Evaluation of Low Cost, User-Centered Alerting Devices for the Mitigation of Flight Crew Spatial Disorientation

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Abstract

The National Aeronautics and Space Administration (NASA) is conducting research into technologies which have the potential to reduce flight crew Spatial Disorientation (SD). While flight deck technology has advanced rapidly over the past fifty (50) years, the reported occurrences of flight crew SD have not decreased. The Cost-Effective Devices for Alerting Research (CEDAR) effort has focused on the identification and development of low cost, user-centered alerting solutions for the purpose of mitigating the occurrence of flight crew SD. This effort seeks to evaluate both existing technologies as well as new and emerging technologies which have a viable path to implementation in commercial aviation within the next five (5) years. This research is intended to develop a proof-of-concept for real-time SD mitigation which could eventually be utilized to improve safety in future air transport operations.

NASA has partnered with the United States Naval Aeromedical Research Unit in Dayton, OH (NAMRU-D) to conduct flight crew SD research utilizing their Disorientation Research Device (DRD), dubbed “The Kraken”. This high-tech simulator features never-before-seen capabilities for side-by-side commercial aviation flight crew SD research, and is capable of re-creating the forces necessary to induce SD illusions in a safe and repeatable manner. Prototype SD mitigation solutions were incorporated into this simulator for scenario-based testing and evaluation using airline pilots within a contextually representative operational environment. SD mitigation technology prototypes designed to provide haptic feedback for both alerting and guidance, as well as innovative visual and aural alerting displays were evaluated.

In December 2014, as a result of analyzing eighteen (18) loss-of-control events, the Commercial Aviation Safety Team (CAST) recommended research into flight deck technologies that have potential to mitigate the problems and contributing factors that lead to flight crew loss of airplane state awareness (ASA) and conditions likely to produce SD. The aviation community (government, industry and academia) have been charged with conducting research into cost-effective, user-centered flight deck alerting systems to alert flight crews; especially for the two conditions that produced SD (sub-threshold rolls and the somatogravic illusion).

Somatogravic illusions are defined as illusions in which “there is a false perception of attitude on exposure to a force vector that differs in direction and/or magnitude from the normal gravitational force” [1]. The sub-threshold roll illusion (aka the “leans” illusion) is a false sensation of roll attitude [1]. A prolonged roll of less than two degrees becomes physiologically imperceptible to the pilot, and can lead to an incorrect perception of aircraft orientation. The sub-threshold roll illusion forms the entry point for the “graveyard spiral”, a maneuver in which the pilot’s corrective action (based on their false perception of aircraft orientation) causes the aircraft to spiral down into the ground. In both of these SD illusions, it is when the pilot attempts to correct the aircraft’s attitude (based on a false perception of its state) that problems arise, sometimes with lethal consequences.

Background

Spatial disorientation has been defined as "an erroneous sense of one's position and motion relative to the plane of the earth's surface"; this erroneous sense stems from the "incorrect perception in magnitude/direction of any of the aircraft control and performance flight parameters" [2]. Control parameters under this definition refer to aircraft attitude and engine power parameters, while performance parameters refer to vertical speed, altimeter, and heading. This definition is broad enough to encompass energy situation awareness (defined as "the ability to know and control the complex combination of the aircraft's airspeed and speed trend, altitude and vertical speed, configuration, and thrust [3]) as the sources of information relevant to both SD and Loss of Energy State Awareness (LESA) phenomenon are common to both.

The research activities summarized here have been motivated by the observation that the incidence of loss of control events (LOC) stemming from SD and LESA appear to be increasing, even as the overall safety of Part 121 and Part 25 operations continues to improve. Research indicates that spatial disorientation and loss of energy situational awareness account for 32% and 19%, respectively, of thirty four (34) LOC accidents over the last decade [4]. These statistics (see Figure 1) are a matter of rising concern as commercial air traffic growth shows little sign of slowing, and accident data suggests that newer airplanes are also vulnerable to these problems.

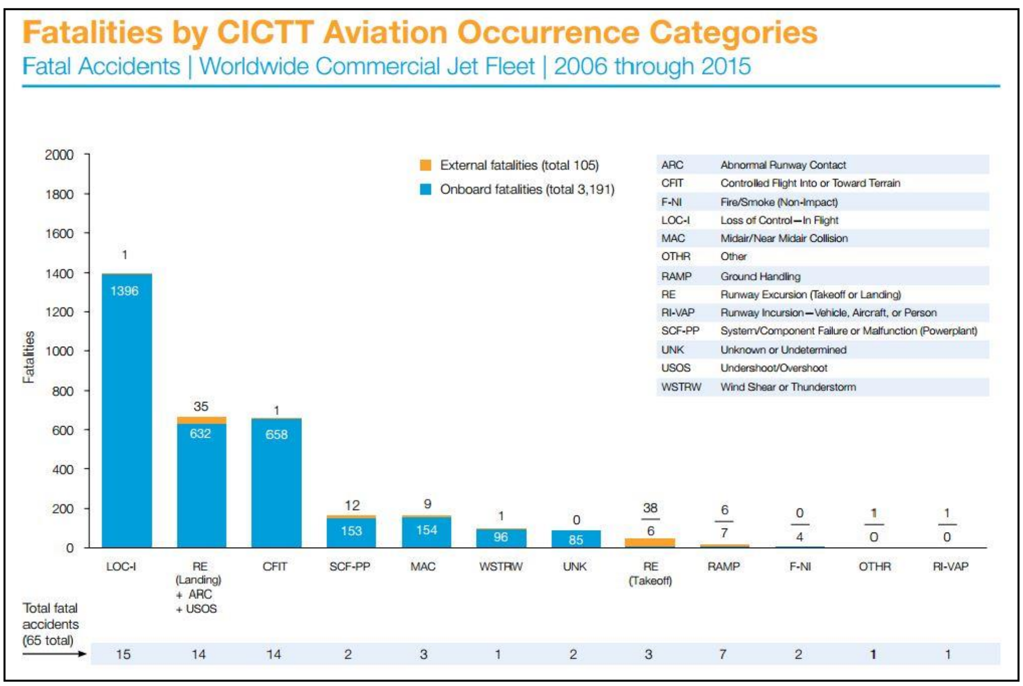

Figure 1. Causes of aviation fatalities in commercial jet fleet (Boeing, 2015)

In light of these statistics, the importance of prognostic analyses for identifying future risks for loss of control precursors such as SD is being widely recognized in the aviation safety community. For example, Belcastro and Foster [5] have raised the importance of identifying currently unforeseen risks for loss of control incidents that may materialize in the context of NextGen operations risks whose causal bases may not be represented in prior accidents. Unfortunately, the latest generation of air transport and business aircraft have display and control features that have not been scrutinized extensively by the aviation research community for vulnerability to SD, additionally these aircraft lack an accident and incident record from which to draw meaningful inferences about SD vulnerability.

Gibb, Ercoline & Scharff [6] present a review of the accidents and incidents related to pilots' SD as foundation for renewed call to action. They cite a 2002 keynote address at the "Research and Technology Organization, Human Factors and Medicine Symposium on Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures" that emphasized the continued role of SD in aviation accidents and incidents for fifty (50) years; underscoring that, despite improved understanding of its etiology and enhanced pilot displays, SD has killed pilots since 1913 and continues to do so. Gibb et al., [6] state that, 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, they observed, at times the new technology plays a contributing factor in SD. SD-related mishaps still occur, and unfortunately, SD is often not formally recognized as a contributing factor in mishaps, and accidents are differentially classified otherwise, e.g., "visual illusion" or "loss of control" (LOC). Gibb presented an assessment of visual spatial disorientation at 2010 annual Aerospace Medical Association conference and cited 25 studies dating from 1947 that illustrated SD's role in mishaps as well as surveys of pilots anonymously sharing their SD experiences. Most striking across all the data from various countries and researchers was the consistency over the years — SD rates are not decreasing.

In December 2014, as a result of analyzing eighteen (18) loss-of-control events, the Commercial Aviation Safety Team (CAST) recommended research into flight deck technologies that have potential to mitigate the problems and contributing factors that lead to flight crew loss of airplane state awareness (ASA) and conditions likely to produce spatial disorientation.

The TASA CEDAR effort is tasked with identifying safety enhancements capable of providing salient alerting solutions to pilots and flight crew operating aircraft while in a state of SD. This research will give special consideration to combating two types of SD illusions in particular; the somatogravic illusion and the sub-threshold roll illusion. Somatogravic illusions occur when the pilot falsely perceives the attitude of the aircraft and there is a force vector present which differs from normal gravitational forces [1].

The sub-threshold roll illusion is a false sensation of roll attitude [1]. A prolonged roll can create a false perception of aircraft orientation. In both of these SD illusions, it is when the pilot attempts to correct the aircraft's attitude that problems arise, sometimes with lethal consequences.

Method

Recent accident and incident data suggest that SD and Loss-of-Energy State Awareness (LESA) for transport category aircraft are becoming an increasingly prevalent safety concern in domestic and international operations. SD can lead directly to a LOC event, resulting in an accident or incident. LESA is typically characterized by a failure to monitor or understand energy state indications (e.g., airspeed, altitude, vertical speed, thrust) and a resultant failure to accurately forecast the ability to maintain safe flight. The leading consequence of LESA is aircraft stall [6].

A Commercial Aviation Safety Team (CAST) study of eighteen (18) loss-of-control events determined that a lack of external visual references (i.e., darkness, instrument meteorological conditions, or both) was associated with flight crew loss of attitude awareness or energy state awareness in seventeen (17) events. CAST recommended research into cost-effective, user-centered alerting concepts for flight crew operating in a state of spatial disorientation during a LOC event (SE-207). In response to this recommendation, NASA has conducted research into innovative alerting technologies utilizing both real-time alerting and predictive alerting [8]. NASA has been conducting research and development in support of this CAST SE as part of the Airspace Operations and Safety Program (AOSP), System-Wide Safety (SWS) Project, under the Technologies for Airplane State Awareness (TASA) sub-project.

The CEDAR experiment utilized the Disorientation Research Device (DRD) located within the Naval Medical Research Unit (NAMRU-D at Wright-Patterson AFB in Dayton, OH). Designed as a reconfigurable advanced centrifuge device to induce spatial disorientation, the DRD has been outfitted with a NASA-designed capsule to emulate the NASA Research Flight Deck (RFD) simulator, with B-787 displays and side-stick control functions. This was done to meet the CAST recommendation to utilize B-787-like display configuration as the reference flight deck when considering new technology concepts under the research SE. The side-stick inceptor force gradients and deflection characteristics mimicked the Airbus A-320 aircraft [9]. The baseline display configuration is shown in Figure 2 below.

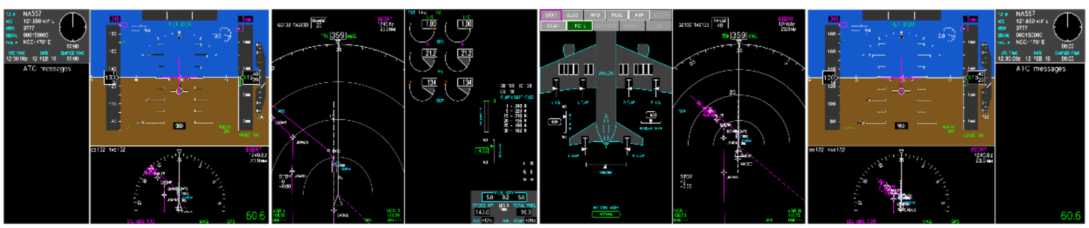

Figure 2 RFD HDD Panel in Baseline Configuration

Alerting Technologies

The purpose of the CEDAR experiment is to evaluate low-cost, user-centered alerting solutions to mitigate flight crew SD. A brief description of each of the prototyped solutions is provided below.

Modified Roll Command Alerting System (RCAS)

The Roll Command Alerting System was a joint research and development effort between Honeywell and Boeing and will be implemented as a baseline capability in all future aircraft designs by Boeing [10]. For the purposes of the CEDAR experiment, NASA has adapted the RCAS to provide alerting in cases where the pilot may be experiencing spatial disorientation due to a series of events which induced the sub-threshold roll illusion. In these cases, all normal RCAS alerts apply, but an additional alert is provided to pilots after sustained bank angles over a period of time which may be the result of the sub-threshold roll illusion. To mitigate the occurrence of sub-threshold roll illusions, the modified RCAS provides roll guidance in the form of visual guidance arrows on the PFD (see Figure 3) and “ROLL LEFT” and “ROLL RIGHT” aural alerts to instruct the pilot of the corrective action needed.

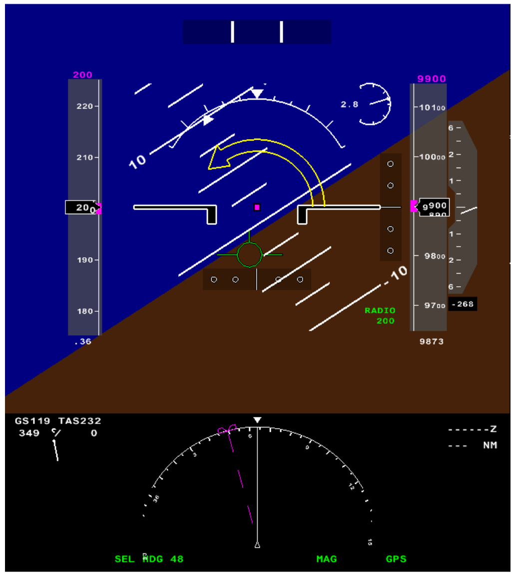

Figure 3. Modified Roll Command Alerting System (RCAS) Visual Alert

Pitch Command Alerting System (PCAS)

The Pitch Command Alerting System (PCAS) is a new alerting concept, designed by NASA to enhance flight crew situational awareness in the pitch axis for the CEDAR experiment. The PCAS is used to alert pilots to the immediate need for pitch correction, particularly for cases where the flight crew may be experiencing the somatogravic illusion. The PCAS alerting design is styled after the RCAS, and the alerting criteria is intended to be adaptable for a given situation. The system will identify when the flight crew may be experiencing a somatogravic illusion in real-time, and will provide directive pitch recovery guidance to improve pilot situation awareness.

The PCAS is intended to integrate with existing pitch visual and aural alerts. The existing visual pitch tape indications (pitch chevrons) for unusual attitude (UA) recovery will remain, with the PCAS overlaid above whenever the alerting criteria is met. The visual indication consists of a large, stationary pointer arrow overlaid above the pitch tape and will initially flash whenever the alert is triggered (see Figure 4). The visual alert is correlated with a “PULL UP” aural alert.

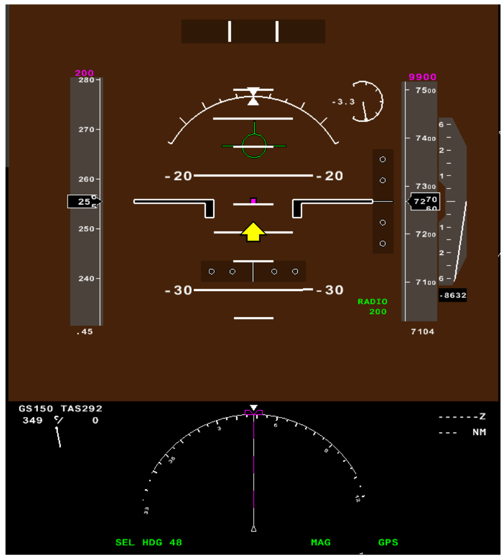

Figure 4. Pitch Command Alerting System (PCAS) Visual Alert

Haptic Alerting System (HAS)

The haptic alerting system utilized the force feedback capability of the active feedback sidesticks installed in the simulator to provide the pilot with haptic cues designed to alert pilots of the potential for spatial disorientation during the CEDAR experiment. The use of haptics is intended to stimulate pilots' touch sensory pathways through side stick vibration (like traditional "stick shakers") designed to supplement the visual and aural alerting guidance presented by the PCAS and modified RCAS systems.

Results

Throughout the course of the TASA CEDAR experiment, twenty (20) pilots evaluated all of the prototype alerts in both the somatogravic and sub-threshold roll illusion scenarios (6 total scenarios) for a total of one hundred and twenty (120) runs (see Table 1) completed in NAMRU-D's DRD simulation facility.

Table 1. CEDAR Scenarios by Type

	Sub Threshold Roll				**Somatogravic Takeoff**		
	Left Bank		Right Bank				
Alerting	RCAS	None	RCAS	None	PCAS	None	***total***
Runs	20	20	20	20	20	20	*120*

The metrics applied to the data collected are outlined in Table 2.

Table 2. CEDAR Qualitative Metrics

Metric	Description	Analysis Method
Control Input Error	Correctness of the pilot's initial input outside of a 5% dead band. $Correct\ Inputs \begin{cases} Somatogravic\ Takeoff - positive\ pitch \\ Sub\text{-}Threshold\ Roll\ Left - positive\ roll \\ Sub\text{-}Threshold\ Roll\ Right - negative\ roll \end{cases}$	Descriptive statistics including the magnitude of the input in the incorrect direction
Time to Take Corrective Action	Time when the pilot's stick input first exceeds a 5% dead band	T-test on the difference between runs with and without alerting for each pilot
Time to Complete Corrective Action	Time when the aircraft pitch is steady between ±5 degrees and the roll is steady between ±3 degrees	

For analysis purposes, the quantitative time-based data was transformed through the measurement of differences. Transforming the time metrics into differences accomplished two things; it compared pilot performance to themselves (not each other), and helped normalize the data so that it did not violate the assumptions of a t-test. The somatogravic illusion runs were t-tested separately while the sub-threshold roll illusions (both Right and Left) were combined. If a result proved to be statistically significant, further testing would show differences between roll directions. The results of the experiment and the accompanying analyses of the data collected are outlined below.

Time to Take Corrective Action

Pilot performance was measured on the amount of time needed to take a corrective action after being given control of the simulated aircraft. A corrective action is considered a stick input outside of the plus or minus five (+/- 5) degree dead band (see Table 3 **Error! Reference source not found.** and Figure 5**Error! Reference source not found.**).

Table 3. Time to Corrective Action by Scenario

Scenario	Alert	Average Time	Std Dev
Somatogravic Takeoff	PCAS	1.84	0.47
Somatogravic Takeoff	None	1.75	0.14
Sub-Threshold Roll Left	RCAS	1.54	0.08
Sub-Threshold Roll Left	None	1.96	0.98
Sub-Threshold Roll Right	RCAS	1.52	0.68
Sub-Threshold Roll Right	None	3.50	8.21

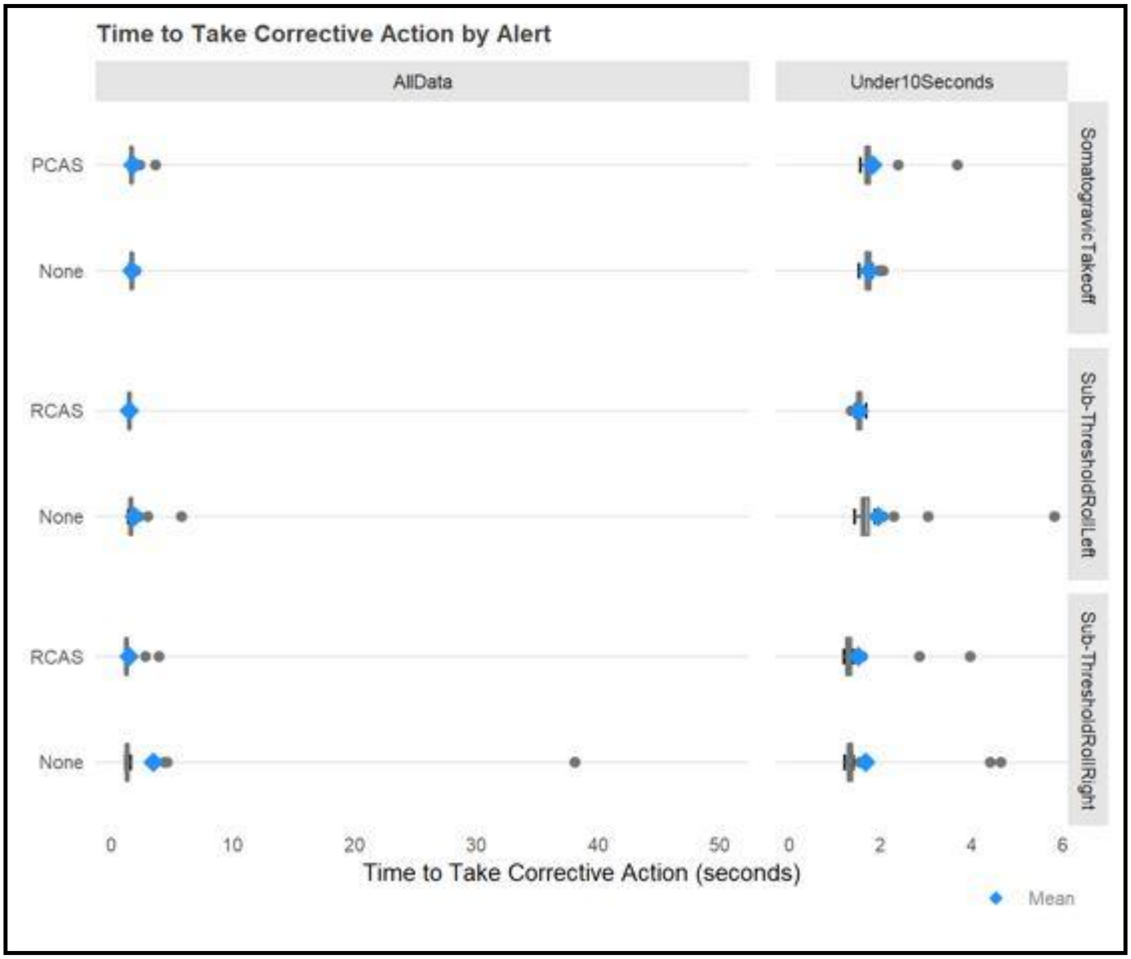

Figure 5. Time to Take Corrective Action

Statistical analysis revealed that pilot response time to the somatogravic alert was slightly higher than the baseline condition, but this difference was not statistically significant (t_{stat} = -0.89, df = 19, p-value = 0.386). Pilot response times to the sub-threshold roll alerts were lower than the baseline condition, but again, the differences were not statistically significant (t_{stat} = 1.29, df = 39, p-value = 0.204).

Time to Complete Corrective Action

The amount of time necessary to complete the corrective action was also measured, to help assess the directional cues contained in the alerting prototypes.

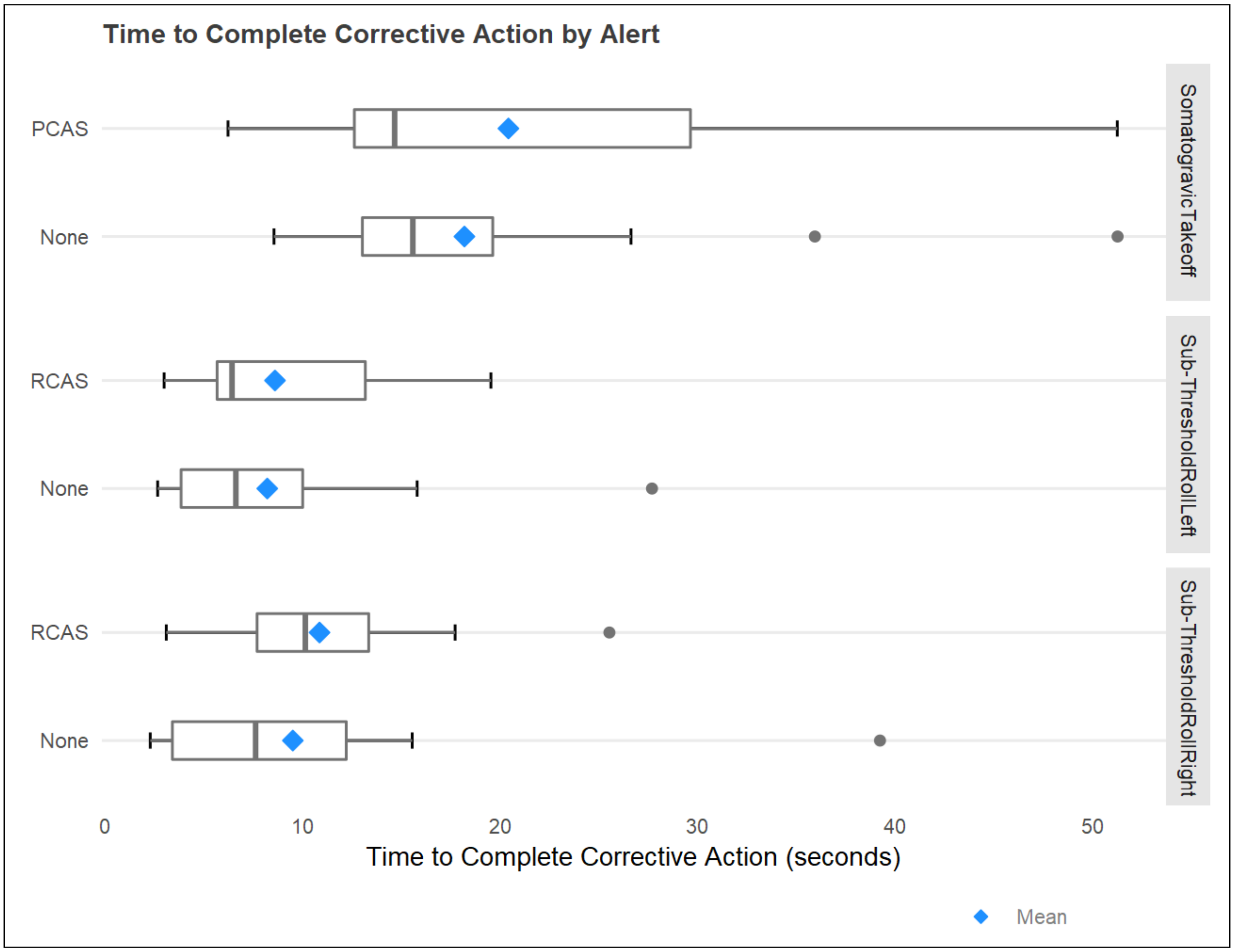

Figure 6. Time to Complete Corrective Action by Scenario Type

On average, pilots took 2.3 seconds longer to complete the corrective action with the PCAS alerting than without (see Table 4), but the difference was not statistically significant (t_{stat} = -0.96, df = 19, p-value = 0.349).

Table 4. Somatogravic Illusion Average Time to Complete Corrective Action

Scenario	Average Difference (None - Alert)	Std Dev
Somatogravic Takeoff	-2.23	10.38

Some pilots saw improvement in time to complete corrective action with the alerting while others took longer without the alerting (see

Table 5). There is no evidence of a statistically significant difference between alerting vs baseline runs (t_{stat} = -0.61, df = 39, p-value = 0.544).

Table 5. Sub-Threshold Roll Illusion Average Time to Complete Corrective Action

Scenario	Average Difference (None - Alert)	Std Dev
Sub-Threshold Roll Left	-0.39	8.15
Sub-Threshold Roll Right	-1.35	9.98

Control Input Error

The stick inputs for pitch and roll were given a dead band of plus or minus five percent (+/-5%) of total stick deflection to isolate intentional inputs from hesitation or accidental input.

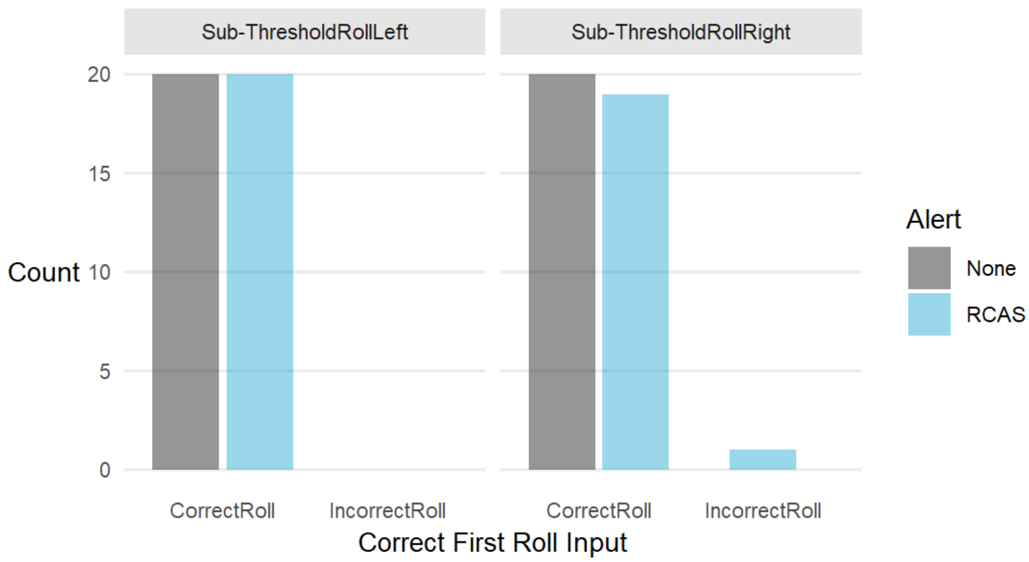

Figure 7. Control Input Error Sub-Threshold Roll

For the somatogravic illusion scenario, there were four incorrect initial pitch inputs (two were from the same pilot). It is believed that this pilot misinterpreted the directional cues to indicate the opposite direction. The inputs are summarized below in Figure 8 and Table 6.

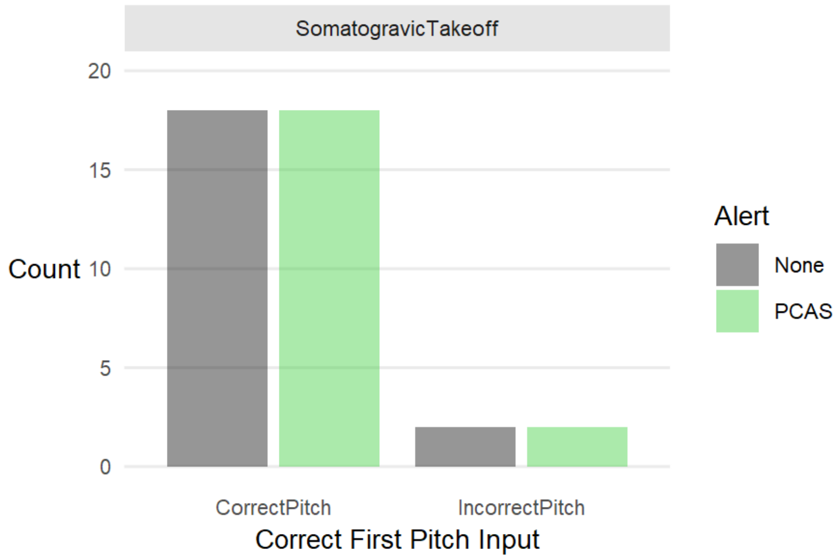

Figure 8. Control Input Error Somatogravic Illusion Scenario

Table 6. Incorrect Initial Pitch Inputs during the Somatogravic Illusion Scenario

Pilot	Scenario	Alert	First Pitch Input	Magnitude Incorrect Pitch Input	Time to Correct Pitch Input
1	Somatogravic Takeoff	PCAS	Incorrect Pitch	0.11	2.39
8	Somatogravic Takeoff	PCAS	Incorrect Pitch	0.89	3.69
8	Somatogravic Takeoff	None	Incorrect Pitch	0.33	1.97
9	Somatogravic Takeoff	None	Incorrect Pitch	0.05	2.06

There were an equal number of incorrect pitch inputs for both the prototyped alerting and baseline conditions (two respectively). In each case, it took two or more seconds for the pilot to realize their mistake and correct their initial incorrect input. These incorrect initial pitch inputs warrant further examination, and may indicate that the directional guidance cues used in the PCAS may require further refinement.

Post-Experiment Questionnaire Results

Each pilot was administered a post-run questionnaire in which they were asked to evaluate the alerting prototypes presented. The post-run questionnaires were administered to rate the somatogravic illusion scenarios and sub-threshold roll scenarios separately. The results of this survey are presented below, separated by scenario type.

Somatogravic Scenario

Of the twenty (20) EPs who completed the somatogravic Illusion scenario, twelve (or 60%) reported experiencing a state of spatial disorientation while eight (or 40%) did not.

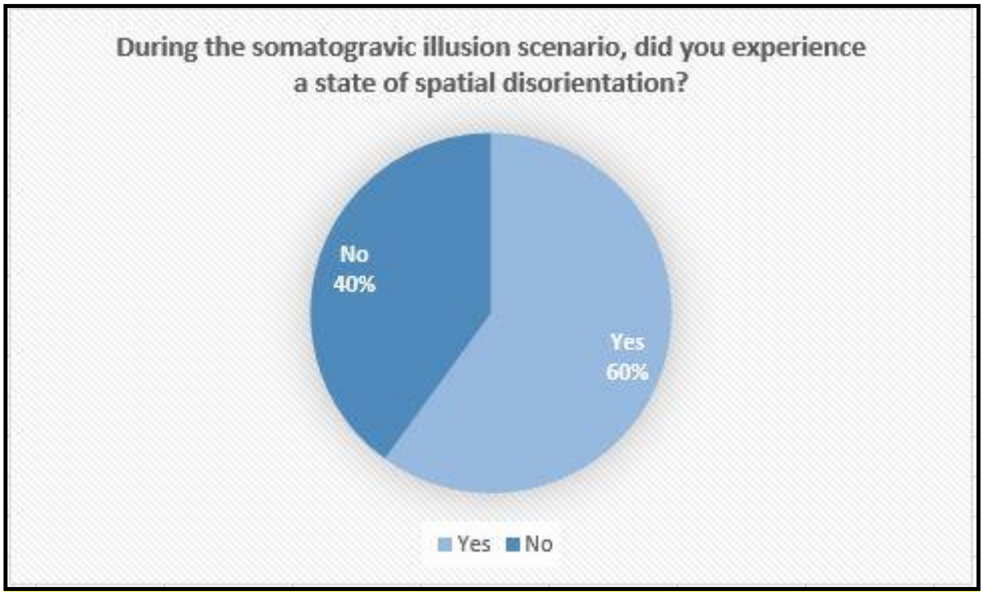

Figure 9. Self-Reported Pilot Spatial Disorientation – Somatogravic Illusion

When EPs were asked whether the prototype solutions presented would prove beneficial for alerting a pilot experiencing spatial disorientation, 18 responded “Yes” (90%), while 2 responded “No” (10%).

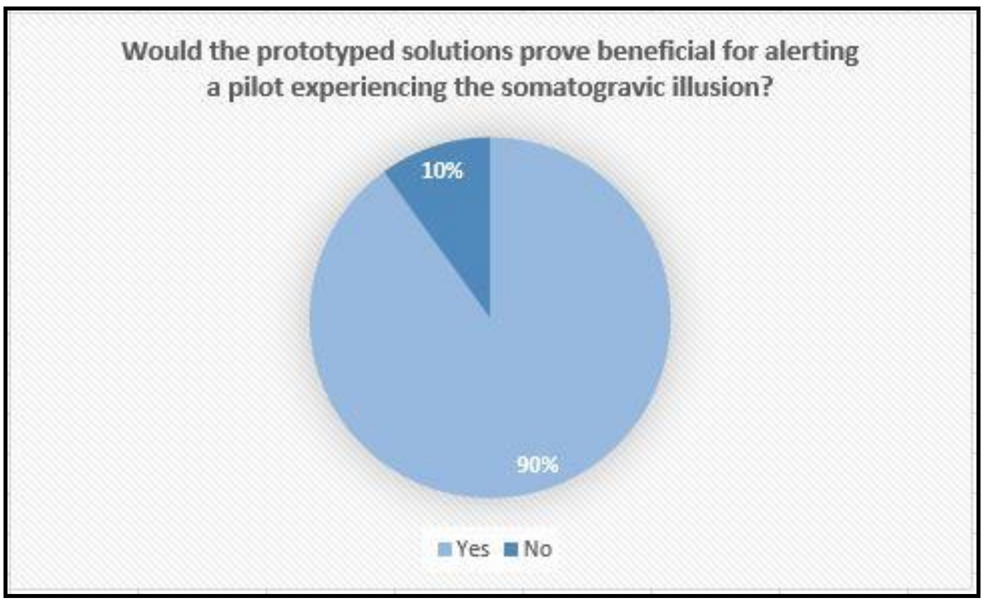

Figure 10. Benefits of Somatogravic Illusion Alerts

EPs were then asked to rate the usefulness of the PCAS alerting sub-components by sensory channel (visual, aural, and haptic) on a scale of 1-10 (1=Not at all useful, 10=Very useful). The visual alert received the highest rating, followed by the aural alert, and then the haptic alert (see **Error! Reference source not found.**).

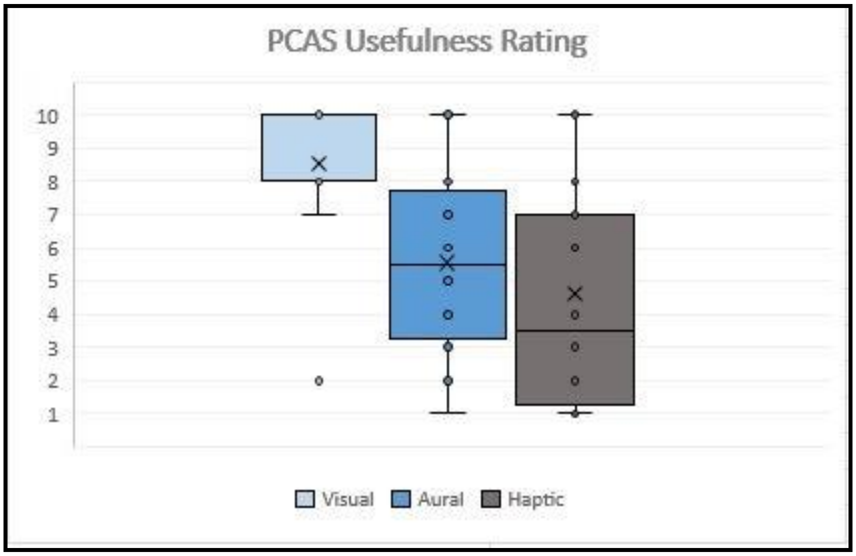

Figure 11. PCAS Usefulness Rating (1=Not at all useful, 10=Very useful)

EPs were also asked to rate their preference for the PCAS alert sub-components on a scale of 1-5 (1=Dislike very much, 5=Like very much). Once again, the visual alert received the highest rating, followed by the aural alert, which was closely followed by the haptic alert (see

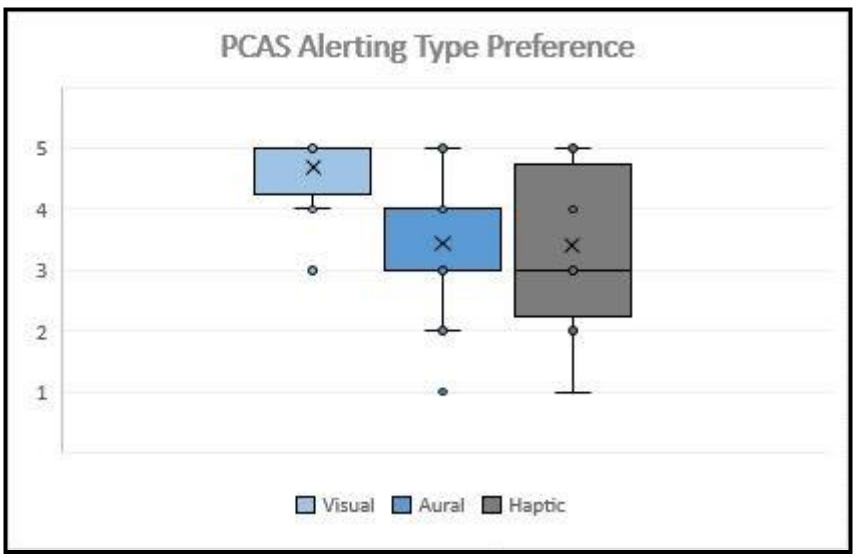

Figure 12. PCAS Alerting Type Preference (1=Dislike very much, 5=Like very much)

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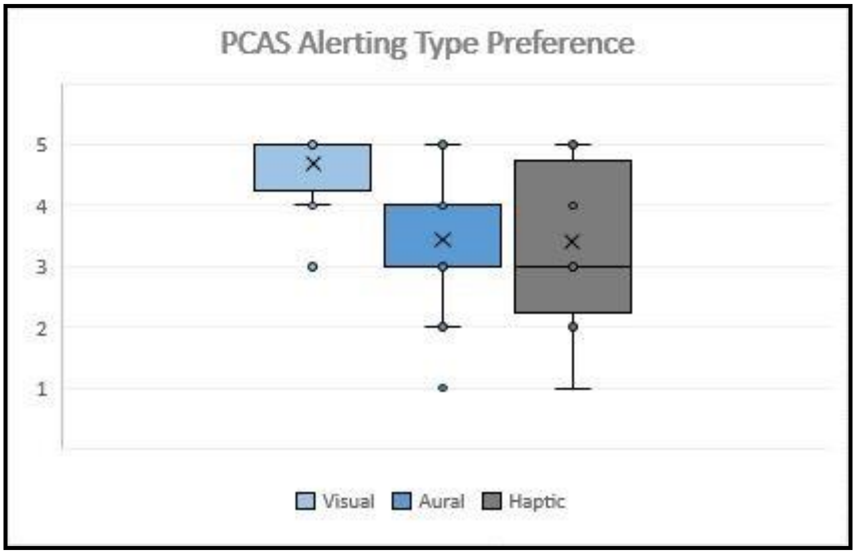

Figure 12. PCAS Alerting Type Preference (1=Dislike very much, 5=Like very much)

Sub-Threshold Roll Scenarios

Of the twenty (20) EPs who completed both of the sub-threshold roll scenarios (one left, one right), six (or 30%) reported experiencing a state of spatial disorientation while thirteen (or 65%) did not, and one EP (or 5%) was uncertain. This rate of spatial disorientation was significantly lower than the somatogravic illusion scenarios, and is most likely due to the milder forces at work for the sub-threshold roll scenario. Also, because the roll rate was below the threshold that is perceptible to the pilot (by design) the EPs may not have been aware that they were in fact spatially disoriented.

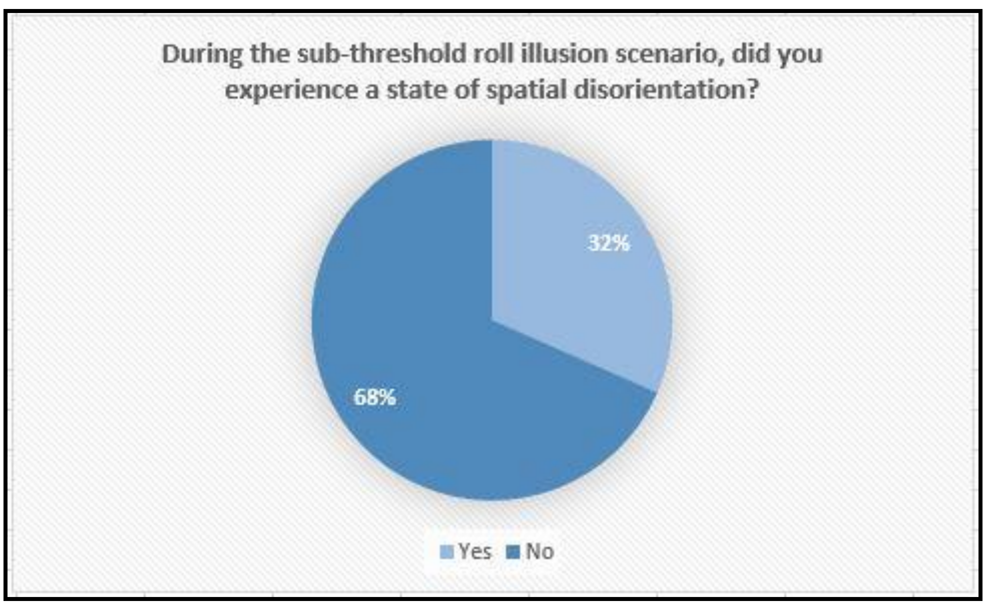

Figure 13. Self-Reported Pilot Spatial Disorientation – Sub-Threshold Roll Illusion

When EPs were asked whether the prototype solutions presented would prove beneficial for alerting a pilot experiencing spatial disorientation, eighteen (18) responded “Yes” (90%), while two (2) responded “No” (10%).

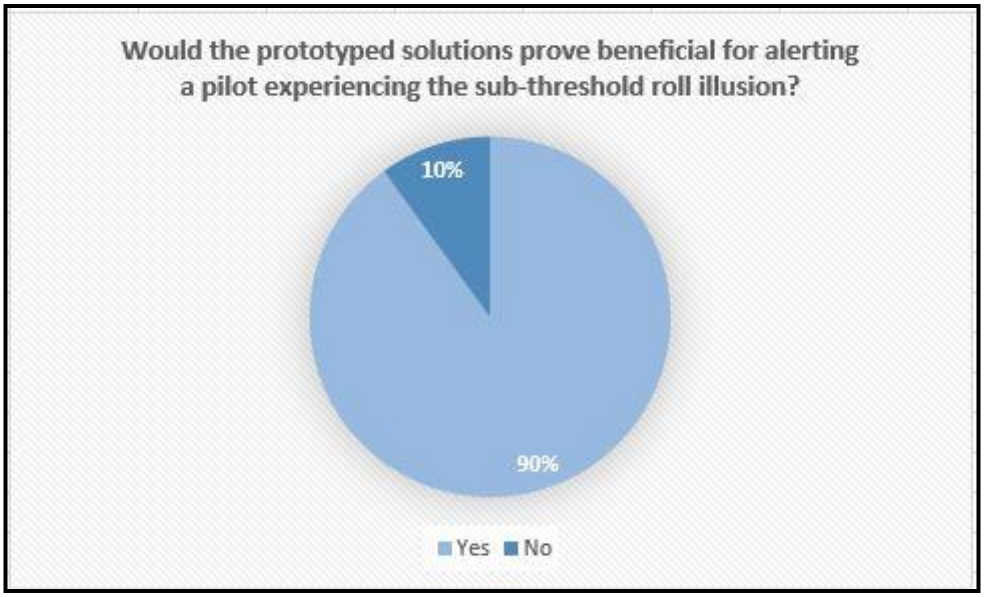

Figure 14. Benefits of Sub-Threshold Roll Illusion Alerts

EPs were then asked to rate the usefulness of the modified RCAS alerting sub-components by sensory channel (visual, aural, and haptic) on a scale of 1-10 (1=Not at all useful, 10=Very useful). The visual alert received the highest rating, followed by the aural alert, and then the haptic alert (see

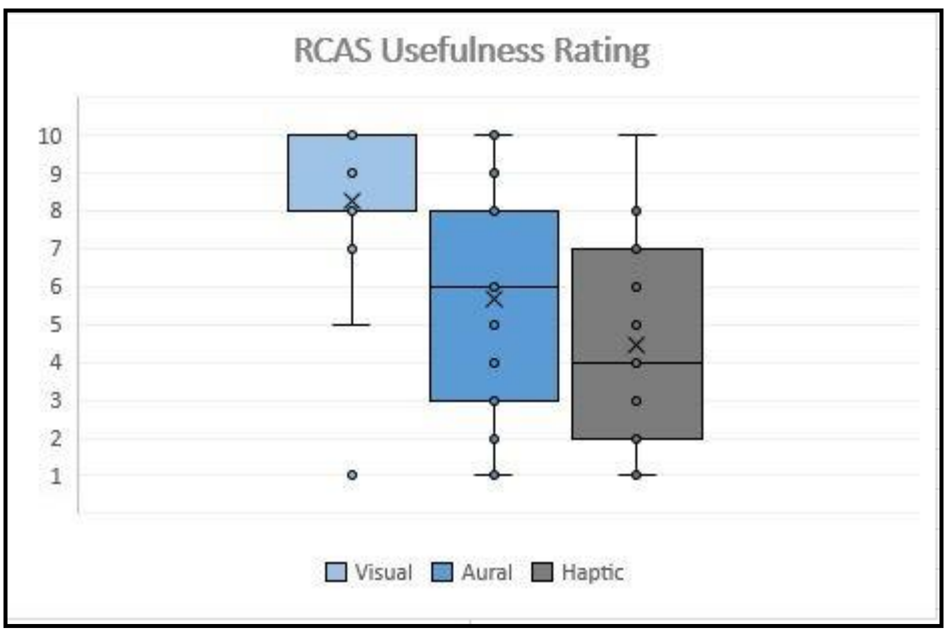

Figure 15).

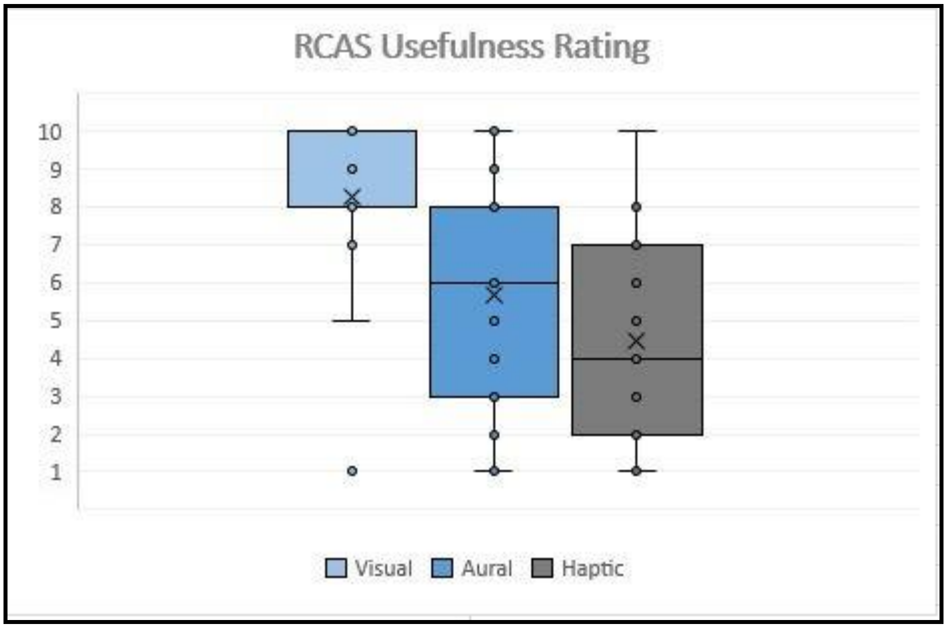

Figure 15. Modified RCAS Usefulness Rating (*1=Not at all useful, 10=Very useful*)

EPs were also asked to rate their preference for the modified RCAS alerting sub-components by sensory channel on a scale of 1-5 (1=Dislike very much, 5=Like very much). Once again, the visual alert received the highest rating, followed by the aural alert, which was closely followed by the haptic alert (see

Figure 16).

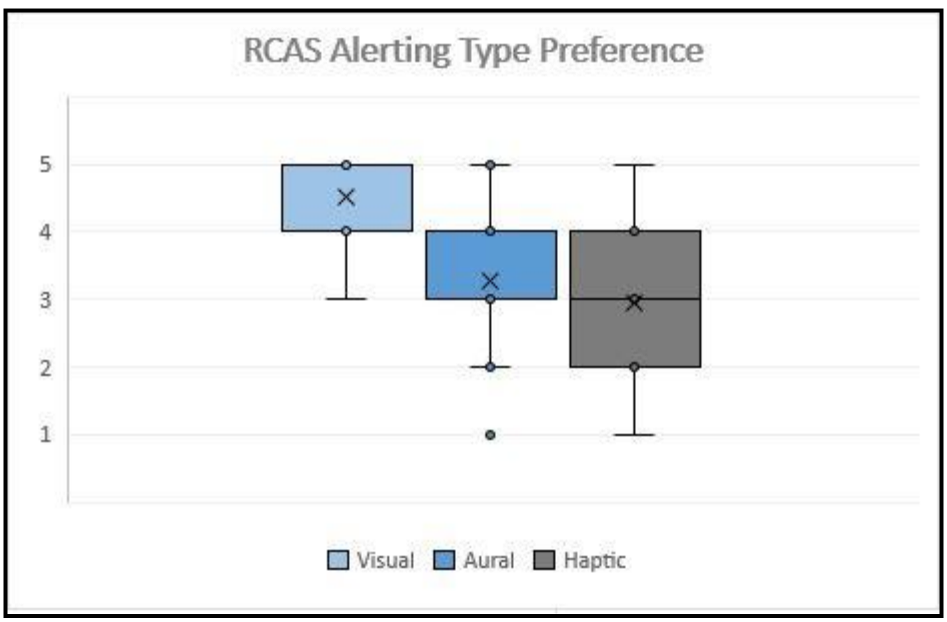

Figure 16. Modified RCAS Alerting Type Preference (*1=Dislike very much, 5=Like very much*)

The results of this experiment provide unique insight into the difficulties associated with developing alerting devices for the mitigation of pilot spatial disorientation. The quantitative results show that the alerting prototypes made no statistically significant difference for any of the performance measures tested, yet pilots overwhelmingly agreed that the prototypes would prove beneficial for alerting those experiencing spatial disorientation.

The results strongly support the hypothesis that the presence of the alerting prototypes will provide equal or improved pilot awareness of the potential for somatogravic and sub-threshold roll illusions when compared to the baseline condition. While statistical analysis revealed equal performance between Condition A (Baseline) and Condition B (Full alerting) configurations, this indicates that further development and refinement of the concepts will be necessary in order to one day achieve improved pilot performance.

Conclusion

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