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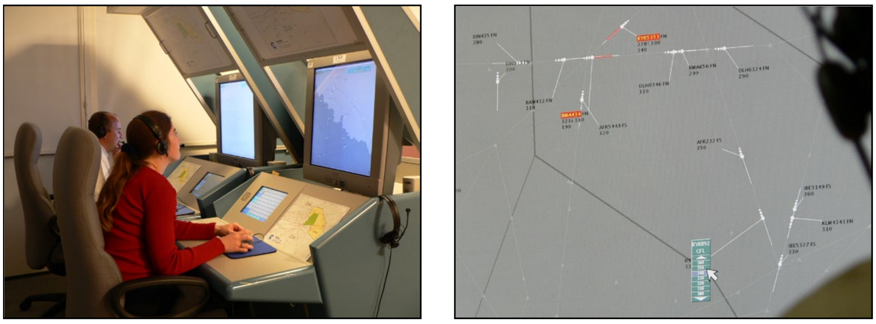
Executive summary

Downlink of TCAS Resolution Advisories: A means for closing the gap between pilot and controller?



RADE-2A Experiments at the E*UROCONTROL Human Factors Lab*

Problem area
The Traffic alert and Collision Avoidance System (TCAS) is the last resort system safety defence against mid-air collisions. TCAS interrogates the transponders of nearby aircraft in order to determine an imminent risk of collision. If TCAS considers another aircraft to be a potential threat, a 'Traffic Advisory' (TA) will be issued to enhance the pilots' situational awareness. TAs do not require any manoeuvres. If a risk of collision is established, TCAS will issue a 'Resolution Advisory' (RA) which instructs the pilots on how to change their vertical rate to avoid a collision. In case both aircraft involved in an encounter receive an RA, these RAs are automatically coordinated. Currently, a controller only becomes aware of an RA if he/she is informed by the pilot. However, it has been empirically established that pilot reports of an RA are often incomplete, incorrect, delayed, or even absent.

In the absence of a timely or complete pilot report, the controller might issue an instruction to the aircraft with the RA. In the worst case, the issued clearance instructs the pilot to manoeuvre in a sense contrary to the RA. Although specifically mandated not to, pilots in some cases follow the ATC clearance rather than the RA. Compliance with a contradictory ATC clearance severely degrades TCAS benefits and, in the worst case, can result in a mid-air collision.

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The mid-air collision over Überlingen in July 2002 illustrates such a situation in a tragic way: Ultimately, the collision between the Boeing 757 and the Tupolev 154 was caused by the decision of the Tupolev crew to follow the (contradictory) ATC instruction rather than the RA. The accident investigation report noted that, at the time of issuing the clearance, the controller was unaware that both aircraft had received an RA.

Description of work

This article describes two empirical studies - an initial study and an experiment - that investigate the impact of displaying Resolution Advisories (RAs), issued by the onboard Traffic alert and Collision Avoidance System (TCAS), to the controller, the so-called Resolution Advisory Downlink Experiments Part 2 (RADE-2). The initial study served to assess and refine a method for evoking RA events in an interactive and realistic air traffic control setting. Using this method, an experiment was conducted to systematically assess the operational impact of RA downlink.

Results and conclusions

The experiment provided evidence for operational benefits of RA downlink, in terms of a lower number of contradictory clearances to aircraft involved in an RA and a better recollection of RA events caused by pilot or controller error. Furthermore, there was no evidence for negative effects of RA downlink, such as cognitive tunneling on the RA event.

Applicability

The RADE-2 studies were the first ATC simulations to systematically assess RA events in an interactive environment. Whereas the initial study served to test the feasibility of the experimental approach, the experiments themselves served to assess the impact of RA downlink on the controllers and their ability to separate traffic.

The RADE-2 initial study and experiment can be considered a successful step in the evaluation of RA downlink and its impact on controller behaviour.

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Downlink of TCAS Resolution Advisories: A means for closing the gap between pilot and controller?

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Downlink of TCAS Resolution Advisories: A means for closing the gap between pilot and controller?

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1 Abstract

The article describes two empirical studies – an initial study and an experiment - that investigate the impact of displaying Resolution Advisories (RAs), issued by the onboard Traffic alert and Collision Avoidance System (TCAS), to the controller. The initial study served to assess and refine a method for evoking RA events in an interactive and realistic air traffic control setting. Using this method, an experiment was conducted to systematically assess the operational impact of RA downlink. The experiment provided evidence for operational benefits of RA downlink, in terms of a lower number of contradictory clearances to aircraft involved in an RA and a better recollection of RA events caused by pilot or controller error. Furthermore, there was no evidence for negative effects of RA downlink, such as cognitive tunnelling on the RA event.

2 Introduction

The Traffic alert and Collision Avoidance System (TCAS)[1] is the last resort system safety defense against mid-air collisions. TCAS interrogates the transponders of nearby aircraft in order to determine an imminent risk of collision. If TCAS considers another aircraft to be a potential threat, a 'Traffic Advisory' (TA) will be issued to enhance the pilots' situational awareness (note that TAs do not require any manoeuvres). If a risk of collision is established, TCAS will issue a 'Resolution Advisory' (RA) which instructs the pilots on how to change their vertical rate to avoid a collision. In case both aircraft involved in an encounter receive an RA, these RAs are automatically coordinated. The implementation of TCAS was prompted by a number of tragic mid-air collisions between 1950 and 1980 (FAA, 2000). Today, the majority of commercial aircraft operating in the European airspace are required to be equipped with TCAS (ICAO, 2007a).

2.1 Implication of RAs for the Pilot and the Controller

The existence of a TCAS RA has direct consequences for the tasks of the aircrew and the air traffic controller: Pilots are required to immediately comply with all RAs, even if the RAs are contrary to ATC clearances or instructions. Furthermore, as soon as permitted by workload, pilots are required to notify Air Traffic Control (ATC) of the RA, including the direction of any deviation from the ATC clearance (ICAO, 2007b). The controller, on the other hand, is not allowed to modify the aircraft flight path once a pilot reports a maneuver induced by an RA, until the pilot reports returning to the previous ATC clearance (ICAO, 2007c). Thus, the occurrence of an RA in the cockpit fundamentally changes the controller's task: In normal conditions (i.e., without an RA), the controller's first and foremost task is to ensure separation of traffic by actively modifying the aircraft flight path, if required. With an RA, in contrast, the controller should not try to ensure separation of the affected aircraft any more.

Currently, a controller only becomes aware of an RA if he/she is informed by the pilot. However, it has been empirically established that pilot reports of an RA are often incomplete, incorrect, delayed, or even absent. An analysis of air proximity occurrences (Airprox) investigated by the Swiss Aircraft Accident Investigation Bureau between 1999 and 2003 revealed that only 28% of the RAs are reported correctly and timely (Rome, Cabon,

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1) TCAS is the only implementation of an Airborne Collision Avoidance System (ACAS). For the understanding of this paper, the terms ACAS (the standard) and TCAS (the implementation) can be considered synonymous.

(http://www.bfu.admin.ch/en/index.htm). The reason for the low reliability of pilot reports is most likely the high level of stress and workload in the cockpit when an RA is issued Favresse, Mollard, Figarol, & Hasquenoph, 2006). Furthermore, the RA report has a lower priority for the pilot than other RA related tasks, in particular, complying with the RA and trying to avoid a potential collision.

2.2 RAs and Contradictory ATC Clearances

If, however, the controller is unaware of the RA, he/she is also unaware of the change in their task, that is, a shift from active control to merely monitoring the conflicting aircraft. In the absence of a timely or complete pilot report, the controller might issue an instruction to the aircraft with the RA (Garcia-Chico & Corker, 2007). In the worst case, the issued clearance instructs the pilot to maneuver in a sense contrary to the RA. Although specifically mandated not to, pilots in some cases follow the ATC clearance rather than the RA (Eurocontrol, 2006; Swiss Aircraft Accident Investigation Bureau, 2005). Compliance with a contradictory ATC clearance severely degrades TCAS benefits and, in the worst case, can result in a mid-air collision.

The mid-air collision over Überlingen in July 2002 illustrates such a situation in a tragic way: Ultimately, the collision between the Boeing 757 and the Tupolev 154 was caused by the decision of the Tupolev crew to follow the (contradictory) ATC instruction rather than the RA. The accident investigation report noted that, at the time of issuing the clearance, the controller was unaware that both aircraft had received an RA (BFU, 2004).

3 Displaying RAs to the Controller

In order to make controllers’ notification of an RA more reliable, it has been proposed to downlink RA information to the ATC system and display it at the Controller Working Position (CWP) (e.g., AGAS, 2003). Technically, downlinking RAs is straightforward and, to a certain extent, already in place: Whenever an RA is generated on board, the aircraft’s transponder provides information about the RA (ICAO, 2007d). This information is received by the ground station through Mode-S radar. So far, RA information is only used for off-line monitoring and analysis, but not displayed to the controller.

3.1 Previous Work on RA Downlink

A number of studies have been conducted in order to assess the feasibility and the operational benefits of RA downlink. In the United States, a series of simulated and live trials were conducted in Baltimore and Boston between 1994 and 1997 (Hoffman, Kaye, Sacher, Carlson, 1995; Walsh, 1997). During the Boston trials, RAs that occurred in real traffic were displayed to controllers in charge of the sector. A total of 2652 RAs were downlinked, and the results concerning technical aspects (i.e., the downlink delay) as well as operational aspects (i.e. controllers' perception of benefits) were rather positive. Because of incompatibilities between existing regulations and RA downlink, though, the FAA's Air Traffic Office decided against the implementation of RA downlink: according to the regulations, controllers are not entitled to issue a clearance to an aircraft, once the aircrew has reported an RA. As RA downlink is not an aircrew report, it does not have any relevance for the question of whether the controller is allowed to issue a clearance. In spite of this, RA downlink might mislead the controllers into believing that they are not responsible for separation.

In France, RA downlink was studied by the Centre d'Études de la Navigation Aérienne (CENA) within the 'Visual Interface for Controllers for the Transfer of Resolution Advisories' (VICTOR) project, carried out in 1994. During the project, a real-time simulator mock-up was developed. Following demonstrations to operational staff, it was noted that RA downlink can, in some situations, increase the controller's understanding of the traffic situation. However, it was concluded that the benefits were too limited to consider the implementation of RA downlink (Moura & Casaux, 1994; Casaux, 1994). Moreover, and similar to the discussion in the USA, it was feared that RA downlink could introduce uncertainty in whether or not the controller is allowed to modify the flight path of the RA aircraft.

In Japan, a near mid-air collision between a DC-10 and a Boeing 747 over Yaizu in January 2001 prompted the Japan Civil Aviation Bureau to investigate the implementation of RA downlink. The Yaizu near miss had been caused by a pilot following the ATC clearance, rather than the TCAS RA suggesting a maneuver in the opposite direction. Like in the Überlingen accident, the controller was not aware that the pilot of the aircraft involved had received an RA in the opposite sense (ARAIC, 2002). The Japanese study concentrated on technical issues concerning the transmission of Mode-S data. To date, there is no information available on the progress of this study.

Thus, empirical studies on RA downlink are still rather scarce. In case they were conducted, the conclusions do not seem compelling. First, the introduction of a new service usually requires an adaptation of the associated procedures and regulations. Stating that a service only delivers limited benefits or could introduce ambiguity if the existing procedures and regulation are maintained, does not fundamentally question the benefit of the service as such. Second, the claim that benefits are very limited appears premature. None of the studies conducted so far systematically contrasted the current situation (i.e., no RA downlink) with RA downlink. Moreover, none of the studies systematically measured operational impacts. These operational impacts refer, above all, to the number of contradictory clearances: if the controller is informed by downlink about the RA, it is unlikely that, given he/she issues a clearance, this clearance is contradictory to the RA. Another potential impact refers to the controller’s ability to predict the evolution of the traffic situation, thereby facilitating the detection of follow-up conflicts.

3.2 The FARADS Project

The Überlingen accident in 2002 has led to a number of recommendations to investigate in detail the feasibility of RA downlink, most notably from the German Federal Bureau of Aircraft Accidents Investigation (BFU, 2004) and the High-Level European Action Group for ATM Safety (AGAS) (AGAS, 2003). As a consequence of these safety recommendations, Eurocontrol initiated the Feasibility of TCAS Resolution Advisory Downlink Study (FARADS).

Within the scope of FARADS, a set of experiments – referred to as the Resolution Advisory Downlink Experiments (RADE) – was conducted. A first experiment, RADE-1, took place in November 2003, with a total of 30 participants from ten European Area Control Centers (ACCs) (cf. Eurocontrol, 2004). The main objectives of this experiment were: to obtain controller feedback on the operational benefits of RA downlink and to assess different Human-Machine Interface (HMI) solutions for RA downlink. The experiment showed that the majority of participants see operational benefits in the provision of RA downlink. Furthermore, a set of requirements for the RA downlink HMI was identified. From a scientific point of view, though, there were some important limitations to the RADE-1 experiment: First, the experiment involved a replay of “canned” traffic scenarios. Thus, participants acted as observers and could not actively control the traffic situations. Second, data primarily related to controller feedback (i.e. subjective data) rather than to controller performance (i.e. objective data).

In order to overcome these shortcomings, the RADE-2 studies were conducted. These studies used a monitoring-and-control real-time simulation environment, rather than replays of traffic scenarios. The RA downlink HMI used in these studies was designed in accordance with the requirements identified in RADE-1. The remainder of this article is dedicated to the description of two studies, namely, an initial study and an experiment.

4 The RADE-2 initial study

The RADE-2 studies were the first ATC simulations in which RAs were investigated in a fully interactive environment. From the early stages of simulation preparations, it was obvious that one of the major challenges was the elicitation of traffic situations in which RAs would be issued. In an interactive setting, a participant acting as a controller would do anything is his or her power to avoid a separation loss and, consequently, an RA. Therefore, a specific method had to be devised to achieve RAs. The RADE-2 initial study, which was conducted over five days from June 27 to July 1, 2005 served to develop and assess such a method.

4.1 Method

Participants. A total of five former or current air traffic controllers participated in the initial study. Of the five controllers, two were genuine study participants (i.e., they were not part of the experimental team and acted as controllers in the simulation runs). One of the participants works at Maastricht Upper Airspace Centre (MUAC), the other one works as Warsaw ACC. The participants' age was 33 and 47 years respectively; both participants had considerable experience as licensed controllers (7 and 18 years).

The other three controllers were former or current area controllers from Copenhagen ACC, Ljubljana ACC, and Warsaw ACC. They were members of the experimental team and acted as Subject Matter Experts (SMEs) in the simulation.

Experimental Environment. The RADE-2 study was conducted on the early Demonstration and Evaluation Platform (eDEP) situated at the Human Factors Lab of Eurocontrol Experimental Centre in Brétigny, France. For the study, eDEP was configured to facilitate a small-scale simulation environment, and a TCAS server[2] was used for the realistic generation of TCAS events. The Eurocontrol AudioLAN system was used for communication between experimental participants on the one hand and simulation pilots and adjacent control sectors on the other. Adjacent sectors were controlled by SMEs. During the initial study, the platform was used in two different configurations, a single and a dual configuration. In the

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2) A computer tool replicating TCAS logic in the ground system and generating RAs.

single configuration, the two Controller Working Positions (CWPs) were operated independently. This means that the two CWPs were staffed by one controller each who had the combined responsibilities of an Executive and a Planning Controller (i.e. Single-Person Operation). In the dual configuration, the two CWPs were staffed by an Executive and a Planning Controller who worked as a team. While the Executive Controller was responsible for separation of aircraft in the sector and radio communication with the pilots, the Planning Controller was responsible for resolving planning conflicts, coordinating with other sectors by phone, and assisting the Executive Controller in the provision of traffic separation. Figure 1 shows the simulation platform in the dual configuration.

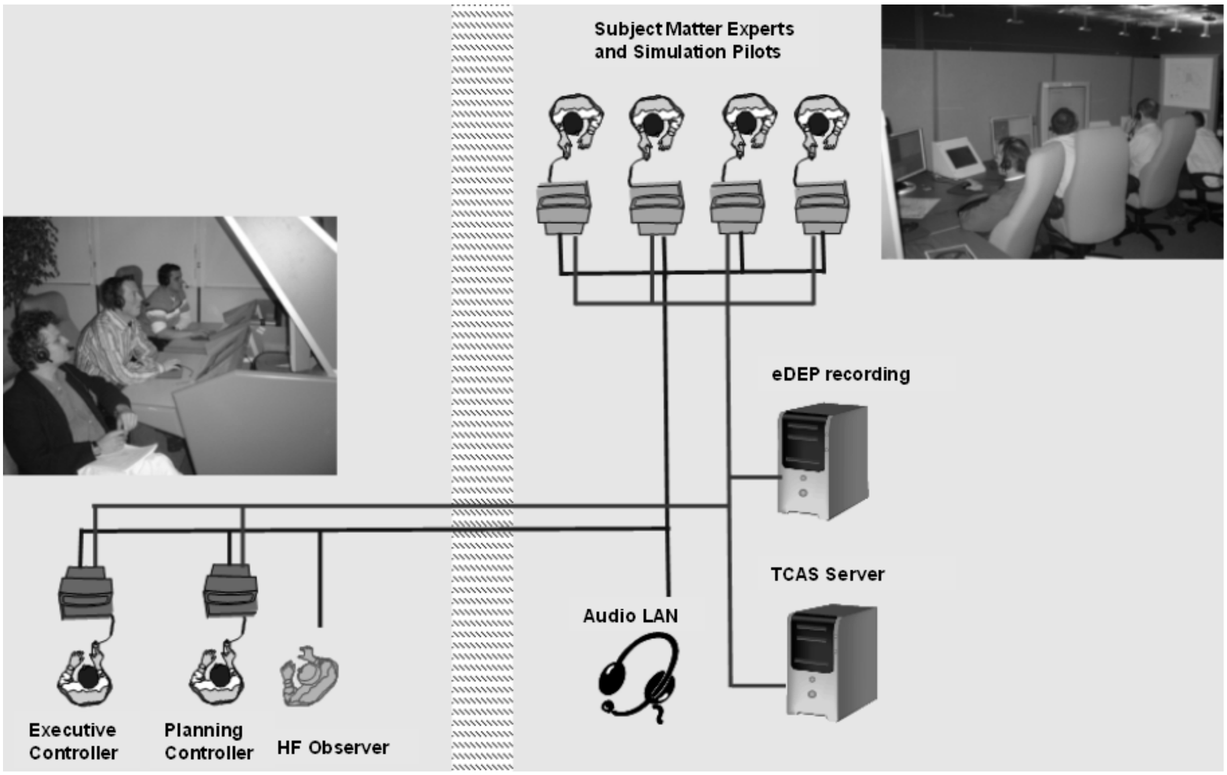

Figure 1: Simulation Configuration used in the RADE-2 Simulations (dual configuration)

In addition to the simulation platform, a tool for TCAS event analysis, referred to as “Interactive Collision Avoidance Simulator (InCAS)” was used. InCAS uses radar data recorded on the simulation platform to rebuild aircraft trajectories. In this way, TCAS behavior can be recreated and TCAS events that occur during a simulation run can be displayed and analyzed off-line.

Procedure. The main aim of the initial study was to test a method for the facilitation of RA events. Therefore, the study did not follow a strict experimental plan, but consisted of a series of simulation runs in which this method was used and refined.

The RA facilitation method heavily depended on the input of SMEs. SMEs were situated next to the simulation pilots and closely observed the evolution of the traffic scenario. Their task was to predict likely controller actions and to identify traffic situations that may trigger the TCAS server to generate an RA. Depending on the identified opportunity for an RA, the SME would then instruct the simulation pilot to behave in a certain way (e.g., making a request, busting the Flight Level, or manipulating vertical speed). SMEs were instructed not to create situations that would compromise simulation realism.

Three different classes of RAs were elicited in the simulation which required different actions from the SMEs:

1. RAs due to controller error: In case a suitable traffic situation for the facilitation of an RA event emerged (i.e. aircraft in proximity or with conflicting trajectories), actions were taken to either induce a conflict or to increase the likelihood of the controller missing a conflict. Examples are: pilots requesting a change of flight level due to turbulence, giving incorrect read-backs, or blocking frequency during critical situations; in addition, controller attention was diverted to different parts of the sector through requests from other aircraft.
2. RAs due to pilot error: Another means to facilitate an RA event consists in deliberately implementing a wrong or unsafe pilot action in a conflict-prone situation. A direct way for implementing a pilot error that is likely to result in the generation of an RA was to have the aircraft bust the cleared level with traffic on the level above or below. Alternatively, the aircraft could make a turn that did not comply with ATC instruction (e.g. heading 030 instead of 330).
3. High Vertical Speed Level off: In order to create an RA that is due to a high-vertical speed before level off, the simulation pilot would maintain a high rate of climb or descent close to leveling-off at the cleared level. This would serve to induce a conflict pattern with a proximate aircraft at an adjacent flight level.

Each simulation run was planned to last a maximum of 45-50 minutes, depending on the exact length of the traffic sample. After each simulation run, controllers were asked to fill in a memory test on the RA situation and to complete a situation awareness questionnaire. Controllers were then de-briefed. For the initial study, the main objective of using questionnaires, memory tests and de-briefings was to assess their suitability for later use in the experiment. Data from questionnaires and memory tests were not systematically analysed.

4.2 Results and Discussion

The RA facilitation method used in the initial study was generally judged as successful by experimenters, SMEs and participants. The RA facilitation method resulted in the generation of RA events (with at least one RA issued to an aircraft) in 11 out of 13 simulation runs. In the remaining two runs, no RAs could be elicited and the simulation run was stopped after 50 minutes. Participants acting as controllers in the simulation stated in the de-briefing that the simulated RA situations were fairly realistic, that is, they could principally occur in real operation.

Nevertheless, experiences from the simulation runs led to some refinements of the method. The most important ones were:

- A decision was made to use the dual configuration (with Planner and Executive Controller) in all measured runs of the future experiment. Participants indicated that this configuration was more realistic than the single configuration (with Single-Person Operation), as it reflects the way of working in most European ATC centers.

- It was noticed that the interaction between the simulation pilots and the SMEs (who instructed the simulation pilots to take certain actions) was quite demanding. A more viable option was to have two SMEs directly acting as simulation pilots. A further member of the experimental team with a commercial pilot license acted as the third simulation pilot and followed instructions from the SMEs whenever required to create an RA situation. A third SME acted as the Planner in the feed sectors.

- A decision was made not to evoke more than one RA situation per simulation run. Having more than one RA event in a simulation run was experienced as compromising the realism of the simulation. Furthermore, the occurrence of several RAs as well as a long delay between the RA event and the subsequent test and de-briefing was shown to impair the participants' recollection of the RA situation. For this reason, it was decided to terminate future simulation runs between 90 and 120 seconds after the RA event had happened.

5 The RADE-2 experiment

The RADE-2 experiment was carried out between October 5 and December 1, 2005. The general aim of the experiment was to analyze the impact of RA downlink on the controller's ability to separate traffic in an interactive control setting. In addition, controllers' attitudes towards RA downlink and the proposed HMI were investigated. With respect to potential benefits, it was assessed whether RA downlink helps to avoid contradictory clearances to aircraft with an RA. Furthermore, it was investigated whether RA downlink facilitates the controller's understanding of the RA event. The RADE-2 experiment was also designed to investigate potential adverse effects of RA downlink. One of these adverse effects is 'cognitive tunneling': the display of RA information could narrow the controller's attention to the RA event on the expense of other traffic in the sector (cf. Thomas & Wickens, 2001, for cognitive tunneling in pilots). For the facilitation of RA events, the method developed in the RADE-2 initial study was used.

5.1 Method

Participants. A total of 12 controllers participated in the experiment. Six participants were from Maastricht Upper Airspace Centre (MUAC) and two from Marseille ACC, from Langen ACC, and from Rome ACC each. The participants' age ranged between 28 and 51 years (M = 35.8, SD = 6.2). Experience as a licensed controller varied between 3 and 28 years (M = 10.8, SD = 7.4).

Experimental Environment. Like in the initial study, the RADE-2 experiment was conducted on the early Demonstration and Evaluation Platform (eDEP) situated at the Human Factors Lab of Eurocontrol Experimental Centre in Brétigny, France. The simulation was run in a dual configuration with a Planning Controller and an Executive Controller controlling one sector. The working positions of both controllers were each equipped with a traffic situation display, a mouse, a head-set with microphone (for communication with simulation pilots and adjacent sectors), and an LCD touch screen (for selection of frequencies and phone lines). All information related to a particular flight was presented on the traffic situation display (i.e. a strip-less environment was simulated). For the generation of RA events, a TCAS server was used.

Human-machine interface and operational procedures for RA downlink. A TCAS RA was displayed on the traffic situation display in line 0 of the aircraft label above the call sign (see Figure 2). The RA display consisted of the letters “TCAS” presented in yellow on a blue background, together with a graphical sign indicating the direction of the RA. In case of an RA reversal, the previous RA direction was shown in brackets. Usually, TCAS RA information was displayed for all aircraft involved in the conflict. In case only one aircraft had a TCAS RA, the intruder was shown with a red frame around the call sign.

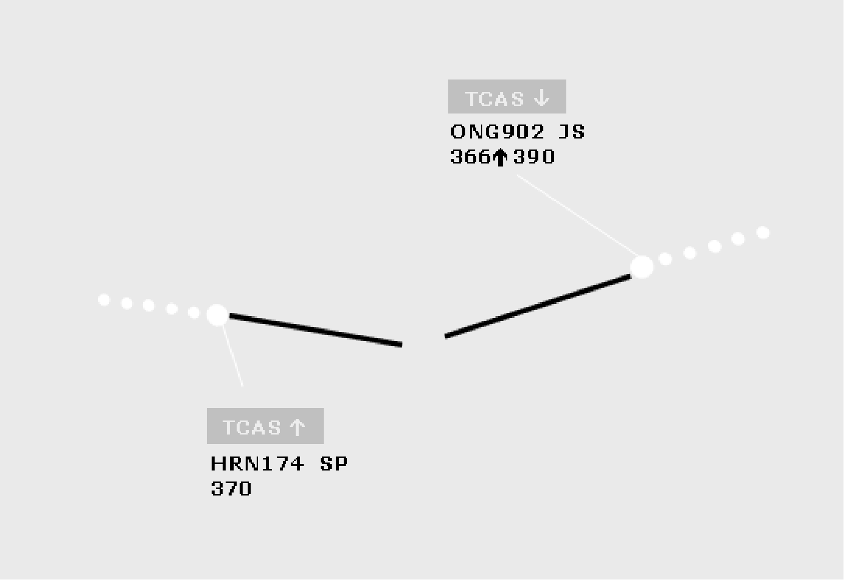

Figure 2: Display of an RA at the Controller Working Position

The following operational procedures were used in the experiment: pilots are required to follow all RAs. RAs should be reported to the controller by voice, regardless of whether or not RA downlink is provided. Once the pilot reports the RA maneuver and until the pilot returns to the original ATC instruction or clearance, the controller should not modify the flight path of an aircraft. These procedures are in line with ICAO regulation at the time of the experiment[3].

Procedure. The twelve controllers participated in teams of two, resulting in six controller teams. The teams were each invited for four subsequent days to the simulation facility. Day 1 was used for controller briefings and familiarization with the equipment and HMI. Also, a number of training runs was conducted. On Days 2 and 3, the measured runs were carried out. On Day 4, unsuccessful measured runs were repeated (see below for success criteria and the number of repeated runs) and the post-experimental de-briefing was carried out.

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[3] Since November 2007, ICAO has limited RA reporting to those RAs that require a deviation from the current ATC instruction or clearance (ICAO, 2007b).

For all experimental runs, controllers were told that they were to work in Cottam Centre, a fictitious facility located in Europe. One of them would be working as the Executive Controller (i.e. having responsibility for separation provision and carrying out R/T with pilots),

the other one would be working as the Planning Controller (i.e. assisting the Executive in the separation provision and coordinating with adjacent sectors). Controllers were on an afternoon shift in the Haren sector, with main traffic streams between FL270 and FL350. The Haren sector borders with two sectors, one in the North and one in the South, and includes a military area. During the simulations, the status of the military area could change from non-active to active with a restriction on a range of flight levels (for more information, see Eurocontrol, 2007).

All measured runs were terminated between 90 and 120 seconds after an RA event had taken place. If no RA event occurred for 50 minutes, the run was categorized as unsuccessful and repeated on Day 4 with a different traffic sample. During the runs, all controller inputs to the working position and all communication with simulation pilots and adjacent sectors were recorded. Shortly after the onset of an RA event, an online probe was administered to assess the controllers' awareness of other traffic in the sector. The online probe consisted of a request concerning an aircraft unrelated to the RA event; controller responses to the request were recorded. After each measured run, participants filled in: (a) a memory test on the RA event, (b) the situation awareness self-rating scale SASHA-Q (Eurocontrol, 2003), and (c) the NASA Task Load Index (Hart & Staveland, 1988). Participants were then subjected to a replay-supported interview carried out by a Human Factors (HF) expert and an operational expert.

Three experimental variables were manipulated in the experiment: (1) RA downlink (present vs. absent), (2) timeliness of pilot report (timely vs. delayed), and (3) controller role (Executive Controller vs. Planning Controller).

1. RA downlink (present vs. absent). In the baseline condition, RAs were not presented on the screen. The only source of information on the RA was the pilot report. In the experimental condition, RAs generated in the cockpit were displayed at the CWP. In both conditions, the pilot was still requested to report the RA.
2. Timeliness of pilot report (timely vs. delayed). It can be reasonably assumed that potential benefits of RA downlink are more prominent, if the pilot report is delayed or even missing. For this reason, report timeliness was included as an experimental variable. In the timely report condition, simulation pilots reported the RA as soon as it was generated. In the delayed report condition, simulation pilots only reported the RA

once the RA situation was resolved (i.e. a clear-of-conflict message was displayed at the pilot position). In both conditions, the pilot reported the RA correctly.

3. Controller role (Executive vs. Planning Controller). In one condition, the participant was working as the Executive Controller. In the other condition, the participant was working as the Planning Controller. As controllers always worked in a team, one simulation run yielded measurements for both levels of this variable (e.g. for the Executive and the Planning Controller).

All levels of the three variables were crossed with each other, yielding a complete 2 x 2 x 2 design with eight experimental conditions. Experimental variables were manipulated within subjects so that all participants were exposed to all of the eight experimental conditions. In order to control for training effects, the presentation order of experimental conditions was balanced over participants using a Latin square. Although the sample size of 12 participants (i.e. six controller teams) did not suffice to realize a full Latin square, the presentation order for the RA downlink condition (present vs. absent) was completely balanced. The presentation order for the controller role (Executive vs. Planning Controller) was necessarily balanced, as one run always involved both controller roles. A slight imbalance occurred for the third variable: over all participants, runs with a timely pilot report were presented on average on position 4.13 of the eight experimental runs; whereas runs with a delayed report were presented on average on position 4.83.

A variable that was not systematically manipulated in the experiment, but taken into account in the data analysis, is the RA cause. Two different causes were distinguished: (1) High vertical rate before level off: in this case, the RA was triggered by fast climbing/fast descending aircraft with an aircraft on the adjacent level. (2) Controller/pilot error: in this case, the RA was caused by an incorrect ATC clearance/action or a pilot not following the ATC clearance.

A total of eight traffic samples were used to realize the eight experimental conditions. This served to avoid repeated exposure of participants to the same traffic sample and thus learning effects. Three more traffic samples were constructed to be used for runs that had to be repeated. Because of the highly interactive nature of the simulation (with controllers and simulation pilots modifying the original trajectories), the actual traffic scenarios resulting from one traffic sample differed between participants.

5.2 Results and Discussion

Results are reported in the following order: after a section on the adequacy of the experimental approach, the results pertaining to operational benefits (i.e., controller performance, situation awareness, workload, and acceptance) are described.

Adequacy of the experimental approach. One of the major challenges in the RADE-2 experiment was to create RA events in an interactive and realistic setting. Out of the planned 48 runs (eight conditions x six controller teams), 12 runs (or 25%) had to be repeated. Reasons were: failure to evoke an RA (2 runs), loss of simulation realism (3 runs) and technical problems (related to AudioLAN, TCAS Server, or the simulation platform: 7 runs). In the end, 48 successful simulation runs were achieved in which (a) an RA event was created and (b) the simulation was experienced as realistic by participants. Out of these 48 runs, 24 were done without RA downlink, and 24 were done with RA downlink. Controller ratings of various aspects of the simulation realism (i.e., the simulated traffic, the RA event, and the pilot behavior) were generally positive. Thus, the approach taken in the real-time simulation allows for an assessment of the operational impact of RA downlink.

Controller performance. Controller performance was measured in terms of the number and type of instructions issued to aircraft involved in the RA event and the number of separation losses following the RA.

During the 48 simulation runs, two ATC clearances were issued to aircraft involved in an RA encounter. Both clearances were issued to aircraft that had received an RA caused by pilot/controller error, and they both contradicted the RA. Furthermore, the two clearances were issued in the condition without RA downlink. One of the clearances was issued in the timely pilot report condition; the other one was issued in the delayed pilot report condition. In both cases, the controllers issued the clearance in an attempt to prevent a follow-up conflict. Although both contradictory clearances occurred in the absence of RA downlink, the number of events is too small to decide conclusively whether the effect of RA downlink is statistically significant or just due to random variation.

Losses of separation that pertained to the aircraft configuration yielding the RA were excluded from the analyses[4]. Other losses of separation occurred in 16 runs (i.e. 33.3% of the total runs). An analysis of these runs revealed that losses of separation were exclusively due to follow-up conflicts occurring as a consequence of the RA maneuver. Thus, all losses of

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[4] The situation that originally led to the RA was experimentally induced. For this reason, it was unsuitable as an indicator of the controller’s ability to separate traffic in the sector.

separation involved at least one aircraft that was previously involved in the RA encounter. Table 1 shows the distribution of separation losses over experimental conditions. As can be seen from the table, the number of separation losses is equally distributed over the four conditions.

Table 1. Number of Separation Losses as a Function of Experimental Conditions

Number of Separation Losses

		RA Downlink	
Pilot Report	present	absent	total
timely	4	4	8
delayed	4	4	8
total	8	8	16

Using the number of separation losses as an indicator of controller performance, there is no evidence for the assumption that RA downlink helps the controller to plan the post-alert situation, resulting in a reduced likelihood of follow-up conflicts. Nevertheless, the absence of separation losses unrelated to the RA event shows that there is no evidence for the cognitive tunneling hypothesis either. According to this hypothesis, the controller's ability to separate other traffic in the sector is impaired by the presentation of RA information.

Situation Awareness. Situation awareness (SA) refers to the controllers' understanding of the traffic situation as well as the ability to predict its evolution (Jones & Endsley, 1996; Endsley, 1995a, 1995b). For the purpose of this experiment, the controller's SA concerned the understanding of the traffic constellation that yielded the RA, as well as knowledge of other traffic in the sector (i.e., not affected by the RA event). Situation Awareness (SA) was measured on the basis of a memory test, an on-line probe, and a self-rating scale.

Like SAGAT (Endsley, 1987), the SA memory test required a recall of various aspects of the traffic situation. Unlike SAGAT though, this recall was specifically focused on the RA encounter. The items in the memory test addressed the understanding of the conflict geometry, namely: the aircraft involved, their cleared level, their state (climbing, descending, or level flight) prior to the conflict, and their approximate heading. Other items addressed details of the RA event (i.e. whether pilots reported and followed the RA, whether the RA induced a follow-up conflict, and what the sense of the RA was). The SA memory test had to be filled in immediately after each simulation exercise. Figure 3 shows the performance in the memory test depending on the RA downlink condition and the cause of the RA. Note that the maximum score on the test was 10.

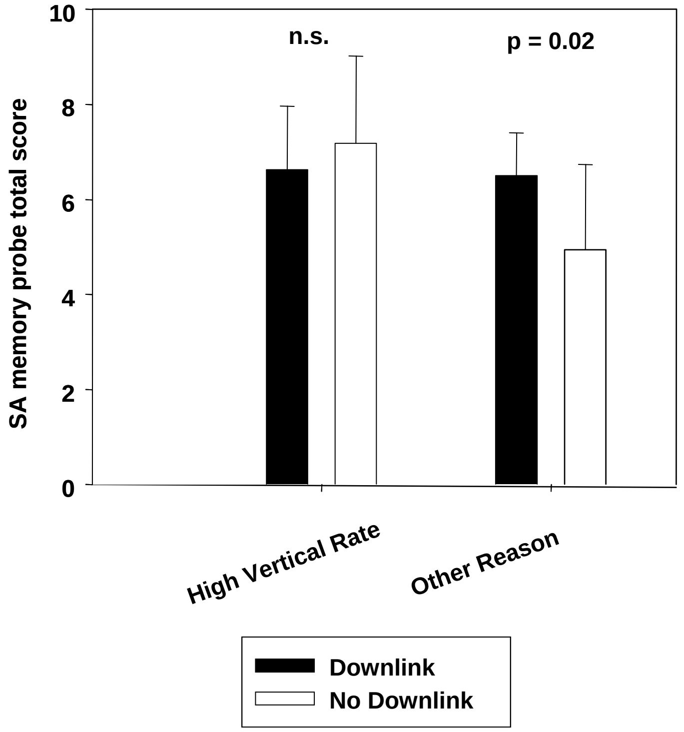

Figure 3: SA Memory Probe Scores as a Function of RA Downlink Condition and RA Cause

Scores were subjected to a three-factorial repeated measurement analysis of variance (ANOVA) using RA downlink (present vs. absent), controller role (Executive vs. Planning Controller), and pilot report (timely vs. delayed) as independent factors. No effect, including the interactions between the three factors, became statistically significant (all *F*'s < 1). A further ANOVA with RA cause (high vertical rate level off vs. pilot/controller error) and RA downlink (present vs. absent) as factors revealed a significant interaction between the two factors ($F(1,11) = 7.18$; $p = 0.02$). This interaction can be interpreted as follows: If an RA is caused by high vertical rate, there is no difference in the SA scores for the two RA downlink conditions ($t(11) = -1.24$; $p = 0.242$). However, if the RA is caused by a pilot/controller error, performance is significantly higher with RA downlink ($t(11) = 2.71$; $p = 0.02$) than without. Thus, there is a beneficiary effect of RA downlink on the understanding of the RA event, in case the RAs were caused by a pilot or a controller error. These are the type of RAs that are operationally relevant for the controller as they yield a deviation from the cleared flight path.

Eurocontrol's SASHA-Q was used as a self-rating scale for SA (Eurocontrol, 2003). SASHA-Q contains specific items on the tool under investigation (in this case, RA downlink), generic items, and an overall SA rating. SASHA-Q was completed by both controllers after each simulation exercise. In the following, only the results referring to the overall SA rating are reported[5].

For the overall SA rating ("How would you rate your overall situation awareness during this exercise?"), an ANOVA with the factor 'RA cause' and 'RA downlink condition' was calculated (see Figure 4). This analysis revealed a main effect of the RA cause ($F(1,11) = 5.57$; $p = 0.04$): Controllers rated their situation awareness higher in runs with RAs caused by high vertical rate than in runs with RAs caused by pilot/controller error. Neither the main effect of RA downlink ($F < 1$) nor the interaction of RA downlink and RA cause was significant ($F(1,11) = 1.73$; $p = 0.22$).

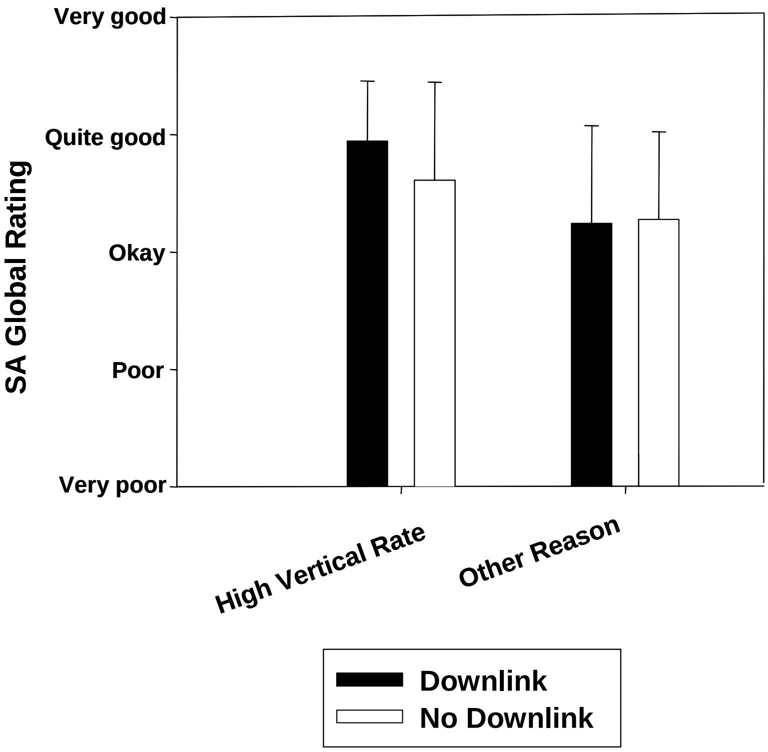

Figure 4: Global SA Rating as a Function of RA Downlink Condition and RA Cause

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[5] For the other generic items, none of the factors "RA downlink", "timeliness of pilot report", and "controller role" or any interaction between them had a significant effect on the ratings.

The measurement of SA on the basis of the on-line probe was carried out as follows: Simulation pilots and SMEs were instructed to make one request immediately after the RA event to the Executive and the Planning Controller each. For the Executive Controller, requests were made by a pilot and concerned level changes, directs or traffic information; for the Planner, requests were made by adjacent sectors and concerned changes of exit or entry conditions. All requests involved aircraft unrelated to the RA event, therefore, the on-line probe served to assess the controller's awareness of other traffic in the sector.

The on-line probe was successfully accomplished in 80 out of the 96 cases (48 runs x 2 controller roles). Of the probes pertaining to the Executive Controller, 34 of the 41 valid probes (i.e. 82.93%) were answered correctly and timely; of the probes pertaining to the Planner 33 of the 39 valid probes (i.e. 84.62%) were answered correctly and timely. Accordingly, seven and six requests were answered delayed or incorrectly by the Executive and the Planning Controller respectively.

The high frequency of correct and timely answers points to a ceiling effect, that is, performance was too high to reveal any impact on SA. Because of the low number of delayed or incorrect responses, no statistical tests were applied. Numerically, though, the number of delayed or incorrect answers is lower with RA downlink (i.e. 5) than without RA downlink (i.e. 8). Thus, there is no evidence that RA downlink narrows down the controller's focus of attention to aircraft involved in the RA encounter.

Workload. Workload was measured on the basis of subjective ratings collected with the NASA-TLX (Hart & Staveland, 1988). The NASA TLX contains six different rating scales. Scores on these scales are usually combined by using a specific weighting technique; however, it has been demonstrated that simply summing up scores also yields valid results (Byers, Bittner, & Hill, 1989; Nygren, 1991). Participants filled in the NASA-TLX at the end of each simulation run (see Figure 5).

According to an ANOVA, neither the RA downlink condition nor the timeliness of the pilot report had a significant influence on the total (unweighted) NASA-TLX score. The interaction between the two factors was also not significant (for all effects, $F < 1$). An analysis with the factors "RA downlink condition" and "RA cause" revealed a highly significant main effect of the RA cause on the NASA-TLX score ($F(1,11) = 19.75$; $p = 0.001$). This effect indicates that controllers experienced less workload in runs in which the RA was caused by high vertical rate before level off than in runs with RAs caused by pilot/controller error (see Figure 5).

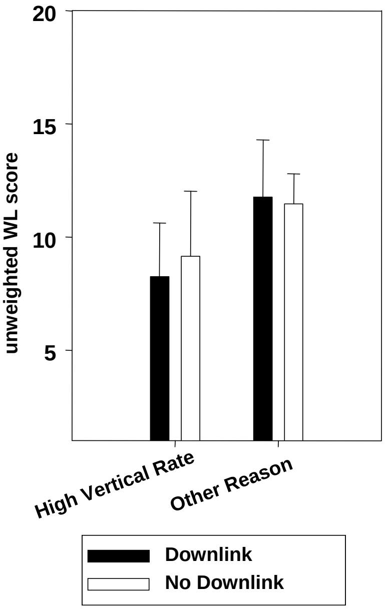

Figure 5: NASA-TLX Scores for RA Downlink Conditions and RA Causes

Controller Acceptance. Controller acceptance referred to the concept of RA Downlink and the proposed HMI. Acceptance was measured on the basis of a post-experimental questionnaire (to be filled in after all runs had taken place) and a de-briefing at the end of the experiment.

In the post-experimental questionnaire, participants were asked to rate the usefulness of displaying RA information to the controller. Answers could be given on a scale from 1 (not at all useful) to 5 (absolutely useful). The participants' answers ranged from 1 to 5 with a mean of 3.6 (*SD* = 1.2). Two participants gave ratings on the negative side of the scale (i.e. 1 or 2), whereas seven participants gave ratings on the positive side of the scale (i.e. 4 or 5). Thus, the majority of participants see benefits in the display of RA information to the controller. Among the benefits named were an increased situation awareness, referring to a better understanding of the RA situation, and a lower likelihood of issuing contradictory clearances to an aircraft involved in an RA. However, the experienced benefits mainly pertain to RAs that yield a deviation from the ATC clearance (usually those caused by pilot or controller error). RAs that do not yield a deviation from the ATC clearance (usually those caused by a high vertical rate before level-off) are regarded by some controllers as nuisance alerts.

A further issue of concern is the pilot/controller responsibility. Generally, it was acknowledged that RA downlink can clarify responsibility for the controller if a pilot departs from the clearance in compliance with an RA, but fails to report this to ATC. In this case, the controller is not responsible for separation any more, but might not be aware of that. However, participants were concerned that RA downlink would not entirely resolve ambiguity. If the pilot does not follow an RA, the controller is still responsible for the aircraft. RA downlink might mislead the controller to assume that he/she is not responsible any more. This concern, though, is based on the assumption that existing ICAO regulations are not modified if RA downlink is implemented.

The specific HMI proposed for RA downlink information was generally appreciated by the participants. Nevertheless, two issues were mentioned that require further attention. One refers to the fact that the RA information presented in the aircraft label may clutter the screen; the other refers to problems in understanding certain RA symbols (in particular, related to the “adjust vertical speed” RA in TCAS Version 7.0).

6 Conclusions

The RADE-2 studies are the first ATC simulations to systematically assess RA events in an interactive environment. Whereas the initial study served to test the feasibility of the experimental approach, RADE-2A served to assess the impact of RA downlink on the controllers and their ability to separate traffic.

The most direct and straightforward indicator of an RA downlink benefit is the absence of controller clearances to aircraft involved in an RA encounter, particularly of clearances that are in contradiction with the RA. In the RADE-2 experiment, a total of two clearances – both contradictory – were issued to aircraft involved in an RA encounter. These clearances occurred in runs without RA downlink. The number of separation losses occurring after the RA event was taken as a further indicator of controller task performance. However, no effect with respect to the impact of RA downlink information on the controller’s ability to separate traffic was found. All observed losses of separation involved aircraft directly affected by the RA event, and the number of separation losses was equally distributed among the condition with and without RA downlink.

One of the potential problems with RA downlink refers to the phenomenon of cognitive tunneling: it is feared that the display of RA information narrows the controller’s attention to the RA event on the expense of other traffic in the sector. Cognitive tunneling was assessed by using pilot requests that were unrelated to the RA event. It was found that the controllers’ ability to respond to unrelated pilot requests is unaffected by the RA downlink condition (absent vs. present). Thus, there is no evidence for cognitive tunneling as a consequence of RA downlink.

With respect to situation awareness, significant results were only found if the type of RA event (i.e., the cause of the RA) was considered in the data analysis. If the RA was due to a high vertical rate before leveling off, there was no difference in the controller's ability to recollect various aspects of the RA situation. If the RA event was caused by a pilot or controller error, though, RA downlink significantly improved the recollection of the RA situation. This latter finding clearly supports one of the intended benefits of RA downlink, which is to increase the controller's understanding of the conflict situation.

As regards controllers' acceptance of RA downlink, the majority of participants saw clear advantages of RA downlink. These were: increased situation awareness, and a lower likelihood of issuing contradictory clearances to an aircraft involved in an RA. However, the experienced benefits mainly pertain to RAs that yield a deviation from the ATC clearance. Downlink of RAs that are due to high vertical rate level off was seen as less beneficial. The reason is that, in the majority of cases, such RAs do not result in a deviation from the cleared flight trajectory.

Altogether, the results of the RADE-2 experiment point to some operational benefits of RA downlink. Contradictory clearances to aircraft involved in an RA were exclusively observed in the absence of RA downlink. Controllers' recollection of RA events caused by pilot or controller error was superior if RA downlink was provided. In contrast, there was no evidence for negative effects of RA downlink, such as cognitive tunneling on the RA event and a lower ability to separate other traffic in the sector.

7 Application of the Results

The RADE-2 initial study and experiment can be considered a successful step in the evaluation of RA downlink and its impact on controller behaviour. However, like any experiment that aims at deriving conclusions from a limited set of laboratory exercises to real operation, the RADE-2 experiment has certain limitations.

Firstly, in real operation, RAs are a fairly rare event. The actual frequency of RA events depends on airspace characteristics and traffic density; however, even if some variation in the frequency is accounted for, handling RA events cannot be considered a nominal controller task. In contrast, participants in the RADE-2 experiment were exposed to one RA event per exercise. The fact that RAs in the simulation were much more frequent and predictable than in real operation is likely to have an influence on controller behaviour. There is no reason to assume that the results on RA benefits (i.e., less contradictory clearances to aircraft involved in an RA, and better understanding of the situation for RAs caused by pilot or controller error) are artefacts of the experimental situation. However, there are aspects that might be influenced by the frequency of an RA event. For instance, whether or not an HMI for RA information is experienced as easy or hard to interpret will depend on the frequency with which controllers are exposed to an RA (and thus, to the RA display).

Secondly, in the experiment, the number of RAs that yield or do not yield a deviation form the ATC clearance were equally distributed. There is evidence, though, that these types of RAs are not equally frequent. Furthermore, RAs that do not yield a deviation form the clearance can, in some respect, be considered “nuisance alerts” for the controller, as they do not change their responsibility for aircraft separation. Thus, in order to evaluate the effect of RA downlink in real operation, knowledge on the absolute number of RA events as well as on the relative proportion of different types of RAs are needed. Recently, a number of monitoring studies on the frequency of TCAS RA events in European airspace has been carried out (e.g. Drozdowski, Dehn & Louyot, 2009; Eurocontrol, 2009).

Finally, the RADE-2 experiment did not take into account false alarms or missed alarms. A false alarm can be defined as an RA displayed on the ground in the absence of an RA on the flight deck. A missed alarm refers to the situation of an RA on the flight deck which is not displayed on the ground. Both situations were not studied in RADE-2. Whereas recent evidence from RA monitoring (cf. Drozdowski et al., 2009) suggests that false RA downlinks may be easy to filter, the rate of missed alarms is still unknown. Potentially, both false and missed alarms have a detrimental influence on the controller’s trust in RA downlink and the ability to separate traffic.

An increasing number of European Air Navigation Service Providers (ANSPs) already fulfill the technical requirements for RA downlink (i.e. ground Mode-S radars, or multidirectional 1030/1090 MHz receiver). When commissioning a new or upgrading an existing ATC system, these ANSPs are faced with the question of whether or not to use the downlinked information for display at the Controller Working Position. Currently, no regulation or guidance material exists for the implementation of RA downlink. In order to support the ANSPs in their decision, empirical evidence on the benefits and drawbacks of RA downlink is required. The RADE-2 experiment can be seen as a first step towards building such a body of evidence.

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