USAF Spatial Disorientation Prevention: A Meta-Analytical Human Systems Integration Perspective

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Human Systems Integration involves the systematic consideration of tradeoffs in system structure or behavior, which affect seven human-centered domains to optimize total system performance and life cycle cost. All too often, HSI is overlooked or poorly practiced, despite the specific directive within DoDI 5000.02 for program managers to plan for and conduct HSI. In the worst of cases, poor consideration of human capabilities and limitations leads to errors, mishaps, and death or serious injury. One such human limitation in aviation is the inability of the pilot to maintain proper spatial orientation during flight, as mismatches between the stimuli present during flight create an erroneous perception of aircraft attitude with respect to the horizon. The consequences include preventable departures from controlled flight and unusual attitudes, unnecessary aircraft ejections, and controlled flight into terrain. Between 1993 and 2013, spatial disorientation contributed to 12% of all Class A Mishaps, resulting in the loss of 65 aircraft and 101 lives. With a fatality rate of 24.9%, disorientation leads all Class A mishap causal factors. While it may not be feasible to prevent all spatial disorientation mishaps, it may be possible to significantly reduce mishap rates through proper tradeoff analysis, resulting in better total system performance and reduced life cycle costs. To that end, this paper will discuss the HSI domains applicable to spatial disorientation and provide a meta-analytical perspective on practicing HSI and its implications for disorientation prevention.

Air Force Instruction (AFI) 63-1201, *Life Cycle Systems Engineering*, defines Human Systems Integration (HSI) as "a disciplined, unified, and interactive systems engineering approach to integrate human considerations into the system development, design, and life cycle management to improve total system performance and reduce total costs of ownership". The recent change to Department of Defense (DoD) Instruction 5000.02 reduced the recognized HSI domains to seven: Manpower, Personnel, Training (commonly MPT), Safety and Occupational Health, Human Factors Engineering (HFE), Survivability, and Habitability. Tradeoffs are made between system features balance total system performance (including the operator) with total life cycle costs (LCC). The instruction also requires the program manager (PM) to plan for and implement HSI beginning early and throughout a system's life cycle in order to optimize total system performance and total ownership costs, while ensuring that the system effectively provides the user with the ability to complete their mission.

Early and iterative consideration of HSI during system design is believed to offer significant payoffs to the total system, including but not limited to increased system availability, reliability, safety, and survivability. However, the intent of this guidance is not always realized, and HSI is often overlooked or poorly practiced. The results can lead to errors, mishaps, even death or serious injury. One such human limitation in aviation is spatial disorientation (SD), in which mismatches between the available environmental stimuli and the ability of the human physiological sensory pathways to accurately perceive these stimuli create an erroneous perception of aircraft attitude with respect to the horizon. The consequences of such orientation illusions can precipitate preventable in-flight loss of control (LOC-I), unusual attitudes (UA), unnecessary aircraft ejections, controlled flight into terrain (CFIT) or other undesirable consequences.

Spatial Disorientation

Spatial disorientation is often indicated as a causal factor in USAF Class A mishaps, particularly in fighter/attack aircraft, and is considered a leading cause of pilot fatalities (R. Gibb, Ercoline, & Scharff, 2011). Recent analysis suggests that, from 1993 to 2013, SD was involved in 12% of USAF Class A mishaps, of which 61.1% resulted in the loss of life (Poisson & Miller, 2014). Estimates in financial terms suggest that these mishaps have generated over $2-billion in property loss and medical costs. However, the true prevalence of SD may be even greater than 25% of all aviation mishaps, possibly as high as 33%, due to inaccuracies and underreporting (R. Gibb et al., 2011). Figure 1 provides a graphical summary of the statistics and trends over the last 35 years based on a meta-analysis of data from five separate publications (R. W. Gibb & Olson, 2008; Gillingham, 1992; Matthews, Previc, & Bunting, 2002; Poisson & Miller, 2014; Sundstrom, 2004). Of concern is the notion that the frequency and severity statistics have historically remained unchanged (R. Gibb et al., 2011); however, best-fit (greatest R^2) trend lines in Figure 1 suggest SD-related Class A mishap frequency peaked in the mid-1990s before returning to historical levels. Of note, a number of factors may be a play, evolving definitions of SD, relative emphasis on education and reporting requirements, or technology improvements.

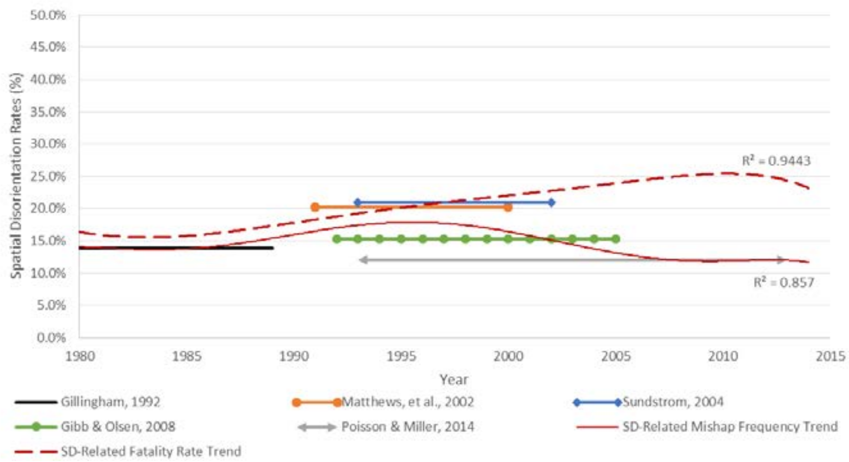

Figure 1. Frequency of SD-Related Class A Mishaps, 1980-2013.

While the primary causes are physiological (mismatches between the visual and vestibular senses), based largely on visual information, certain psychological factors contribute to the experience of SD (R. Gibb et al., 2011). These include cognitive tunneling, loss of situational awareness (SA), visual capture and clutter, and task saturation. For example, “pilots who have lost SA through being out-of-the-loop may be both slower to detect problems,” (Endsley, 1997). Effectively, these psychological factors increase the risk of physiological modality conflicts: the wrong combinations of which ultimately set the stage for experiencing one of the three types of SD: Unrecognized, Recognized, and Incapacitating. Unrecognized (Type I), reflects a state where the pilot is unaware of the disorientation and believes their aircraft is responding well to inputs. Type II, Recognized, involves the pilot’s awareness of conflicting orientation cues. Finally, Type III or Incapacitating, occurs when the pilot is aware of the disorientation, but cannot correctly adjust or recover.

HSI Considerations for Spatial Disorientation Mishap Reduction

Some researchers have argued that technology has made no effect in mitigating SD incidents; rather, technologies such as night vision goggles, heads-up displays, helmet/head-mounted displays (HMDs), or other technology has rather changed the types of errors committed by increasing perceptual and cognitive demands (R. Gibb et al., 2011). The result is an increased likelihood of SD due to visual clutter, reduction of peripheral vision cues, cognitive tunneling, task saturation, or other cognitive factors. However, the systems in question were designed for purposes other than SD mitigation, primarily to enhance pilot SA. Arguments against these technologies suggest that they fail to improve some aspects of SA and contribute to SD. However, this research suggests that technology solutions rely on the HSI plan and its human-centered considerations, primarily from the HFE, MPT, and Survivability domains to assist pilots in maintaining normal expected flight parameters.

Manpower, Personnel, and Training

The Manpower, Personnel, and Training HSI domains are often interlinked due to inherent domain interdependencies and the direct impact of tradeoffs among these domains. In HSI terms, the Personnel domain is concerned with the types of people and their required knowledge, skills, and abilities (KSAs). Requirements definition for this domain is driven by performing task analyses and descriptions within existent career fields. Conversely, Manpower focuses on the number of each type of personnel possessing the specified KSAs. Finally, Training covers development of the KSAs required to operate and maintain the system of interest (SOI). Thus, once a certain set of KSAs to perform their duties, an example tradeoff concerns the economics of hiring and training.

According to the USAF Officer Classification Directory, entry into the Pilot career field as a Pilot Trainee with Air Force Specialty Code (AFSC) 92T0 has two KSA requirements beyond those necessary to obtain a commission in the USAF: the abilities to pass a Flying Class I physical and obtain the required security clearance via initiation of a background investigation. The candidate selection process generally assesses medical fitness, anthropometry, and educational achievement (Carretta, 2000). The progression toward becoming a fully qualified pilot in a particular major weapon system (MWS) varies with each airframe, but follows the same basic path: Initial Flight Screening (IFS), Specialized Undergraduate Pilot Training, MWS-specific transition and operational training, and MWS-specific upgrade training.

Today, preventative SD training strategies focus on familiarization with the causes of SD, defining specific illusions, and recognizing these illusions through classroom instruction. Per AFI 11-403 *Aerospace Physiological Training Program*, aircrew receive their first exposure to SD during their initial Aerospace Physiology course, which covers the characteristics of SD types, basic physiology and contributing factors, and related illusions. AFI 11-403 also requires all fighter/attack students be trained in an SD-demonstrator. Refresher training is required every five years and includes review of these topics and further demonstration as necessary. Alternative methods include SD-specific simulators, in-service simulators, and in-flight demonstration (R. Gibb et al., 2011). SD-specific simulators are capable of producing motion and visual cues necessary for inducing SD under representative workloads. In-service simulators can be tailored to provide training for a limited set of SD-producing scenarios, but are incapable of replicating many realistic experiences. Finally, in-flight demonstration promotes the most realistic scenarios and can be applied to develop both recognition and recovery skills. However, enhanced aircrew training does not guarantee significant improvements to SD-related mishap trends; it is merely one contributing perspective.

In summary, trades among the MPT domains could include enhanced manpower and personnel analyses towards the goal of reducing task saturation and unrecognized SD. Alternately, improvements in training may increase the likelihood of recognizing SD onset before situations grow out of control or SD becomes debilitating.

Human Factors Engineering

The HFE domain seeks to account for human capabilities and limitations in the SOI's development and evolution in order to optimize human-machine performance in SOI operation and maintenance. These design considerations are governed by MIL-STD-1472G, which addresses human factors design specifications and principles. The goal of the presented criteria and principles is to achieve required user performance, manpower readiness, personnel-equipment reliability, and design standardization. SD results as a consequence of our limited capability to resolve visual, vestibular and proprioceptive cue conflicts, which can often be mediated or induced by other cognitive limitations as noted. Research designed to investigate SD prevention strategies cover a wide array of topics, including alternative attitude references, multimodal cueing, or synthetic vision systems. In each case, the primary goal is to provide pilots with intuitive information via alternative presentation and/or supplemental cues.

Traditional attitude information has been presented using the Sperry design, which is an inside-out attitude reference. Alternatives to this design include an outside-in attitude indicator (AI) and the Arc-Segmented Attitude Reference. Research has somewhat confirmed that the two alternative designs are more intuitive than inside-out AI leading to performance improvements (Poisson, Miller, Haas, & Williams, 2014; Self, Breun, Feldt, Perry, & Ercoline, 2002); yet these have not been reliably demonstrated in-flight. Additionally, researchers developed a spatial disorientation geometric command icon (a diamond) designed to be easily interpreted. Evaluations of this icon demonstrated increased performance on UA recovery tasks (Small, Fisher, & Keller, 2005).

Other technologies incorporate multimodal (auditory and tactile) cueing and synthetic vision systems (SVS) to help maintain orientation. Multiple Resource Theory suggests that auditory cueing (including three-dimensional) can improve SA when visual attention is under high workload, but the advantages may be limited. Tactile cues offer a variety of strategies for conveying various information to the operator such as signal localization, cue pulse rates, varying the fundamental vibration frequency, and linear and radial spatial flow (Lawson, Cholewiak, Brill, Rupert, & Thompson, 2015), which might prove useful to convey orientation information. Synthetic vision systems provide an artificial view of the environment by combining computer-generated imagery, guidance displays, and on-board sensors. Integration of these technologies is believed to improve flight safety, SA, and orientation (Prinzel & Kramer, 2006) through augmentation of basic flight information.

It should be noted that for SD to become recognized, multiple cues must be present and visual cues must be directly observed. Therefore, each of these visual displays suffer when breakdowns occur in the pilot's scan path under low visibility conditions, preventing the gathering of visual cues which might result in the cue conflict necessary for SD to be recognized. These cues may provide the pilot with early information that their perception of spatial orientation is degrading, encouraging the inclusion of the attitude indicator in their scan path.

Table 1.
Summary of Mishap and Fatality Rates per Million Flight Hours.

Study	Years (FY)	Aircraft	Flt Hrs	Mishap Rate	(#)	Fatality Rate	(#)
Holland, et al., 1995	1980-1989	A-10	2.09	3.83	(8)	6.22	(13)
		F-15	1.80	5.57	(10)	3.34	(6)
		F-16	2.06	7.75	(16)	6.30	(13)
		Overall	5.95	5.71	(34)	5.38	(32)
Sundstrom, 2004	1993-2002	A-10	1.19	5.89	(7)	4.21	(5)
		F-15	1.96	1.02	(2)	1.53	(3)
		F-16	3.70	4.05	(15)	2.70	(10)
		Overall	6.85	3.50	(24)	2.63	(18)
Poisson & Miller, 2014	1993-2013	A-10	2.35	3.83	(9)	2.56	(6)
		F-15	3.52	1.70	(6)	0.85	(3)
		F-16	6.78	3.69	(25)	2.65	(18)
		Overall	12.84	3.19	(41)	2.18	(28)

Table 2.
Cost and SD Type Summary by Aircraft per Million Flight Hours.

Aircraft	Flt Hrs	Type I	(#)	Type II	(#)	Type III	(#)	Total	Cost
A-10	1.19	4.21	(5)	0.84	(1)	0.00	(0)	6	$66,647,399
F-15	1.96	0.51	(1)	0.51	(1)	0.51	(1)	3	$77,903,113
F-16	3.70	3.51	(13)	0.27	(1)	0.00	(0)	14	$259,427,142
Overall	6.85	2.77	(19)	0.44	(3)	0.15	(1)	23	$403,977,654
Frequency			83%		13%		4%		

Survivability

Survivability concentrates on the SOI characteristics that reduce risk of acute and/or chronic illness, disability, injury, or death in the event of fratricide, detection and attack, hostile or extreme environments, system faults, or other hazardous occurrence. In the aviation environment SD is one of the many physiological incident risks present. In fact, some suggest that SD-related Class A mishaps exhibit a probability of fatality that is 2.85 times greater than other Class A mishaps between 1993 and 2013 (Poisson & Miller, 2014). Table 1 summarizes extrapolated mishap and fatality rates for the three most often studied fighter/attack aircraft in the current USAF inventory (the A-10, F-15, and F-16) (Holland & Freeman, 1995; Poisson & Miller, 2014; Sundstrom, 2004). Table 2 breaks the data down by SD type and includes the mishap costs. Based on this, Sundstrom (2004) recommended re-evaluation of installing Automatic Ground Collision Avoidance Systems (Auto-GCAS) in USAF fighter aircraft.

Such systems promise stark impacts on reducing type I and III SD mishap rates. According to the data in Table 2, the types accounted for a combined 87.0% of the relevant mishaps. Furthermore, Sundstrom suggests that, CFIT resulted in 68% of the reported disorientation mishaps. By taking over for an unresponsive, possibly disorientated or incapacitated pilot, it is conceivable that Auto-GCAS might avoid as much as 59% of these mishaps, based on the combined probability of CFIT and Type I or III SD, depending on the MWS and its mission profile.

Most technology intended to mitigate aircraft mishaps has focused primarily on recovery, meaning the system's benefits are realized after a pilot has become disoriented. While the capability of systems such as Auto-GCAS can partially reduce the occurrence of specific types of SD and related mishaps through automated recovery, the need to react and recover in the first place might be eliminated by proactively preventing the effects of disorientation. If successful, a proactive approach might alert a pilot to potential impending SD scenarios. Effectively, Type I and III incidents are recognized (Type II) early or not experienced at all. If that is the case, where Auto-GCAS may avoid 59% of relevant SD-mishaps, a prevention strategy may increase the figure to 87% or more.

HSI Cost-Benefit Trades of Preventing Disorientation

From 2009 to 2013, Class A Mishaps totaled approximately $2.6B in financial losses based on data obtained from public USAF Accident Investigations Boards reports. Human factors were identified in 71.7% of these accounting for roughly $1.95B of the reported financial losses. In a perfect world, perfect HSI and HFE would eradicate all human error and subsequent mishaps. However, SD has a physiological component that cannot be completely eliminated, only reduced. If realized, a decrease in SD-related mishaps translates to fewer fatalities and lost aircraft, increased total system performance, and potentially reduced total LCC. Any reduction in these areas constitutes a strong argument for increased investment in HSI. For SD prevention, long term solutions will involve some combination of training and technology, with specific implications for manpower and personnel.

First, it is essential to understand that the human capability for orientation is fundamentally limited by our physiology: it did not evolve to traverse the atmosphere. Disorientation is thus an inherent in-flight risk that cannot be mitigated through design, but rather must accepted and minimized. Realizing this, it is incumbent upon the PM and HSI personnel to consider the HSI implications of each requirement. For example, certain generation five fighter capabilities (HMDs, thrust vectoring, etc.) pose significant concerns for orientation, specifically the ability to resolve cues mismatches during off-axis viewing or movement. Accounting for such activities in the use case and/or concept of operations (CONOPS) will drive their consideration within the solution space.

Specifically, the CONOPS and use cases shape the ensuing task analysis, which for aviation is increasingly important as the integration of cockpit automation has led to the evolution of the pilot's supervisory control role. The tasks with which the pilot will be assigned from this analysis also imply particular orientation solution strategies such as cockpit automation. Finally, integration of new technologies requires some level of operator training, in this case for both SD and the technologies. For the USAF, this could mean reduced mission readiness during upgrades.

These questions are normally answered early in development, assuming HSI activities are initiated as recommended. Addressing them early in the acquisition process often leads to the return on investment (ROI). According to the DoD Operating and Support Cost Estimation Guide, development costs on average account for 7% of the program lifecycle cost, of which early HSI activities are a small piece. For many programs, this can translate to millions of dollars annually for all system development activities. At a fraction of this budget, HSI activities require a modest investment above the necessary cost implications of the requirements and design tradeoffs. Unfortunately, HSI does not necessarily translate to direct system procurement savings, as additional development and integration costs are incurred to procure the system. The majority of a system's LCC is incurred during operations and sustainment, and the conventionally accepted "golden rule" is 70% (Jones, White, Ryan, & Ritchel, 2014), but the associated decisions are made early in development. Likewise, the HSI ROI is often overlooked.

The implication is that significant drivers of operations and sustainment costs need to be accounted for from the early stages of development, including HSI. Mishaps with human-related contributions pose an opportunity for to quantify the ROI. Summarizing the economic costs of SD (damages, lost aircraft, medical bills, etc.) of related Class A mishaps between 1993 and 2013, including those directly tied to individual programs (A-10, F-15, and F-16) led to interesting LCC savings estimates and implications based on the effect of Auto-GCAS and potential impacts of improved SD and CFIT prevention (Table 3). Per this analysis, the entire USAF fleet could see potential annual savings totaling approximately $96.1M, and fighter/attack aircraft account for $30-35M of this estimate.

These estimates are based on a number of assumptions. The first is a 100% reduction in preventable SD mishaps, which is likely not feasible. Secondly, the analysis only accounts for reported incidents leading to a Class A mishaps. Many SD incidents go unreported due to misidentification, lack of economic or casualty consequences, or pilot attitude and culture. Third, much of the data required transformation to arrive at these estimates, so they are only as good as the accuracy of the sources. Furthermore, aircraft specific estimates are based on the number of lost aircraft during the periods of interest and the reported flyaway costs. Finally, estimates for the entire fleet do not necessarily account for the relative contributions by individual MWS or fiscal year, potentially inflating the savings.

Table 3.
Summary of HSI Life Cycle Cost Impacts with Respect to Spatial Disorientation

Study	Aircraft	#Lost A/C	Flyaway Cost ($M)	Economic Cost ($M)	Observed CFIT Impact ($M)	Est. LCC Savings ($M)	Auto-GCAS Impact ($M) Cumulative	Auto-GCAS Impact ($M) Annual	Prevention Impact ($M) Cumulative	Prevention Impact ($M) Annual Avg
Sundstrom, 2004	A-10	7	$18.8	$66.6	$66.6	$12.8	$39.4	$3.9	$58.0	$5.8
FY1993-2002	F-15E	2	$31.1	$77.9	$38.0	$21.1	$46.1	$4.6	$67.7	$6.8
	F-16A	2	$14.6	$29.7	$29.7	$9.9	$17.5	$1.8	$25.8	$2.6
	F-16B	2	$18.8	$23.0	$15.9	$12.8	$13.6	$1.4	$20.0	$2.0
	F-16C	9	$14.6	$182.6	$166.7	$9.9	$108.0	$10.8	$158.8	$15.9
	F-16D	1	$18.8	$24.2	--	$12.8	$14.3	$1.4	$21.1	$2.1
	Fighter/Attack	23	--	$404.0	$317.0	$79.4	$238.9	$23.9	$351.3	$35.1
Poisson & Miller, 2014	A-10	9	$18.8	($169.2)		$12.8	$100.0	$4.8	$147.1	$7.0
FY1993-2013	F-15A/C	2	$27.9	($55.8)		$19.0	$33.0	$1.6	$48.5	$2.3
	F-15B/D/E	4	$29.9	($119.6)		$20.3	$70.7	$3.4	$104.0	$5.0
	F-16A/C	20	$14.6	($292.0)		$9.9	$172.7	$8.2	$253.9	$12.1
	F-16B/D	5	$18.8	($94.0)		$12.8	$55.6	$2.6	$81.7	$3.9
	Fighter/Attack	40	--	($730.6)		$74.8	$432.0	$20.6	$635.3	$30.3
	All Aircraft	65	--	$2,320		$1,578	$1,372	$65.3	$2,017	$96.1

Perhaps the greatest supposition is the inherent hypothesis that investment in HSI with respect to both SD and the larger efforts will actually realize potential LCC reductions associated with future mishaps. Only known risks can be mitigated or reduced, but it is impossible to identify all circumstances and failure modes during risk analysis. It is entirely likely that new, emergent failure modes may occur that were not yielded during the risk analysis. The lack of guarantee on total LCC reduction associated with HSI investment might sway the decision away from the venture. In this case, the effectiveness to which the need is communicated will drive the decision: the key might be to appeal for the additional HSI perspective, which might identify new, unique risks and mitigation strategies. Finally, the given savings estimates apply to only SD prevention, which is but one topic impacted by HSI.

Conclusion

At 2.85 times more likely to be fatal than all other Class A mishaps, those involving disorientation result in substantial financial costs and significantly impact the flight safety. While the manpower and personnel HSI domains exert little influence on the experience of SD, they bear some of the consequences through injury and/or loss of life. However, considerations for training, HFE, and survivability exhibit the most promise for mishap prevention. Technologies like Auto-GCAS are predicated upon first experiencing disorientation, UA, LOC-I, etc. A more proactive approach might identify impending scenarios so that a pilot can correct the situation prior to experiencing disorientation. This requires early investment in HSI efforts to affect the HFE and training domain tradeoffs. The SD considerations only account for a small piece of the overall effort, but the ROI can be described as of millions of dollars saved, aircraft and lives saved, or mission readiness and execution.

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