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TESTING A MULTIDIMENSIONAL NONVERIDICAL AIRCRAFT COLLISION AVOIDANCE SYSTEM, EXPERIMENTS 3, 4

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Veridical displays represent realistic scenes. State spaces are *nonveridical* displays representing n -dimensional information. This research tests an aircraft separation maintenance display based on a nonveridical state space. In two experiments, licensed general aviation pilots flew flight scenarios, trying to deviate as little as possible from a pre-assigned course while still maintaining standard enroute separation from traffic. Flight performance using only a veridical cockpit display of traffic information with conflict alert capability was compared to performance augmented by a 4D nonveridical state space collision avoidance system. Results suggest that nonveridical display enhances operator performance on an aircraft separation maintenance task.

The present research examines an aircraft separation assurance display based on a nonveridical state-space. The term *veridical* means “coinciding with, or representing, physical reality.” *State spaces* are *nonveridical* representations common to engineering. A state space can be constructed from any quantifiable features, and can describe the state of a dynamic, multidimensional system at some current or future time t .

Motivation for This Work

Background. Currently, U.S. commercial aircraft do not fly point-to-point, but follow segmented jet routes in enroute airspace (the “long-haul” airspace starting about 40 miles [64 km] from airports). These jet routes add unnecessary travel distance and time. By enabling direct flight from departure to destination, airlines could lower fuel use by up to 6% (Operations Research and Analysis, 1998). Full implementation of direct flight will require advanced technology to minimize enroute air traffic conflicts (Krozel, 2000).

Enroute “conflicts” are defined as any two aircraft approaching within 5 nautical miles (nm) and 1,000 ft (9.3 km/304.8 m) of each other. Direct routing is expected to increase the base conflict rate because it transforms air traffic control (ATC) from a 2D spacing problem into a 3D spacing problem, increasing airspace complexity and conflict probability (Azuma, Neely, Daily, & Correa, 1999; Xing & Manning, 2005).

To minimize conflicts, veridical displays of traffic information have been developed, including map-view ATC displays and cockpit displays of traffic information (CDTI), 2D conflict resolution displays (Johnson, Battiste, & Holland, 1999), coplanar displays (Pekela & Hilburn, 1998; Thomas & Wickens, 2005), and 3D veridical displays (Canton, Refai, Johnson, & Battiste, 2005; Granada, Quang Dao, Wong, Johnson, & Battiste, 2005; Naikar, 1998).

Some systems make use of separation-maintenance technology to predict and even help resolve conflicts between aircraft. Cockpit variants of veridical *collision avoidance systems* (CAS) have been developed (Johnson & Battiste, 1999; van Gent, Hoekstra, & Ruigrok, 1998). The most widely known is TCAS ([Traffic Alert and Collision Avoidance System], Kuchar & Yang, 2000). However, TCAS has a short time lookahead. Strategists must now focus on systems with lookaheads sufficiently long to allow gentle aircraft maneuvers.

Veridical displays have difficulty displaying certain kinds of maneuver information. In response, researchers have turned to nonveridical display. For instance, NASA’s En Route/Descent Advisor (Green & Vivona, 2001) allows aircraft spacing by positioning individual traffic icons on a slider representing desired arrival time-at-destination. Van Dam, Appleton, Mulder, and van Paassen (2006) tested a nonveridical CDTI allowing speed+heading combination maneuvers. Both devices have demonstrated their effectiveness on difficult air traffic scenarios.

Maneuver space. Knecht and Smith, (2001) proposed the concept of *maneuver space* (MS). Maneuver space has been defined by the military as “the physical space within which one can maneuver.” Now, MS is redefined as *a 4D state space unique to each aircraft, dimensionalized by that aircraft’s a) heading, b) speed, c) altitude, and d) available maneuver time. MS represents all conflictual and non-conflictual maneuvers achievable by that aircraft within a fixed period of time, given the obstacles predicted along each potential maneuver’s hypothesized path.*

Maneuver space is a maneuver **hypothesis-tester**. It has seven key attributes:

- 1) Each translucent cube inside MS represents **one maneuver** (one autopilot setting of heading, speed, altitude).
- 2) Therefore, moving within MS represents **resetting the autopilot**.
- 3) **Colored MS** represents “**unsafe**” maneuvers (predicted to yield separation failure).
- 4) **Color** represents **available maneuver time** (minutes until separation failure).
- 5) **3D MS-center** represents **current autopilot setting**.
- 6) Therefore, **no avoidance is needed unless MS-center is colored**.
- 7) Maneuvers involving multiple conflicts are colored for the single conflict *closest in time*.

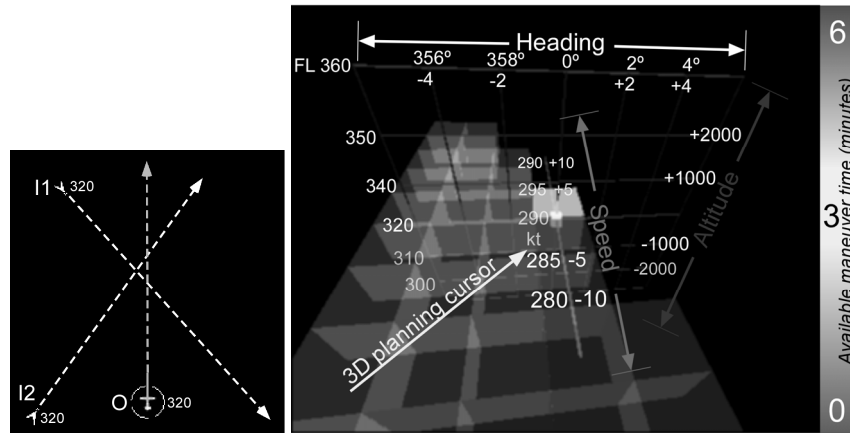


Figure 1. (Left) Three aircraft, all traveling 290 kt indicated airspeed (.78 mach) at flight level 32,000 (FL 320). The pilot’s own ship (ownship, O) must maneuver to avoid two intruders (I1, I2). (Right) A view of the resulting 4D MS.

In Figure 1, the entire translucent, colored structure is called a *conflict region (CR)*—a set of numerically contiguous maneuvers predicted unsafe by a *conflict probe* (Kuchar & Yang, 2000), given a specified lookahead time.

Preliminary Development

A 4-Dimensional Collision Avoidance System (4CAS) was coded by the author. In “Experiment 1” (Knecht, 2007), eight general aviation (GA) pilots flew nominal straight-line courses threatened by traffic. Comparing CDTI-only trials (with no conflict alert or resolution capability) to 4CAS+CDTI trials, with 4CAS present, average path length, maneuver onset time, and duration of pilot deviations were significantly shorter, maneuver complexity was lower, and enjoyability-of-use was reported as significantly greater. In “Experiment 2” (Knecht, 2008), using four matched-pair, mirror-image scenarios with higher traffic density, with 4CAS present, 12 GA pilots averaged shorter path lengths, smaller deviations from path, greater minimum separations, shorter maneuver onset time, fewer (and briefer) pilot deviations, fewer types and numbers of maneuvers made, and reported greater ease of avoiding traffic.

System improvements were made. Below, results of the latest-generation system are reported.

Experiment 3

Method

Participants. Twelve GA pilots volunteered with informed consent, nine male, three female. Median age was 46.0 (range 20-69, mean 45.2, SD 15.5), median flight hours 995 (range 100-13300, mean 2025, SD 3645). All pilots held a private license, eight held instrument ratings, five were certified as both Certified Flight Instructor (CFI) and Certified Flight Instructor-Instrument (CFII), five held Commercial ratings. One held the Air Transport Pilot (ATP) rating. All received \$50US for participating.

Apparatus. A part-task flight simulator similar to Knecht (2008) was used, based on Microsoft Flight Simulator (FS2004), with its Boeing 737-400 model and Artificial Intelligence (AI) Traffic. This simulated enroute air traffic and generated recordable latitudes, longitudes, headings, ground speeds, and vertical speeds for ownship and traffic.

The CDTI. A custom CDTI displayed a top-down, moving map of physical space, with ownship occupying

display-center. Traffic was depicted as chevrons aimed in the direction of travel. Text data tags showed traffic flight level (FL). Zoom buttons allowed selectable map widths/heights of 5-200 statute miles ([sm], 8-322 km). In CDTI-only mode, pilots clicked directly on the B737 autopilot to maneuver.

The CDTI updated and wrote data to file every 2.5 s., except during a *pilot deviation* (PD, [FAA, 2006]), that is during failure to maintain 5 NM/1,000 ft aircraft separation. Then, sampling rate increased to 25 Hz.

Experiment 3's CDTI differed from that of Experiments 1-2, in that its traffic icons were also linked to the 4CAS conflict probe. When ownship separation was threatened, CDTI traffic icons were also colored by time to contact, using the same color scheme as 4CAS. The intent was to present a more challenging, fairer comparison of the two displays, in that the CDTI now alerted for separation failure (although not for possible solutions).

4CAS. 4CAS showed the MS and CRs corresponding to real-time traffic. Each CR's translucent, colored, cubes depicted autopilot settings predicted to lose separation with traffic within 6.0 minutes. Cube color represented available maneuver time (minutes-to-predicted separation failure). Colors were based on three anchor RGB values, with intermediate values linearly interpolated. A color/time reference bar was displayed under the MS.

The MS was rotatable around its vertical and horizontal axes. A 3D planning cursor moved within MS, allowing selection of avoidance maneuver. To resolve a conflict, users simply positioned the 3D cursor in a black "safe" region of MS and then hit the "Execute" button. This reset the B737 autopilot, initiating the maneuver. The 3D cursor was translucent, and stayed put after maneuver planning. A smaller cube represented real-time values of heading/speed/altitude. After maneuver completion, the display recentered itself to again represent current autopilot settings as occupying MS-center. A message box displayed "NO MANEUVER NECESSARY," changing to the alert "MANEUVER!!" as necessary.

Task. The overall task was to stay generally on-course (path+altitude), deviating for traffic as necessary, returning to course when clear of traffic. A red dot at the end of the nominal flight path signified the "destination." For greater accuracy, program shutdown was automatic, triggered by point-of-closest approach to destination.

Experimental design. Repeated-measures were used, with scenario presentation order counterbalanced by Latin squares. Half the 12 pilots started in the CDTI-only condition, flying the first four scenarios, followed by a short break, followed by the CDTI+4CAS condition using mirror-image scenarios in the same presentation order. The remaining pilots ran similarly, but with the CDTI+4CAS first. Pilots were not told they would repeat scenarios.

Flight scenarios. Like Experiment 2, Experiment 3 employed straight-and-level "primary conflict" traffic generated via the custom Traffic Creation Utility. FS2004's AI Traffic mode was used only to create distractor and blocking traffic for a single "standard background." During experimental trials, unique primary traffic was added to the standard background to create each individual traffic scenario.

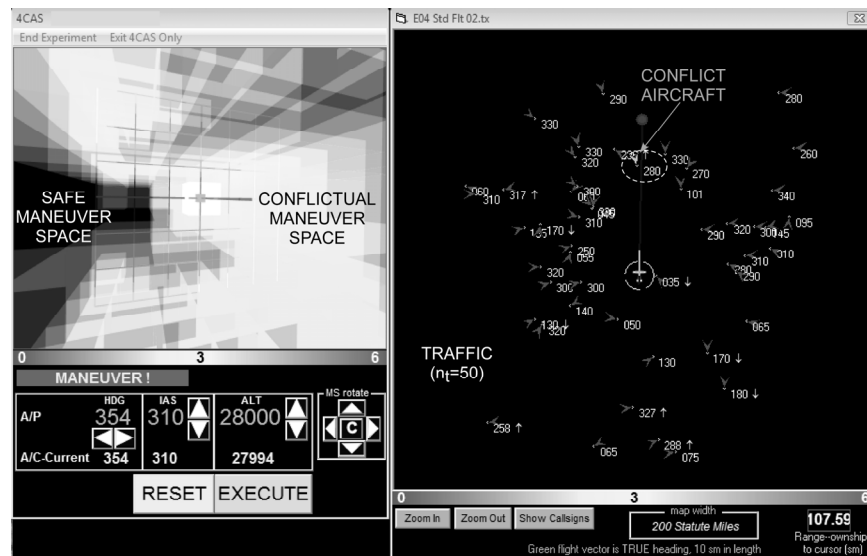


Figure 2. (Left) Annotated view of 4CAS display; (Right) CDTI, showing traffic from Experiment 4.

Figure 2 depicts scenario 2 (annotated, from Experiment 4). All Experiment 3 scenarios began in mid-flight, at 32,000 ft (FL 320), indicated airspeed (IAS) of 280 kt (.76 mach). Scenarios emulated enroute free flight (RTCA,

1995) in that aircraft were not restricted to normal odd-or-even flight levels by thousands (no “East-West Rule”).

The CDTI portrayed the ownship flying nearly north (354°). Each of the five 10-min base scenarios had a mirror-image (generated by affine transform) for use as the repeated measure. All primary traffic (generated by the Traffic Creation Utility) converged toward the ownship straight and level from various angles, shaping the conflict.

All scenarios were “close calls” in both heading and altitude. To test false alarms, one mirror-pair contained a near-conflict, but technically required no avoidance.

Within the CDTI’s maximum viewable area, each scenario maintained traffic density of 10-12 primary aircraft (median 11) plus an additional 11-16 secondary, distractor/blocking aircraft (median 12.5)—approximately double Experiment 1’s primary traffic density, and triple its overall density. One participant, a professional FAA ATC instructor, judged the overall traffic densities as “moderate” (his word) compared to real-life, everyday enroute traffic.

Dependent measures. These are shown in Table 1 and detailed in Knecht (2007, 2008).

Training. Training was brief, about 25-30 min. Pilots received a one-page instruction sheet describing the task. They next received a one-page description of the CDTI and one for 4CAS, as appropriate. They then practiced on two training scenarios as desired before starting data collection. After completion of three test scenarios, pilots received a short break, and then retrained similarly for the second half.

Results

Table 1 summarizes relative performance of CDTI-only trials versus 4CAS+CDTI trials for 12 participants x 5 trial-pairs each = 120 total trials. Distributional non-normalities dictated nonparametric statistics (Hollander & Wolfe, 1999)—Wilcoxon’s paired-ranks test, with McNemar’s test for false alarms. DVs 2-9 reflect matched-scenario pair difference scores (4CAS+CDTI trial – CDTI-only trial). DVs 2-4, 6-9 are significant in favor of 4CAS.

Table 1. Experiment 3, CDTI-only vs. CDTI+4CAS trials.

Dependent variable (DV) ⁽¹⁾	Median, (mean), or n (CDTI-only)	Median, (mean), or n (CDTI+4CAS)	P (2-tail)	P (1-tail)
Efficiency Measures				
1 False alarms ⁽²⁾	n=4	n=1	.250	
2 Unnormalized path length (sm) ⁽³⁾	64.533	64.450	.0001	
3 Normalized 3D path length (std units--SU) ⁽³⁾	12.146	11.971	.008	
4 3D maximum deviation from path (SU) ⁽³⁾	1.048	1.040	.085	.043
5 Rmin (scenarios w no PDs, n=74, SU)	1.097	1.233	.078	
Safety Measures				
6 Rmin (scenarios w ≥1 PD / pair, n=22, SU)	.987	1.240	.006	
7 Maneuver onset time (sec) ⁽³⁾	43.4	35.0	.031	
8 Pilot deviations (experiment-wide counts)	n=13	n=1	.008	
9 Pilot deviations, average duration (sec)	(19.1)	(7.6)	.010	

(1) Measures 2-7 compare matched scenario pairs.

(2) Computed only for the 2 scenarios per pilot where maneuver was unnecessary (n=24)

(3) Computed only for the 8 scenarios where maneuver was necessary (n=96)

Rmin is the scenario-wide 3D normalized minimum range between ownship and traffic (Knecht and Hancock, 1999) where *x*- and *y*-differences reflect lateral separation (NM), and *z* reflects altitude differences (ft). *Rmin* can be used bimodally, as a measure of efficiency when separation is legal, and as a measure of safety when separation fails. Used as an efficiency measure, only *error-free* scenarios were averaged (no PDs). Less separation therefore implies greater efficiency, with no violation of mandated separation. Used as a safety measure, only *error* scenarios were averaged (those with PDs). Therefore, more separation implies greater safety.

Individual differences. Given that the CDTI now gave conflict alert, nine of 12 pilots in the CDTI-only condition independently discovered an interesting *maneuver titration* strategy. For example, a pilot might start a turn to solve a conflict. If, after completing that turn, the CDTI still showed conflict, the turn was increased by a degree or two, “titrating” the maneuver until the traffic icon changed color to indicate conflict resolution.

In many cases, maneuver titration proved efficient—sometimes more efficient than using 4CAS, if DV5, (Table 1) is all we consider. However: 1) DV2-3 were significant in favor of 4CAS, whereas DV5 was only a trend in favor of the CDTI; 2) Titration appeared significantly less safe (DV6-9); 3) If the pilot picked an inefficient maneuver to start with (e.g., a left turn instead of a more-efficient right turn)—then, titration exacerbated that inefficiency.

Experiment 4

Method

Participants. Eight licensed GA pilots volunteered with informed consent, seven male, one female. Median age was 50.0 (range 38-61, mean 48.6, SD 7.1), median flight hours 650 (range 138-1503, mean 729, SD 581). Four held instrument ratings, one was a Certified Flight Instructor (CFI), two held Commercial ratings. All received \$50US.

Apparatus. The apparatus of Experiment 3 was used, with one exception: 4CAS was enhanced to subtract ownship maneuver execution time from time to contact. Maneuver execution time data were collected for a wide range of off-nominal maneuvers ($\pm 45^\circ$ heading, ± 35 kt IAS, and $\pm 4000'$ altitude). Separate *h,s,a* modeling functions were parameterized by minimizing least-squares fit to FS2004 performance data. Log functions were selected to represent heading and speed changes. A linear function was selected for altitude changes. Modeling functions were coded into the 4CAS/CDTI time-to-contact algorithm, and allowed estimation of maneuver execution time to <10 sec accuracy.

Task, experimental design, dependent measures and training. These were similar to Experiment 3.

Flight scenarios. These were similar to Experiment 3, with a few exceptions. First, ownship starting altitude was lowered to 28,000' to allow more headroom, with initial speed set at 310 kt IAS (.76 Mach). Second, with false alarm rate having been explored in Experiments 1-3, the no-conflict scenarios were deemed unnecessary. Four mirror-image conflict scenario pairs were therefore tested per pilot.

Finally, traffic density was more than doubled from Experiment 3. Primary traffic was 24-28 aircraft (median 25.5), plus an additional 20-27 secondary, distractor/blocking aircraft (median 23.5). One participant, a professional FAA ATC tower control instructor, judged the overall densities as "heavy" (his word) compared to real-life, East-coast traffic (itself some of the U.S.' heaviest traffic).

Results

Table 2. Experiment 4, CDTI-only vs. CDTI+4CAS trials.

Dependent variable ⁽¹⁾	Median, (mean), or <i>n</i> (CDTI-only)	Median, (mean), or <i>n</i> (CDTI+4CAS)	P (2-tail)
Efficiency measures			
1 Unnormalized path length (sm)	65.998	65.628	.002
2 Normalized 3D path length (std units, SU)	12.717	11.714	.0002
3 3D maximum deviation from path (SU)	1.287	.696	.00004
4 Rmin (scenarios w no PDs, <i>n</i> =38, SU)	1.075	1.105	.872
Safety Measures			
5 Rmin (scenarios w ≥ 1 PD / pair, <i>n</i> =26, SU)	.944	1.047	.028
6 Maneuver onset time (sec)	36.6	29.1	.001
7 Pilot deviations (experiment-wide counts)	<i>n</i> =17	<i>n</i> =4	.028
8 Pilot deviations, average duration (sec)	(20.7)	(4.0)	.002

(1) Measures 1-6 compare matched scenario pairs.

Table 2 summarizes the relative performance of CDTI-only trials versus 4CAS+CDTI trials for 8 participants x 4 trial-pairs each = 64 total trials. Measures 1-3, 5-8 are significant in favor of 4CAS.

Individual differences. Here, six of eight individuals titrated their maneuvers in the CDTI-only condition. With a correct initial guess, the results were generally good. However, incorrect guesses led to far more effort with far poorer results. Given the high traffic density and complexity, incorrect guesses were common.

Discussion

Veridical means "coinciding with, or representing, physical reality." *Maneuver space* is defined here as a 4D nonveridical state space unique to each aircraft, dimensionalized by that aircraft's a) heading, b) speed, c) altitude, and d) available maneuver time. Maneuver space represents conflictual and non-conflictual maneuvers achievable by that aircraft within a fixed period of time, given obstacles predicted along each potential maneuver's path.

This work constitutes Experiment 3 and 4 in a series of tests of a nonveridical, MS-based 4D collision avoidance system called 4CAS. 4CAS is not meant to replace veridical traffic displays—merely to augment them.

In Experiment 3, 12 licensed GA pilots flew five matched-pair, mirror-image scenarios with traffic and geometry similar to Experiment 2. To provide a more competitive comparison, the CDTI was enhanced to add conflict

alert (but not resolution) capability. The CDTI+4CAS condition showed performance superiority over the baseline CDTI for three out of five dependent measures of maneuver efficiency, and four of four measures of maneuver safety.

In Experiment 4, eight licensed GA pilots flew four matched-pair, mirror-image scenarios with very heavy traffic (median=49)—double that of Experiment 3. Maneuver execution time was subtracted from the available maneuver time on both displays. The CDTI+4CAS condition showed performance superiority over the baseline CDTI for three out of four dependent measures of maneuver efficiency, and four of four measures of maneuver safety.

Taken together, the entire series of four experiments suggests that human operators can safely, effectively use such a 4D nonveridical aircraft maneuver safety display.

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References

- Azuma, R., Neely III, H., Daily, M., & Correa, M. (1999). Visualization of conflicts and resolution in a “free flight” scenario. *Proceedings of IEEE Visualization '99* (pp. 433-436, 557).
- Canton, R., Refai, M., Johnson, W.W., & Battiste, V. (2005). Development and integration of human-centered conflict detection and resolution tools for airborne autonomous operations. *Proceedings of the 13th International Symposium on Aviation Psychology* (pp. 115-120). Columbus, OH: Ohio University Press.
- Federal Aviation Administration. (2006). *Order 7110.65R Air traffic control*. Washington, DC: Author.
- Granada, S., Quang Dao, A., Wong, D., Johnson, W.W., & Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit situation display for distributed air-ground operations. *Proceedings of the 13th International Symposium on Aviation Psychology*. (pp. 279-284). Columbus, OH: The Ohio University Press.
- Green, S.M., & Vivona, R.A. (2001, August). *En route Descent Advisor Concept for Arrival Metering*. Guidance, Navigation, and Control Conference, Montreal, Canada.
- Hollander, M., & Wolfe, D.A. (1999). *Nonparametric statistical methods* (2nd ed.). New York: Wiley.
- Johnson, W.W., Battiste, V., & Holland, S. (1999). A cockpit display designed to enable limited flight deck separation responsibility. *SAE Transactions, Journal of Aerospace*, 108(1), 1041-1062.
- Knecht, W.R. (2007). Testing a nonveridical aircraft collision avoidance system: Experiment 1. *International Journal of Applied Aviation Studies*, 7(1), 60-82.
- Knecht, W.R., & Hancock, P.A. (1999). Separation maintenance in high-stress free flight using a time-to-contact-based cockpit display of traffic information. *Proceedings of the 4th Annual Meeting of the Human Factors and Ergonomics Society*. (pp. 16-20). Santa Monica, CA: Human Factors and Ergonomics Society.
- Knecht, W.R., & Smith, K. (2001) The manoeuvre space. In D. Harris (Ed.), *Engineering psychology and cognitive ergonomics*. Aldershot: Ashgate.
- Krozel, J. (2000). *Free flight research issues and literature search*. Los Gatos, CA: Seagull Technology.
- Kuchar, J.K., & Yang, L.C. (2000). A review of conflict detection and resolution modeling methods. *IEEE Transactions on Intelligent Transportation Systems*. 1(4), 179-89.
- Naikar, N. (1998). *Perspective displays: A review of human factors issues*. Retrieved December 13, 2006 from Australian Government, Dept. of Defense, Defence Science and Technology Organisation Web site: <http://www.dsto.defence.gov.au/publications/2069/DSTO-TR-0630.pdf>.
- Pekela, W.D., & Hilburn, B. (1998, Sept). *Air traffic controller strategies in resolving free flight traffic conflicts: The effect of enhanced controller displays for situation awareness*. AIAA and SAE World Aviation Conference, Anaheim, CA.
- Radio Technical Commission for Aeronautics (January, 1995). *Report of the RTCA board of directors' select committee on free flight*. RTCA, Incorporated, Washington, DC.
- Thomas, L.C., & Wickens, C.D. (2005). Display dimensionality and conflict geometry effects on maneuver preferences for resolving in-flight conflicts. *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*. (pp. 40-44). Santa Monica, CA: Human Factors and Ergonomics Society.
- Van Dam, S.B.J, Appleton, R., Mulder, M., & van Paassen, M.M. (2006, September). *Comparison of two interfaces for supporting pilots in airborne self-separation tasks*. International Conference on Human-Computer Interaction in Aeronautics, Seattle, WA.
- van Gent, R.N.H.W., Hoekstra, J.M., & Ruigrok, R.C.J. (1998, May). *Free flight with airborne separation assurance: A man-in-*

the loop simulation study. International Conference on Human-Computer Interaction in Aeronautics, Montreal, Canada.