

Development and Evaluation of a Collision Avoidance Display for Supporting Pilots' Decision Making in a Free Flight Environment

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Abstract

In a Free Flight Environment, pilots have multiple goals for a safe flight. These goals change as the flight progresses. As the flight progresses, pilots have the freedom to choose flight paths, maintain spatial separation and consider environmental conditions with minimum intervention from Air Traffic Controllers. These factors constitute pilots' new tasks. An innovative airborne display has been developed to support pilots' cognitive control model. The graphic display presents conflict geometry to enable pilots to resolve conflicts. The display also provides a means of bridging the gap between aircraft performance and environmental constraints. This paper describes the development and evaluation of this display.

Keywords

Human and Machine Interactions, Collision Avoidance Systems, Situation Awareness, Mental Workload, Ecological Interface Design (EID).

1. Introduction

Global air traffic flow is expected to double by 2025 (Sheridan, 2009; Hollnagel, 2007). The current Air Traffic Management (ATM) systems may not be able to support the growing amount of air traffic, higher and faster aircraft. As a result, flying activities may increase the rate at which controller process flight information and likelihood of air conflicts and mental workload in a congested airspace may increase. To cater for this increase, individual pilots under free flight environment are allowed to choose a flight path to maintain self-separation (RTCA, 1995).

To fly aircraft, pilots monitor and control the aircraft, and interact with navigation systems. In doing so, they make decisions. Cognitive processes affect these decisions as they performed navigational tasks. The types of knowledge and cognitive demands vary with tasks. Tasks change as aircraft moves from controlled to uncontrolled airspace. As pilots orient themselves in space, they change the flight path to circumnavigating air traffic or weather conditions as an important feature in a free flight environment.

In this paper, we focus on investigating pilots' cognitive control model in a free flight environment. Despite its importance, pilots' cognitive control model of flight path changing has not been studied extensively under the free flight environment. For example, a pilot's decision-making processes in the changing flight path are influenced by information to include fuel, safety and/or efficiency. However, pilots' subjective weighing of this information is not sufficient if there are to operate in this environment.

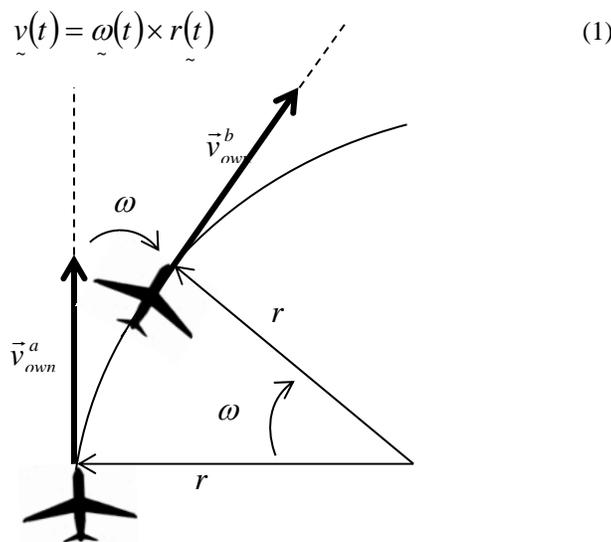
Previous studies related to the development of collision avoidance have been investigated (Johnson, et al., 1997; Van Dam, Mulder, and Van Paassen, 2008). However, according to Helleberg, Wickens and Xu (2007) lack of a system to suggest possible manoeuvres to resolve air conflict enable pilots to consider each decision based on safety, efficiency, fuel and completing the task successfully. Therefore, this work has developed a collision avoidance display to address this limitation. The proposed display shows geometry of conflict information that affords pilots to prefer routing.

2. Pilot's Flight Manoeuvres in Airspace

This section introduces pilots' issue as related to orientation in space. Pilots use basic flight parameters such as speed, heading and altitude to maintain the correct aircraft orientation in space. In doing so, they controlled aircraft along a specific flight path.

According to Wickens (2002), spatial awareness is an inseparable part of pilots' task of moving the aircraft through space. If spatial awareness is not updated, they may find flying activities difficult to carry out or comprehend aircraft orientation in space. This difficulty often causes a loss of minimum separation standard, for the following reasons: Firstly, the aircraft longitudinal axis does not always point in the direction of the aircraft flight paths. For example, wind direction may cause the aircraft longitudinal axis to change orientation in space. Pilots' spatial awareness of flight paths becomes difficult as this axis changes direction in space. Secondly, the effects on aircraft axes (i.e., lateral, longitudinal, normal) are interrelated. For example, any controlled action about the lateral axis also changes the aircraft's altitude (i.e., rotating the aircraft's longitudinal axis about the lateral axis changes aircraft's vertical motion). Thirdly, a pilot needs to choose the correct rates of turn with a specific speed and/or, decide when to initiate roll manoeuvre. These two variables pose a challenge to the unaided pilot's control hypothesis and could make the difference between avoiding the protected airspace and violating it. Finally, pilots must operate within the aircraft limitations. Compliance with these constraints may be in conflict with the pilots' objective to achieve the desired flight state and predict the future flight path. However, this issue needs to be considered from the perspectives of both aircraft performance and human factors. From the perspective of aircraft performance, pilots perform flight manoeuvres to change the flight paths and maintained minimum separation standards.

Aircraft manoeuvres involve a change in velocity and can be resolved into radial and tangential components (see Figure1). The curved flight path at the chosen moment is:



The tangential ac Figure 1. Top view of a right turn written as the derivative of two functions,

$$\vec{a} = \frac{d \vec{v}}{dt} \quad (2)$$

$$\vec{a} = \frac{d \vec{\omega}_t}{dt} \times \vec{r}(t) + \vec{\omega}_t \times \frac{d \vec{r}}{dt} \quad (3)$$

where $\frac{d \vec{\omega}_t}{dt} \times \vec{r}$ and $\vec{\omega} \times \frac{d \vec{r}}{dt}$ are the tangential and radial acceleration respectively, \hat{u} is the unit normal vector for the aircraft trajectory and \vec{r} is its instantaneous radius of curvature.

Substituting equation (2) into (3), the following expression is obtained

$$\underset{\sim}{a} = \frac{v^2}{R} \underset{\sim}{\hat{u}} + \underset{\sim}{\omega}_I \times \frac{d \underset{\sim}{r}}{dt} \quad (4)$$

From equation (3), the aircraft is experiencing acceleration during turning manoeuvres.

As the aircraft begins to accelerate to become airborne, there is a change in velocity. The change in velocity tends to make fluid in passenger's semicircular canals in their middle ears to move due to inertia, thus providing the passenger with flight manoeuvre information (i.e., such as the aircraft is rolling). As a consequence, the perception of this information and its interpretation is consistent with flight manoeuvres as the aircraft continues, for instance, to make a turn. However, if there is a sudden change in the aircraft direction (i.e., such as the aircraft returning to a level flight), the opposite of this sensation is perceived by the passengers (i.e., perception of an opposite turning manoeuvre). This sensation is a matter of great concern to passengers' comfort and often results in motion sickness (Golding et al., 2003) and spatial disorientation (Young, 2003). In terms of safety-related issues (such as physical problems) passengers usually find it difficult to walk or stand during the flight manoeuvres. Therefore, the aircraft should be flown at the recommended rate of turn, bank angle and heading otherwise some passengers will experience a loss of balance. This situation has an implication for designing a display.

2.1 Conflict Resolution

In any flight situation involving more than one aircraft crossing each other flight path, air conflict can arise. To fly an aircraft, pilots process vast amount of information. The information they process may be simple or complex, clear or distorted, complete or incomplete and need to fill in the gaps. All of the above mentioned issues may have an effect on pilots' decision making. Decision making is of fundamental importance to pilot activities (Jenkins et al., 2008). Pilots monitor and control the aircraft, and interact with other automated display systems. In doing so, they decide what information is critical for a safe flight. This information may include type of manoeuvre required to avoid obstacles.

A pilot strategic or tactical manoeuvre is essential to conduct a change of the flight path to avert the conflict situation. Pilots performed a tactical manoeuvre when the current environment required them to change the flight path immediately or delay response due to unforeseen danger. Thus, it is a short-term decision making process. For example, aircraft performance constraints may prevent pilots maintaining the current flight path or due to ATC regulations. Factors that may influence pilots' decision in this situation include lateral or vertical minimum separation standards. Strategic manoeuvre, on other hands, is about planning and implementing pilots' decision to meet the overall objective of conflict avoidance. However, a pilot may not be stratified with current aircraft performance or air traffic conditions; therefore, he or she may need to reconsider his first decision by changing aircraft heading or speed as illustrated in Figure 2.

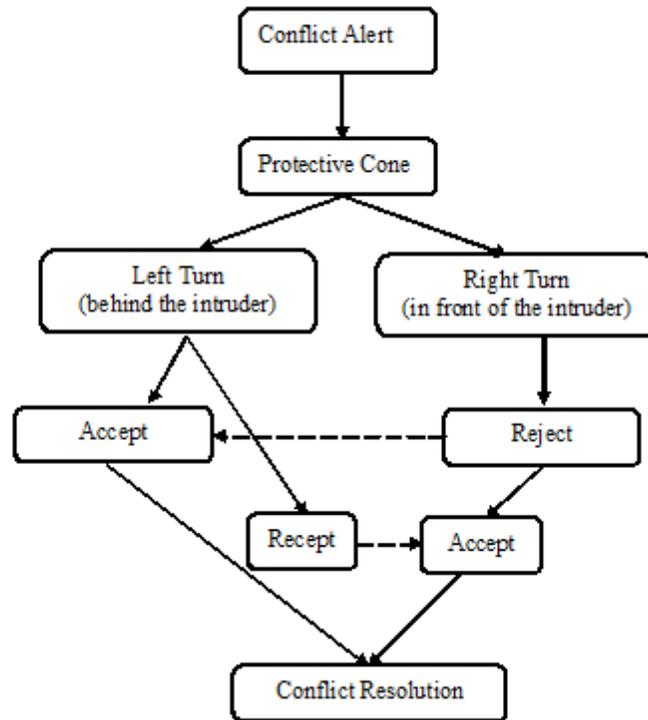


Figure 2. Aircraft Resolution Decision Model

Similarly, to the adaptation of the flight route selection heuristic, the reconsideration of the flight route choice (i.e., pilots' second decision) may be as a result of pilots' experience made in the previous flight (i.e., rule based behaviour) (Rasmussen,1983). To evaluate the future trajectory; pilots need to operate at a level of knowledge-based behaviour. For example, the acquired knowledge on this level enables pilots to predict the future trajectory of aircraft that is possible for a particular conflict scenario,

3. Developing and Evaluating Goals for a Flight Collision Avoidance System

To support pilots to resolve conflict under the Free Flight environment, a new display such as Flight Avoidance Collision System (FCAS) to maintain self-separations with minimum supervision from air traffic controllers (ATC) is required. As shown in Figure 2, a pilot strategic or tactical manoeuvre can be captured by using the cognitive model (Rasmussen).

3.1 The Design Objectives

The development of Flight Collision Avoidance Display (FCAS) focused on three goals to support pilots with low and high level of flight information to avoid collision. The first goal supports pilots with a low level of flight information:

- Flight altitude,
- Conflict angle,
- Relative speeds;
- Relative positions
- Ground Speed
- Loss of Separation(LOS)

A pilot's collision avoidance manoeuvres is directed at making a change in flight path as effective as possible for lateral separation. For instance, aircraft in conflict situations is a problem of relative position of

two moving aircraft in a stated circumstance under no wind conditions. This situation is best reduced to problems of relative motion as shown in Figure 3 and given by

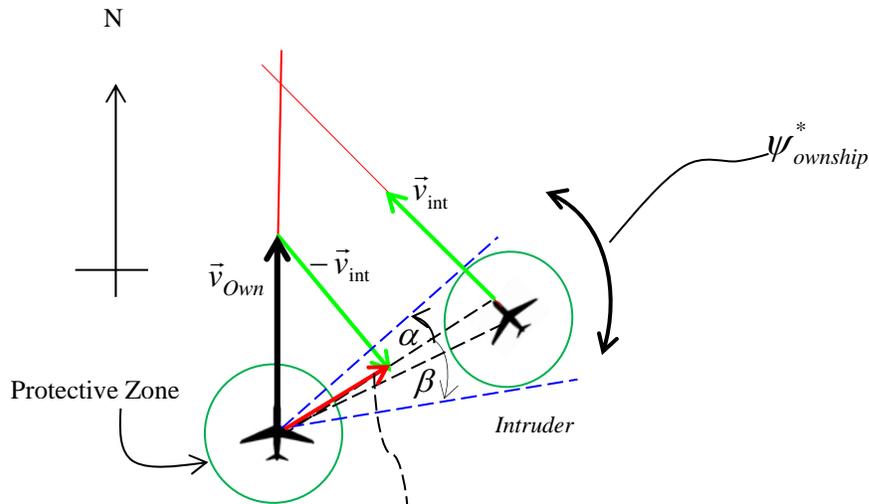
$$\vec{v}_{own} = \vec{v}_{own/int} + \vec{v}_{int} \quad (5)$$

$$\vec{v}_{own/int} = \vec{v}_{own} - \vec{v}_{int} \quad (6)$$

where \vec{v}_{own} is the velocity of Ownship and \vec{v}_{int} is the velocity of the Intruder, relative velocity of Ownship (referred to his or her own aircraft) to the Intruder (is a name termed for another aircraft).

The second design goal is to support pilot with high level of information by using a protective cone (see Figure 3). The purpose behind making use of the protective cone in the design (i.e., functional information) is as means of bridging the gap between aircraft performance and environmental constraints. For example, a car headlight affords drivers to drive at night to avoid obstacles or destinations.

By analogy, the protective cone affords pilots to avoid conflict while maintaining the same speed with minimum deviation from the desired path (see Bach, et al., 2009 for detailed discussion). As shown in Figure 3, to perform a heading change, pilots (i.e., Ownship) are required to rotate the relative velocity vector in a clockwise or anticlockwise direction so that the relative velocity vector is at least tangential to the Intruder protective zone or preferably outside the protective cone



where, $\psi_{ownship}^*$ is the Ownship heading, α is the angle between the relative velocity vector and the protective cone boundary, β is the angle between the relative velocity vector and the Intruder's heading, and $\psi_{ownship}$ is the Ownship heading.

The third design goal is to support pilots with visual information about the flight path in accordance with aircraft ground speed vector. The ground speed vector is used to predict Ownship and Intruder intended flight path.

3.2 The Evaluation goals

To investigate the design objectives of FCAS, the study focused on comparing the effectiveness of FCAS (based on Ecological Interface Design, see Section 4 for a brief discussion) to a control display (non-ecological interface design) as shown in Figure 4. Different forms and features of the display are compared.

The evaluation may be viewed as the independent factors shall be collision avoidance display formats (non EID display, EID display- with protective cone) as presented in Figure 5. To measure flight performance during the experimental runs, a dependent variable shall be the minimum of separation standards. A turn back manoeuvre to the original flight path is not considered here.

4. Ecological Interface Design (EID)

Ecological Interface Design (EID) approach addresses pilots' cognitive interaction with the environment and not human cognitive limitations (Vicente and Rasmussen, 1992). EID has been applied and prove useful in a variety of domains including and only, for example, nuclear power plants, aviation and medical field by making environmental constraints visible to pilots, for example. The visibility of these constraints favours the reduction of pilots' cognitive workload activities. The reduced cognitive workload activities enable pilots to focus on both anticipated and unanticipated events in a complex system, thus improve performance. According to Vicente (2002) EID is a theoretical framework for designing FCAS based on two the conceptual tools:

- Abstraction Hierarchy (AH)

The five levels of AH are mapped to form pilots' activity needed to achieve related goal such as conflict resolutions. The EID approach begins at the highest conceptual level down to the detailed physical system by considering environmental constraints and not human limitations and capabilities. These five levels include functional purpose, abstract function, general function, physical function and physical system. The AH enable pilots to move up and down these levels. These levels are supposed to answer pilots' questions in relation to conflict resolution activities. For example, pilots will like to know how far and/or close is their aircraft to intruder safety zone. How fast or slow pilots should have to fly in order to avoid collision? What bank angle is required for turning manoeuvres without exceeding aircraft performance limitations? What is the aircraft maximum and minimum heading required to avoid conflicts? Which way to turn behind or in front of the Intruder? What is the proposed of manoeuvring cost versus safety?

At the lower level of the hierarchy is detailed information about the physical system on how the functional purpose of the system can be achieved. The physical system enables pilots to interact with the system at the physical functional level. Above the physical functional level is the general function describing physical processes. The physical processes enable pilots to perform tasks at the abstract function level. These processes are influenced by external constraints that are based on standard rules, laws or tests on which the main objective or purposes of the system can be achieved. The uppermost level of the abstraction hierarchy is the functional purpose of the system. The purpose of the proposed system is to provide the safe passage to a destination. This level presents a deeper understanding of the system.

- Skills, Rules, Knowledge (SRK) of Rasmussen's (1983) framework.

The five levels of AH are controlled based on Rasmussen's (1983) pilots' skills, rules, knowledge behaviour. For example, skill-based behaviour requires little or no cognitive resources once pilots are familiar with the task. Pilots operating at this level should be able to focus on higher cognitive tasks such as problem solving (Wickens and Hollands, 2000). Pilots should be able to use low information to act directly on the interface.

Rule-Based Behaviour (Rasmussen, 1983) deals with specific types of system operations and is goal related. It involves practiced, sometimes-automatic behavioural sequences using well-established rules formed from experience and controlled by a set of stored rules or procedures. For example, rule based behaviour may be used to verify or modify existing knowledge. Further, the mapping between the environmental constraints and those information forms that are directly processed by pilots in the interface should be consistent. However, knowledge-based behaviour on the hand is assigned to novel situations. Pilots need this behaviour to identify, interpret and ascertain a system's status in normal or abnormal situations. In a situation where there is no skill or rules knowledge behaviour exists, it is important that a display enables pilots to perform a task at the level of knowledge-based behaviour. Thus, an EID is a

possible approach to handle both primary and secondary tasks in a way that supports pilots' cognitive limitations when interacting with the environment in unexpected situations (Vicente and Rasmussen, 1992).

5. Method

From aircraft performance prospective, resolving conflict or interception of waypoints at a constant rate of turn and speed-select mode could be challenging for pilots for the following reasons: Firstly, selecting or choosing the correct rate of turn for a specific roll manoeuvre at high speeds would require pilots' quick response to unexpected events. Secondly, pilots' decisions to act earlier or delay the initiation of the selected roll manoeuvre could lead to violating or avoiding the Intruder's protective zone (Xu and Rantanen, 2007; Sheridan, 2009). The latter depends on the type of display used to perform the selected manoeuvre to avoid air traffic (Ellis, McGreevy and Hitchcock, 1987). These two variables will pose a challenge to pilots without a system support to make control hypotheses visible, in terms of integration and precise coordination of information presented.

5.1 Flight Simulator

To examine self-separation related issues in a free flight environment, we developed two collision avoidance displays as presented in Figure 5. Twenty one participants were recruited from the Swinburne University and Aviation Community in Melbourne via advertisements on campuses. Participants were students and professional pilots. The participants' ages range between 22 and 75 years old and categorised into experimental (11) and control (8) group. In appreciation for time and valuable contribution to research, participants received an incentive in form of \$30 iTunes gift card. The experiment lasted approximately an hour.

The evaluation was conducted on a standard desktop computer and colour monitor (using 1024 x 768 XGA with a graphics card) with the inclusion of a Saitek Pro Flight System. The simulator software was written in C++ language and MATLAB. The software enables pilots to avoid obstacles by tracking, navigating, maintaining or deviating from the intended flight path. The algorithm is a level-aircraft conflict resolution of flying a twin-engine aircraft in no wind conditions (Bach, et al., 2009). Aircraft Dynamics was not modelled here.

The scenarios are modelled based on two aircraft currently en route maintaining constant altitude, speed and heading, however, conflicts exist. In this study, participants were asked to fly simulated Instrumental Flight Rules tasks. The two experimental test runs consisted of three (3) blocks of three minutes each was administered to the participants within which a conflict will occur. In each scenario, heading ranging between 133 and 037 were randomly assigned to Ownship at FL130, and speed of 356kts. The Ownship is allowed to manoeuvre to avoid conflict. The intruder is to maintain constant heading ranging between 220 and 337 were randomly at FL130 and speed of 300kts. We made a set of assumptions and built a full free flight scenario to make data available for conflict detection and resolutions (see Table 1).

Table 1 Safe Flight Navigation

Scenarios	Conflict Resolution
Head-On Approach	A level left or right turn conducted at the current airspeed and a roll angle of > 0 or < 0 was required to escape a collision
Port Approach (left side)	A level left or right turn conducted at the current airspeed and a roll angle of > 0 or < 0 was required to escape a collision
Starboard approach (right side)	A level left or right turn conducted at the current airspeed and a roll angle of > 0 or < 0 was required to escape a collision



(a) Non EID

(b) FCAS- EID

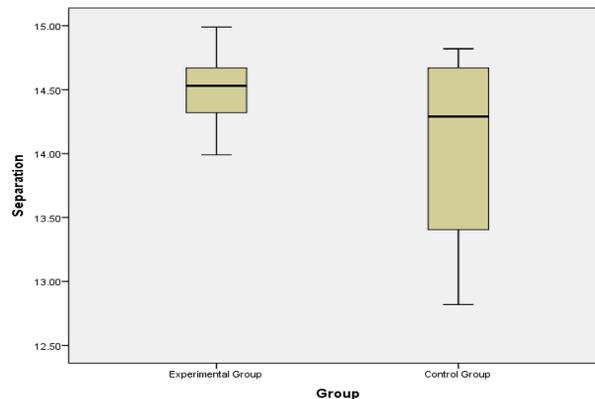
Figure 4. Screenshots of Collision Avoidance Display formats

The two displays shown in Figure 4 were tested. The display shown in Figure 4a was used for the control group. The display presented information with top down view about the other aircraft relative positions and track up orientation. In contrast to control group display, the experimental group display shown in Figure 4b. This display, added an indication of other aircraft's heading, a protective cone and relative velocity vector. This display tested the conceptual effect of providing a protective cone and relative velocity vector to avoid a collision.

6. Results and Discussion

The overarching hypothesis is that FCAS, designed to improve pilot situation awareness, helps pilots perform manoeuvres to avoid separation conflicts with aircraft intruding into their flight path. The underlying hypotheses are as follows. A pilot using the FCAS compared to those who only have the standard instrumentation will violate separation constraints less often.

The proposed FCAS was tested utilising a simple algorithm of a level-aircraft conflict resolution (Bach, et al., 2009). In our simulation study, we used a simple model in no wind conditions. Pilot's collision avoidance results are presented in Figure 4. The analysis revealed that there was a statistically significant difference between experimental (i.e., with EID, see Figure 4b) and control groups (i.e., control display, see Figure 4a) in pilots' abilities to maintain minimum separation standards. The experimental group was more engaging ($M = 14.51, SD = .28$) than the control group ($M = 14.04, SD = .75$), a statistically significant difference, $M = .059, t(19) = 2.011, p = .059, d = 0.63$. The results revealed an increased in loss of minimum separation between the Intruder and the Ownship for the control group. The results are graphically displayed in Figure 5.



(c)

Figure 5. Comparison of collision avoidance displays

Although the scenario presented here is simple, it is possible to compare the results from this simulation to real experimental data. Further, an analysis of pilots flying behaviour through numerical data have highlighted that pilots with contemporary instrumentation display (non EID) tend to fly close to the intruder. In contrast to EID, the contemporary instrumentation did not offer sufficient information to resolve conflict which may have resulted in reducing the minimum separation standard as supported from numerical findings. Another interesting finding is that both groups did not exceed the bank angle limits. Furthermore, pilots in the experimental group commented positively on the use of FCAS to avoid imminent potential conflict.

7. Conclusion

The development of this instrumentation is designed primarily to display traffic information in the form of geometric visual representations of vectors. The simplicity of this system is to demonstrate the use these vectors and evaluation of the FCAS. The used of FCAS suggests that pilot actions to avoid the programmed conflict were effective as against contemporary instrumentation display. This result can be attributed to that fact that pilots find the protective cone useful in maintaining self-separation. However, almost all pilots reply more on rules based behaviours to resolve conflict. Finally, our future plan is to include system dynamics to capture more and more details of the pilots' decision-making.

References

- Bach, R., Farrell, C., and Erzberger, H., (2009) "An Algorithm for Level-Aircraft Conflict Resolution," NASA/CR-2009-214573
- Ellis, Stephen R., McGreevy, Michael W. and Hitchcock, Robert J., (2007). "Perspective traffic display format and airline pilot traffic avoidance". *Human Factors*, Vol 29(4), pp. 371-382.
- Golding, J. F., Bles, W., Bos, J. E., Haynes, T. and Gresty, M. A., (2003) "Motion Sickness and Tilts of the Inertial Force Environment: Active Suspension Systems vs. Active Passengers" *Aviation, Space, and Environmental Medicine* 74, (3), pp. 220-227
- Helleberg, J., Wickens, C. D., & Xu, X., (2007). Pilot Maneuver Choice and Safety in a Simulated Free Flight Scenario.
- Hollnagel E., (2007). "Flight decks and free flight: Where are the system boundaries?" *Applied Ergonomics* 38 (4) pp. 409-416.
- Jenkins, D. P., Stanton, N. A., Salmon, P. M. Walker, G. H. & Rafferty, L., (2008). Using the decision-ladder to add a formative element to naturalistic decision making research. HFI DTC report no HFIDTC/2/WP4.6.1/2.
- Johnson, W. W., Battiste, V., Delzell, S., Holland, S., Belcher, S., and Jordan, K., (1997). Development and demonstration of a prototype free flight cockpit display of traffic information. *SAE transactions*, 106, 1566-1582.
- Krozel, J., and Peters M., (1997) "Strategic Conflict Detection and Resolution for Free Flight" Proceedings of the 36th Conference on Decision & Control San Diego, California.

- Rasmussen, J., (1983) "Skills, rules, knowledge; signals, signs, and symbols, and other distinctions in human performance models" *IEEE Transactions on Systems, Man and Cybernetics*, 13, 257-266.
- RTCA (1995). "Final report of the RTCA board of directors' select committee on free flight". Washington, DC: RTCA, Incorporated.
- Sheridan, Thomas B., (2009). "Human Factors Research Needs for NextGen-Airportal Safety" NASA/CR-2009-21537
- Van Dam, S. B., Mulder, M., & Van Paassen, M. M. (2008). Ecological interface design of a tactical airborne separation assistance tool. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, 38(6), 1221-1233.
- Vicente, J., (2002) "Ecological Interface Design: progress and challenges," *Human Factors*, 44(1), pp.62-78
- Vicente, K. J. & Rasmussen, J. (1992). "Ecological Interface Design: Theoretical foundations" *IEEE Transactions on Systems, Man and Cybernetics*, 22, 589-606.
- Wickens, C. D., & Hollands, J. G., (2000). *Engineering psychology and human performance* (Third Edition ed.). Upper Saddle River, New Jersey: Prentice-Hall Inc.
- Wickens C.D.,(2002). "Situation Awareness and Workload in Aviation" *Current Directions in Psychological Science*. 11(4) 128-133.
- Xu, X., and Rantanen, E. M., (2007) "Effects of Air Traffic Geometry on Pilots' Conflict Detection With Cockpit Display of Traffic Information" *The Journal of the Human Factors and Ergonomics Society* 49: 358
- Young, L. R., (2003). In "Spatial Orientation". *Principles and Practice of Aviation Psychology*. P. S. Tsang and M. A. Vidulich, Eds. New Jersey, Erlbaum 69-114.

Biography

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