). Future research could consider how aircraft types interact with environmental conditions, such as turbulence, as a risk factor for SD.

Toxicology Findings in SD Accidents

The current analysis found that one-quarter of all fatal SD GA accidents included positive toxicology findings. Further, the majority of these positive toxicology findings were potentially impairing substances, using drug classifications identified by the NTSB report on Drug Use Trends in Aviation (NTSB, 2020). The most prevalent substances identified in these accidents were sedating antihistamines, followed by antidepressants, THC (and its metabolites), and sedating pain relievers (Figure 6). The prevalence of potentially impairing substances in this report is much higher than that reported in previous studies, which only found 7% of cases positive for a potentially impairing substance (Collins & Dollar, 1996). However, changes in pharmaceutical drugs, drug availability, and laboratory drug testing capabilities across decades make it difficult to properly compare rates between reports. Regardless, the relatively high occurrence of toxicology findings for impairing substances—sometimes two or more impairing substances at once—certainly has implications for SD occurrence in these accidents.

There are limitations in the current evaluation of toxicology findings to note. Namely, it cannot be assumed that the presence of an impairing substance necessarily means that a pilot was impaired at the time of the accident. For example, the primary metabolite of THC is not psychoactive; thus, a positive finding may be due to the use of the primary impairing substance days before the accident. Some studies, such as the 2020 NTSB Update to Drug Use Trends in Aviation report, exclude ethanol findings, as ethanol can be produced by microbial actions in postmortem tissues (Kugelberg & Jones 2007), and the NTSB did not have the ability to evaluate the source of ethanol in the cases they reviewed. However, the present study evaluated ethanol-positive cases individually and only included ethanol results determined to be from antemortem ingestion. Such reviews were performed by toxicologists from CAMI's Forensic Sciences laboratory. Finally, the positive toxicology findings in these cases may come from different biological sources (e.g., blood versus tissue samples), which further obscures the interpretive potential of impairing drugs on the pilot's abilities at the time of the accident.

Regardless of whether the positive toxicology findings reflect an impaired cognitive or physiological state at the time of the SD, these findings support trends observed by the NTSB surrounding overall drug usage in aviation. Both the 2014 and 2020 NTSB drug trend reports emphasized the necessity for research concerning the impact of drug use on aviation safety and for the continued evaluation of the relationship between drug use and aviation accidents (NTSB, 2014; 2020). Performance-based testing specific to piloting an aircraft is not available for many of these drug categories, making it impossible to know how long after taking a substance a pilot may be potentially impaired. Altogether, potentially impairing drug usage represents an independent risk factor in SD accidents, in particular due to its potential impact on the complex functions of spatial orientation and situation awareness.

Finally, even if the potentially impairing substances did not influence the pilot at the time of the accident, a portion of these findings do indicate a potential medical condition that may have an impact on SD. For example, antidepressants were the second most prevalent drug type noted in these findings. Cases positive for antidepressants, benzodiazepines, or other psychotropic medications may indicate undisclosed medical conditions that could impact flight at any time for a pilot. Further, these findings are particularly relevant in tandem with FAA medical results. While most pilots, including those with positive toxicology findings, had valid FAA medicals, the majority of pilots who did not have valid medicals had positive toxicology findings. Overall, these findings may suggest that conditions that could potentially influence SD are being underreported, either because pilots are not disclosing them during an FAA medical or because the pilot was not being current on their medical.

Limitations

The current analysis has several limitations associated with both the investigation of SD solely through accident reports and with the overall nebulous concept of SD. Many similar yet distinct definitions of SD have been used in the scientific literature in relation to aviation (Benson, 1978; Gillingham, 1992; Navathe & Singh, 1994; Gillingham & Previc, 1993). While definitions typically agree that SD occurs when there is a mismatch between the perceived motion or location and reality, definitions differ in their emphasis on the individual or aircraft as well as whether to specify that this mismatch occurs due to erroneous sensory information (Benson, 1978; Navathe & Singh, 1994; Gillingham & Previc, 1993). While the current study uses the definition provided by Gillingham & Previc, 1993, there are different strengths and potential applications for any of these definitions.

Given that NTSB accident reports rely on the identification of SD by different individuals, it is unclear what definition or criteria are used to identify likely SD in accidents. For example, it is possible that SD is associated with such high fatality rates because NTSB investigators may be more decisive in identifying SD in fatal accidents without access to pilot interviews. Previous work has found discrepancies in SD classification in military accidents, likely due to different approaches in identifying SD (Lyons et al., 1994). Further, while numerous surveys have identified the prevalence of SD in military populations (Matthews et al., 2002), no such studies exist for GA. Therefore, the true prevalence of SD in GA is unclear, making it difficult to put the current analysis of fatal SD GA accidents in perspective.

Conclusion

Spatial disorientation poses a distinct threat within general aviation due to the fatalities associated with its occurrence. The present study evaluated recent rates of SD in GA in relation to previous studies in the 1970s and 1990s. Overall, fatal SD GA accident occurrence is lower than in previous studies, though the occurrence of SD is just as fatal. In line with historical research, risk factors including IMC, low pilot flying experience, VFR into IMC, and the climb and en route phases of flight were documented. New potential risk factors were also identified, including the prevalence of SD in turboprop and turbojets, as well as an increase in positive toxicology findings for potentially impairing substances. Overall, more research into SD is necessary to understand the true incidence of SD in GA and to tailor awareness and education efforts to this dangerous occurrence.

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