

COMPARISON OF PILOTS' AND CONTROLLERS' CONFLICT RESOLUTION MANEUVER PREFERENCES

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The role of the air traffic controller in future air traffic management systems is that of a passive monitor, who intervenes in potential conflict situations only if pilots, aided by onboard traffic displays, fail to implement safe and timely conflict resolutions. Yet, such scenarios are entirely plausible and even likely, particularly in busy airspaces. However, it is also likely that an air controller will seek to implement a resolution that is different from what the pilots had planned, resulting in confusion, delays, and safety risks. This paper examines pilots' and controllers' maneuver preferences and potential sources for dissonance in conflict resolution situations. Data on pilots' maneuver tendencies were gathered from an extensive review of past literature; controllers' preferences were obtained from an experiment that systematically manipulated simulated ATC scenario difficulty and conflict geometries. Results indicate largely similar maneuver choices between controllers and pilots, but suggest a need for further research.

INTRODUCTION

The present efforts for the National Airspace System (NAS) modernization rely heavily on the concept of free flight, which represents a historical paradigm shift in the sharing of responsibility of the safety of flight between cockpit crews and ground-based air traffic controllers. The key component necessary for this shift is the cockpit display of traffic information (CDTI), which will offer pilots a detailed view of other aircraft in the vicinity of their 'ownship' as well as various automated tools for effective conflict detection and resolution (Battiste & Johnson, 1998; Johnson, Battiste, & Bochow, 1999; Johnson et al., 1997). Unlike the Traffic Alert and Collision Avoidance System (TCAS), which provides pilots with automated resolution advisories (RAs) merely seconds before impending collision, CDTI allows for up to 20 minutes look-ahead time and strategic planning of conflict avoidance maneuvers. Given this time and consequently availability of alternative maneuvers, it is plausible and in the light of evidence indeed likely that pilots' maneuver choices are subject to idiosyncratic biases and preferences.

The role of the air traffic controller in the mature free flight environment, on the other hand, is that of a system monitor, intervening only if pilots do not implement safe and timely conflict avoidance maneuvers (Dekker & Woods, 1999; Metzger & Parasurman, 2005; Wickens, Mavor, Parasuraman, & McGee, 1998). Also controllers will be aided by automation. However, differently timed alerts and different solutions suggested by airborne and ground-based systems may cause undesirable behaviors and performance decrements in the human operators involved in the conflict (Song & Kuchar, 2003). A recent example of such dissonance between airborne TCAS and ground-based air traffic control (ATC) is the 2002 mid-air collision occurred between a Russian passenger jet and a DHL cargo jet over the Swiss-German border. Yet, it is not sufficient to synchronize different alerting systems and their respective algorithms, as daunting as that task may be. Given the strategic nature of future air traffic management (ATM) operations it is likely that both human pilots and air traffic controllers or -managers will preempt automated aids and devise

conflict resolutions unaided and independently from each other. Few such solutions may need to be eventually implemented, but in case a controller needs to intervene in conflict resolution, dissonance between pilot's and controller's respective solutions may cause delays and misunderstandings. Therefore, it is imperative that also unaided human performance in conflict resolution is studied.

PILOTS' MANEUVER PREFERENCES

Pilots' maneuver preferences and tendencies for conflict resolution have been reported in numerous studies (see Rantanen, Wickens, Xu, & Thomas, 2004 and Thomas & Rantanen, 2006, for a review), although paucity of empirical data particularly in high fidelity pilot-in-the-loop simulations makes systematic investigation of the topic difficult. From a reasonably large body of literature, however, some conclusions may be drawn.

Time-pressure appears to be an important driver of the kinds of maneuvers that pilots choose to use with a CDTI (maneuver tendency) to avoid conflicts with other traffic. It is also important to consider some of the inherent properties of maneuvers on the three different axes defined by the vertical (climbs vs. descents), lateral (turning) and longitudinal (slowing or speeding) dimensions that can be used to avoid a loss of separation. Furthermore, it should also be kept in mind in that current FAA regulations (CFR 91.113) dictate procedures only for lateral maneuvering and that TCAS (which can be seen as a precursor to CDTI and which is standard—and indeed mandatory—equipment in today's cockpits) directs only vertical maneuvers.

Early CDTI research using commercial aircraft simulators offers mixed evidence about pilots' maneuver preferences in traffic avoidance scenarios using a CDTI. Some results point to lateral preference (Smith, Ellis, & Lee, 1984; Ellis, McGreevy, & Hitchcock, 1987) while other results suggest vertical preference over lateral maneuvers (Abbott et al., 1980; Chappell & Palmer, 1983). Palmer (1983) found that increased time pressure eliminated a lateral preference, which is consistent with a set of studies carried out at University of Illinois, in-

volving GA pilots with light aircraft handling dynamics, and relatively shorter (less than 2 minute) look-ahead time for the CDTI. All of the Illinois studies show a strong preference for vertical maneuvers over both lateral and airspeed maneuvers (Wickens, Gempler, & Morphew, 2000; Merwin & Wickens, 1996; O'Brien & Wickens, 1997; Alexander & Wickens, 2001, 2002; Wickens, Helleberg, & Xu, 2002; see Merwin, Wickens, & O'Brien, 1998; Alexander, Merwin, & Wickens, 2005, for summary reviews).

It may also be concluded from all of the Illinois studies that pilots avoided making airspeed maneuvers. Of other research, only Chappell and Palmer (1983) found that pilots preferred airspeed adjustment to avoid conflicts; in other experimental studies airspeed was not an option available to pilots.

The general tendency to favor vertical maneuvering over both lateral and airspeed maneuvering under time pressure is consistent with two particular characteristics that differ across the three axes. Vertical maneuvering can more rapidly avoid a loss of separation than can airspeed maneuvering, and airspeed maneuvering in turn is more time effective than lateral maneuvering (Krozel & Peters, 1997). This is consistent with the control order of dynamic systems (Wickens, 1986): vertical maneuvering is a 2nd order control of position, airspeed is a 2nd order control with a substantial lag, and lateral is a 3rd order control. Higher control orders impose greater lag to change position. Higher control orders also impose greater cognitive complexity on pilots trying to visualize the effectiveness of the maneuvers (Wickens, 1986). Thus lateral maneuvers are more complex than vertical ones. Effects of speed adjustments realized with considerable lags and they are difficult to visualize on a CDTI representing space, while speed directly affects time.

The preference of vertical over airspeed and lateral maneuvers under time pressure can hence be understood in terms of desire to avoid maneuvers that take longer to accomplish and also result in high cognitive workload. For the same reason, pilots also tend to avoid complex dual axis maneuvers (e.g., climbing or descending turns, or changing airspeed while turning).

Despite the very valid and understandable reasons to prefer vertical conflict avoidance maneuvers, past research that has measured safety suggest that vertical maneuvers are less safe than lateral maneuvers (Wickens, Helleberg, & Xu, 2002; Alexander & Wickens, 2001, 2002), leading to longer time 'in conflict'. The explanation may be that because their lower order and quicker effect, vertical maneuvers can be accomplished later (closer to predicted loss of separation) than lateral maneuvers, making them more flexible. Hence, pilots may simply initiate vertical maneuvers later than other maneuvers, offsetting their speed advantage.

From the above review of literature on pilots' conflict avoidance maneuvering preferences it is clear that very few or definitive conclusions may be drawn. Cockpit procedures and pilots' conflict avoidance performance—aided by both displays and automated conflict detection and avoidance systems—is an area in a need for more research. However, to our knowledge, however, air traffic controllers' respective preferences for conflict resolution maneuvers have been studied even less. The purpose of this research was to examine sys-

tematic biases in controllers' maneuver choices under different conflict geometries and traffic situations.

CONTROLLERS' MANEUVER PREFERENCES

Even under mature free flight and with fully functional CDTIs and other airborne systems, pilots' task of traffic avoidance are likely to remain very different from that of air traffic controllers. Pilots' primary concern is their own aircraft and their attention will hence in all likelihood be limited to only those other aircraft that pose a threat of loss of separation in an immediate future. On the other hand, air traffic controllers are primarily concerned of the 'big picture' and work to create traffic flows that are conflict-free in much longer time spans than pilots. Furthermore, controllers always have multiple aircraft and multiple potential conflicts to monitor, and hence management of their own workload has a high priority. It may hence be hypothesized that controllers will implement conflict resolutions much earlier than pilots and that their maneuver preferences primarily reflect guarding against excessive workload and maintenance of orderly flows of air traffic.

Method

Subjects. A total of 51 air traffic controller trainees from the Civil Aviation Flight University of China participated in the experiment.

Apparatus. A custom-designed ATC simulator was used for the experiment. The simulation program was written in C++ and ran on desktop PCs. The simulator mimicked the display system replacement, which is currently replacing the plan view displays in U.S. en route centers. A simulated data link provided communications between controllers and computer-generated aircraft.

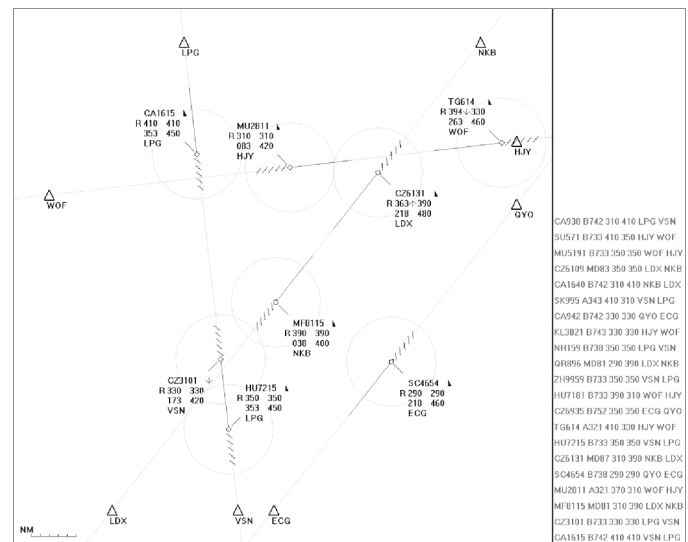


Figure 1. A screenshot from an experimental scenario. Aircraft traversed across a fictional en route sector along four bidirectional airways. Conflicts occurred at different angles at airway intersections, as well as on the same airway in opposite and overtaking situations.

Design. All participants controlled traffic in four 30-minute scenarios using the same airspace (Figure 1). Traffic traversed along four airways across a simple sector, with conflicts occurring at airway intersections or along the same airways. Conflict angles were thus 0° (overtaking), 50°, 90°, 130°, and 180° (opposite). Scenario (and conflict resolution) difficulty was also manipulated the number of aircraft, number of climbing and descending aircraft, required vertical separation minima (1,000 or 2,000 ft), and timing of events (simultaneously unfolding events increased complexity). The four experimental conditions are depicted in Table 1. The computer recorded and time-stamped all controller actions. The simulator also included a conflict detection algorithm that recorded a time to conflict between two aircraft.

Table 1
Design parameters of the experimental scenarios

Parameter	Scen_1	Scen_2	Scen_3	Scen_4
No. Aircraft	17	30	21	37
Scenario Complexity	Simple	Simple	Complex	Complex
Mean No. of Simul. Acft	4.59	8.39	4.31	8.39
SD No. of Simul. Acft	1.38	2.09	1.03	1.91
Max No. of Simul. Acft	7	11	6	11
Proportion climb/desc	0.00	0.40	0.00	0.43
Mean Gnd Spd of Acft	329.59	319.67	427.14	436.89
SD of Gnd Spd of Acft	27.23	29.88	27.04	23.67
No. of DL Requests	6	6	6	6
Total No. of Conflicts	5	8	13	21
No. Conflicts, CA = 45	3	1	2	0
No. Conflicts, CA = 90	1	2	2	2
No. Conflicts, CA = 135	0	0	3	6
No. Conflicts, CA = 0	0	0	3	0
No. Conflicts, CA = 180	1	5	3	13

Results

All conflicts were recorded by the simulator and matched with subsequent controller actions. The subjects performed a total of 630 conflict resolutions across the scenarios. There was a strong preference for vertical maneuvers, with 75.7% of conflict resolutions involving either climb (39.9%) or descend (35.7%) commands, in almost equal proportions. Speed control was used in 19.4% of conflict resolutions, with speed decrease more popular than increase (12.8% vs. 6.5%, respectively). Vectoring (heading changes) was used in only 5% of the resolutions, with no difference between left and right turns.

Conflict geometry resulted in some appropriate maneuver preferences. Speed control was used in the same-heading cases more than in other conflict angles and vectoring was used more in the acute conflict angles than others. With respect to vertical geometries, controllers did not reverse the aircrafts' vertical trajectories, that is, ask descending aircraft to climb or climbing aircraft to descend. Otherwise, the maneuver choices appeared not to have been affected by conflict geometry.

There were no significant differences in maneuver preferences between the scenarios, that is, the controllers did not hesitate to command altitude changes in scenarios where all traffic were in level flight (scenarios 1 and 2) or prefer vertical

maneuvers more in scenarios where aircraft were climbing or descending when entering the sector (scenarios 3 and 4). Taskload imposed on the controllers did not affect maneuver choice, either, nor did the requisite 2,000-ft vertical separation minimum in scenarios 3 and 4 deter controllers from applying vertical separation in these scenarios.

The controllers acted on an impending conflict on the average about 3 minutes prior to loss of separation (LOS). These times are probably low due to the experimental setting with a relatively small sector and heavy traffic load, also in the easiest condition (scenario 1). There were no significant differences between applications of different maneuvers, although speed changes were commanded slightly earlier than heading and altitude changes. This was entirely appropriate, as speed changes take longer to achieve their desired effect than altitude or heading changes. There were, however, significant differences between scenarios (taskload conditions), analyzed by a mixed-model ANOVA, with subject as a random factor, $F(3, 612) = 34.48, p < .001$. In the lowest taskload scenario controllers implemented conflict resolutions 4.1 minutes prior to LOS but only 2.6 minutes prior to LOS in the most difficult condition (scenario 4). Pairwise comparisons (Tukey's test) showed that scenario 1 was significantly different from all other scenarios, and scenario 3 (mean = 2.94 s) different from scenario 4. There were no statistically significant differences between subjects ($F < 1$), suggesting a homogenous subject population.

DISCUSSION

The results were not completely unexpected. There are powerful and valid reasons for application of vertical separation in conflict situations, for these provide controllers with a fail-safe solution to conflicts. There exists evidence for controllers' preference for vertical separation in other contexts (Rantanen & Nunes, 2005) and the present experiment shows that they also seek to actively apply vertical separation whenever possible. That this was the case also in the easiest scenario with lowest taskload, as well as in the complex scenarios with 2,000 ft vertical separation minima (which would make vertical separation more difficult to implement) attests to the strength of this preference. From review of the literature on pilots' maneuver tendencies it appears that the same reasons are also behind controllers' maneuver choices, although some important differences were also found (e.g., time pressure seemed not to have an impact on controllers' maneuver choices but it has been shown to increase tendency for vertical maneuvers for pilots).

Vectoring (lateral maneuvers) was the least popular resolution maneuver. The most plausible explanation for this is that vectoring necessarily increases controllers' workload, as by such maneuvers they also assume navigation responsibility for the aircraft. Hence, turning an aircraft on a heading to avoid a conflict automatically requires closely monitoring the aircraft and providing the pilot with rerouting instructions for resumption of own navigation in a timely manner (as soon as the conflict has been resolved). Furthermore, in the airspace employed in this experiment, diverting aircraft away from their planned routes (i.e., airways) necessitated careful check-

ing that it would not result in conflict with aircraft in adjacent routes. Vertical (altitude) or longitudinal (speed) maneuvers preserved traffic flows along regular routes and thus reduced the problem space for the controller to those routes and their intersections, greatly simplifying their monitoring task.

There are, however, multitude of factors present in each conflict situation and analyses as presented here are still too superficial to allow drawing of definite conclusions. Further research is therefore recommended where controllers and pilots are presented identical conflict situations and allowed to work out their own solutions to them. Only such direct comparisons would reveal whether there are dangerous dissonances between airborne and ground-based conflict resolutions. Finally, the importance of structure in traffic flows was clearly evident in controllers' preference to limit conflict resolution maneuvers to regular, predetermined routes in our experiment. Under the envisioned free flight such structures will largely disappear. Implications of lack of structure on controllers' workload and their ability to intervene quickly and effectively if pilots are unable to resolve impending conflicts should be carefully examined before expanding free flight procedures to busy airspaces where such interventions may become necessary.

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