EUROCONTROL

RADE-1 Experimental Report

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Abstract

EUROCONTROL's Feasibility of ACAS Resolution Advisory Downlink Study (FARADS) is investigating the feasibility of showing simplified ACAS resolution advisories (collision avoidance advice given to pilots) on controller screens. As part of this study, an experiment was conducted in which resolution advisories (RAs) were displayed to controllers. This experiment took place from 17 November to 28 November 2003, and a total of 30 controllers from ten European Area Control Centres participated. The majority of the participants see clear operational benefits in the provision of RA information to the controller. Because RA downlink is faster and more reliable than a pilot report of an RA, it can support the controller's anticipation of aircraft manoeuvres. This can be considered an improvement in situational awareness. Furthermore, most participants expect RA downlink to decrease the likelihood of contradictory ATC clearances to the conflict aircraft.

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ACAS	Simulation	Experiment	

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EXECUTIVE SUMMARY

EUROCONTROL's Feasibility of ACAS Resolution Advisory Downlink Study (FARADS) is investigating the feasibility of showing simplified ACAS resolution advisories (collision avoidance advice given to pilots) on controller screens. As part of this study, an experiment was conducted in which resolution advisories (RAs) were displayed to controllers.

This experiment took place from 17 November to 28 November 2003, and a total of 30 controllers from ten European Area Control Centres participated. Controllers were exposed to four different HMIs, one without RAs (this version served as the control condition), and three with RAs displayed in a different manner. Five different ACAS scenes were used, which referred to different causes for the RAs (a pilot error, an ATC error, a false alert, high vertical rates of the aircraft, or a combination of these).

In order to experimentally control the situations in which RAs are displayed, controllers were exposed to replays of traffic scenarios. This setting aimed to mimic an On-the-Job Training (OJT) situation, in which an instructor monitors the performance of a trainee.

The aim of the experiment was to gather controller feedback on the concept of RA downlink as well as on the different implementations of RA downlink. Also, the effect of RA information on controllers' understanding of the traffic situation was investigated. Furthermore, eye-point-of-gaze measurements were used in order to assess the controllers' allocation of attention to safety-critical information on the screen.

The results of the eye-point-of-gaze measurements did not yield any significant differences between the different HMIs, and the different downlink delays. For the understanding of the traffic situation, the only significant result related to a better knowledge of the issued RAs in case RA information was displayed on the radar screen. The understanding of the conflict geometry and the further development of the traffic situation, in contrast, did not differ.

Nevertheless, the majority of the participants see clear operational benefits in the provision of RA information to the controller. Because RA downlink is faster and more reliable than a pilot report of an RA, it can support the controller's anticipation of aircraft manoeuvres. This can be considered an improvement in situational awareness. Furthermore, most participants expect RA downlink to decrease the likelihood of contradictory ATC clearances to the conflict aircraft, and to facilitate the provision of traffic information, either to the conflict aircraft or to third-party aircraft.

In order to realise these benefits, though, two requirements need to be met: First, it needs to be ensured that the RA information on the screen does not pose too high demands on the controller's attentional resources. This means that a careful design of the human-machine interface (both in terms of the detail of RA information and the kind of alert) is required. In particular, the controller needs to be aware as soon as possible of whether an RA yields a deviation from the cleared flight path or not.

Second, operational procedures for the use of RA information need to be defined. The majority of participants expressed a preference for procedures that retain the current responsibilities of pilots and controllers. This includes that RA downlink should only be used

for informational purposes; and no obligations for additional controller actions should arise from the display of RAs.

List of Abbreviations

ACAS	Airborne Collision Avoidance System
ACC	Area Control Centre
AGAS	European Action Group on ATM Safety
ASL	Applied Science Laboratories
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ANOVA	Analysis of Variance
EPOG	Eye Point of Gaze
EATMP	European ATM Programme
F	Test statistic for an ANOVA
FARADS	Feasibility of ACAS Resolution Advisory Downlink Study
FL	Flight Level
GPWS	Ground Proximity Warning System
HMI	Human Machine Interface
Hz	Hertz
ICAO	International Civil Aviation Organization
LCD	Liquid Crystal Display
M	Mean
MS	Microsoft
Ms	millisecond
MTCD	Medium-term Conflict Detection
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (the Netherlands)
NM	Nautical Mile
OJT	On-the-Job Training
RA	Resolution Advisory
RADE	Resolution Advisory Downlink Experiment
R/T	Radio Telephony
RVSM	Reduced Vertical Separation Minima
SA	Situational Awareness
SASHA	Situational Awareness Measurement for SHAPE
SHAPE	Solutions for Human-Automation Partnerships in European ATM
SD	Standard Deviation
SSAP	European Strategic Safety Action Plan
STCA	Short-term Conflict Alert
T	Test statistic for a t-test
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System

1. INTRODUCTION

1.1 Background

The high level European Action Group on ATM Safety (AGAS) aims to determine how to make European ATM safer, particularly following the mid-air collision over Überlingen on 1 July 2002. AGAS has recommended a study to determine feasibility of downlinking ACAS (Airborne Collision Avoidance System) Resolution Advisories (RA) for display on controller screens. The AGAS recommendations [1] were accepted by the Provisional Council in April 2003. The investigation of RA downlink has now been incorporated into the European Strategic Safety Action Plan (SSAP).

Potential benefits of downlinking RAs are perceived to be:

- Avoiding contradiction between guidance of air traffic controllers and RAs.
- Improving the controllers' awareness of the traffic situation, including evasive manoeuvres by pilots that follow the RAs.
- Reducing the risk of follow-up conflicts and facilitating planning of the post-alert situation (e.g. support controllers in the revision of the sector plan).

EUROCONTROL has launched the Feasibility of ACAS Resolution Advisory Downlink Study (FARADS) to examine the feasibility of showing simplified ACAS resolution advisories (collision avoidance advice given to pilots) on controller screens. There are several human factors (controller-centred) issues associated with downlinking RAs that need to be resolved. Examples of such issues are: human-machine interface implementations; the possible occurrence of false alerts, nuisance alerts and missed alerts; controller acceptance of the concept and organisational/cultural characteristics at ATC centres. For this reason, an experiment, referred to as RA Downlink Experiment 1 (RADE 1), was conducted in which RAs were displayed to controllers.

1.2 Overview of the experiment

The basic design of this experiment was that controllers were exposed to four different HMIs, one without any RA (this HMI version served as the control condition), and three with RA advisories displayed in a different manner. Five different ACAS scenes were used, which were combined with all four HMI design solutions. In addition, the delay between the generation of RA in the aircraft and the display of the RA on the controller screen was varied. The RA Downlink Experiment 1 (RADE 1) took place from 17 November to 28 November 2003; and a total of 30 controllers from ten European Area Control Centres (ACCs) participated in the experiment.

The main aim of the experiment was to get (subjective) controller feedback on the concept of RA downlink as well as on the different HMI's for RA downlink. Also, the effect of RA information on controllers' understanding of the traffic situation was investigated. Furthermore, eye-point-of-gaze (EPOG) measurements were used in order to assess the controllers' allocation of attention to safety-critical information on the screen.

In order to experimentally control the situations in which RAs are displayed, controllers were exposed to replays of traffic scenarios. These traffic scenarios were based on real incidents. This means that the role of the controller in the trials was limited to an observer role; no active instructions to an aircraft were possible. This experimental set-up was presented to the controllers as a situation comparable to supervising a trainee. In many of the scenarios, the controllers claimed that they were able to predict the RAs.

1.3 Terminology

The following terminology is used in this report:

- ACAS is the generic term for airborne collision avoidance systems.
- TCAS is the brand name for a specific airborne collision avoidance system.
- TCAS I is a specific implementation of a TCAS which includes traffic advisories (TAs)
- TCAS II is a specific implementation of TCAS which includes traffic advisories (TAs) and resolution advisories (RAs).

Throughout the report, ACAS and TCAS are used synonymously. Preference is given to the generic term ACAS. In some of the questionnaires handed out to the controllers, though, the term TCAS was used, as it is more familiar for the controllers. When reporting the responses to these questions, the original wording is used.

1.4 Structure of the report

This report is structured as follows:

- Chapter 2 – specifies the aims and objectives of the experiment
- Chapter 3 – describes the experimental design
- Chapter 4 – describes experimental environment
- Chapter 5 – outlines the conduct of the experiment
- Chapter 6 – contains results and discussion
- Chapter 7 – provides the conclusions to be drawn from the experiment
- Chapter 8 – gives recommendations for future work on RA downlink

The list of references and the appendices (containing questionnaires used during the experiment and details of the Experimental Design) can be found at the end of this report.

2. AIMS AND OBJECTIVES OF THE RA DOWNLINK EXPERIMENT

2.1 General aim

The general aim of the RA Downlink Experiment 1 (RADE 1) was

- to present controllers with the concept of RA downlink as well as with different implementations of RA downlink – Human Machine Interface (HMI) versions, downlink delays,
- to gather initial feedback about the operational usefulness of RA downlink,
- to assess the different types of HMIs, and

- to assess and measure controllers' visual reactions to RA displays.

2.2 Evaluation objectives

The general aim of the RA downlink experiment as described above was further detailed in a number of evaluation objectives. These are listed below.

Objective 1: Evaluate controllers' acceptance of RA downlink. Within Objective 1, the following questions were investigated:

1. Do controllers see any operational benefits associated with the display of RA information?
2. Do controllers see any operational disadvantages associated with the display of RA information?
3. Do controllers anticipate any legal problems associated with the display of RA information on the controller screen?[1]
4. Do controllers see the need for procedural changes associated with the display of RA information on the screen?

Objective 2: Evaluate RA downlink in different operational scenarios. One objective of the experiment concerns the specific conditions in which RA downlink may offer advantages and disadvantages. Within Objective 2, the following questions were investigated:

1. In which operational scenarios is RA downlink considered as beneficial?
2. In which operational scenarios is RA downlink not considered as beneficial?

Objective 3: Evaluate the impact of RA downlink malfunction. The safety implications of RA downlink malfunction were discussed. Within Objective 3, the following questions were investigated:

1. In which way can RA downlink malfunction cause a safety-critical situation?
2. How can the effects of an RA downlink malfunction be mitigated?

Objective 4: Evaluate the technical implementation of RA downlink. The implementation of RA downlink requires a number of technical decisions, for instance, concerning the delay for displaying the RA and the filtering of specific types of RAs. Within Objective 4, the following questions were investigated:

1. What is the maximum acceptable delay between the generation of the ACAS alert and the display of the RA on the controller screen?
2. What is the preferred technical implementation in terms of the filtering of RAs for display on the controller screen?

Objective 5: Evaluate the different HMI versions for the display of RA information. The experiment makes use of three different HMIs for the display of RA information. These HMIs differ with respect to two dimensions: (a) the RA information displayed, and (b) the type of alert. Within Objective 5, the following questions were investigated:

1. How do controllers evaluate the three different HMIs?

[1] Although controllers are not legal experts they, have strong opinions about consequences associated with changes of rules and regulations which affect their acceptance.

2. What is an operationally usable RA display balancing the value of information with cluttering the display?
3. What is an adequate way of alerting controllers to RAs?

Objective 6: Assess the impact of RA information on controllers' situational awareness. Situational awareness refers to the controllers' understanding of the traffic situation. Within Objective 6, the following questions were investigated:

1. Does the provision of RA information on the controller screen affect the controller's understanding of the traffic situation?
2. Are there any differences in the situational awareness between the three different HMIs for the display of RA information?
3. Are there any differences in the situational awareness between different delays for downlinking RA information?

Objective 7: Assess the impact of RA information on visual behaviour. In the experiment, eye-point-of-gaze measurements were used to investigate the controller's behavioural responses to RA information (such as eye-blink rate, and scanning behaviour). Within Objective 7, the following questions were investigated:

1. Does the provision of RA information affect the controller's allocation of attention to information displayed on the screen?
2. Does the provision of RA information affect the controller's visual workload (as indicated by the eye-blink rate)?
3. Are there any differences in the allocation of attention and the visual workload between the various RA displays?

3. EXPERIMENTAL DESIGN

3.1 Independent variables

Three independent variables were manipulated in the RA downlink experiment: (1) ACAS theme, (2) HMI solution, and (3) downlink delay.

3.1.1 ACAS theme

One manipulation in the experiment concerns the conditions that led to the RA being issued. These conditions are referred to as “ACAS themes”. Five different ACAS themes were used in the experiment:

- Theme I (ATC error): An incorrect ATC clearance caused the RA.
- Theme II (Level off): The RA was triggered by fast climbing/fast descending aircraft (aircraft were following the ATC clearance).
- Theme III (False RA): The RA was issued due to a fault in the ACAS equipment.
- Theme IV (Combination Pilot and ATC error): An incorrect ATC clearance combined with a pilot mistake caused the RA.
- Theme V (Pilot error): The pilot did not follow an ATC clearance resulting in an RA being issued.

These themes reflect types of common real-life RA occurrences.

3.1.2 HMI versions

There were four different HMI versions, one without RAs, and three with RAs displayed in different ways.

- HMI0 (Status Quo): In the basic HMI version, there is no RA displayed on the radar screen.
- HMI1 (Minimum set): In the minimum set condition, there is a simple indication of an RA without the sense of the movement prescribed by the RA. Controllers were alerted to the RA information only visually.
- HMI2 (Intermediate set): In the intermediate set condition, there is an indication of the RA together with the exact sense of RA. Controllers were alerted to the RA information only visually.
- HMI3 (Enhanced set): In the enhanced set condition, there was an indication of the RA together with the exact sense of the RA. The condition involved an auditory and a vibration alert (i.e., a vibrating cushion attached to a chair) in addition to the visual alert.

Figure 1 shows the minimum set HMI. In this interface, the controller is notified about the RA with the acronym “TCAS” in the labels of the conflict aircraft. Figure 2 shows the intermediate and enhanced set HMIs. In these interfaces, the controller is given an indication of the sense of RA. In the presented example, LD5 and LC5 stand for “limit descend and limit climb to 500 feet per minute” respectively. A list of possible RAs and their abbreviations can be found in the Appendix C.

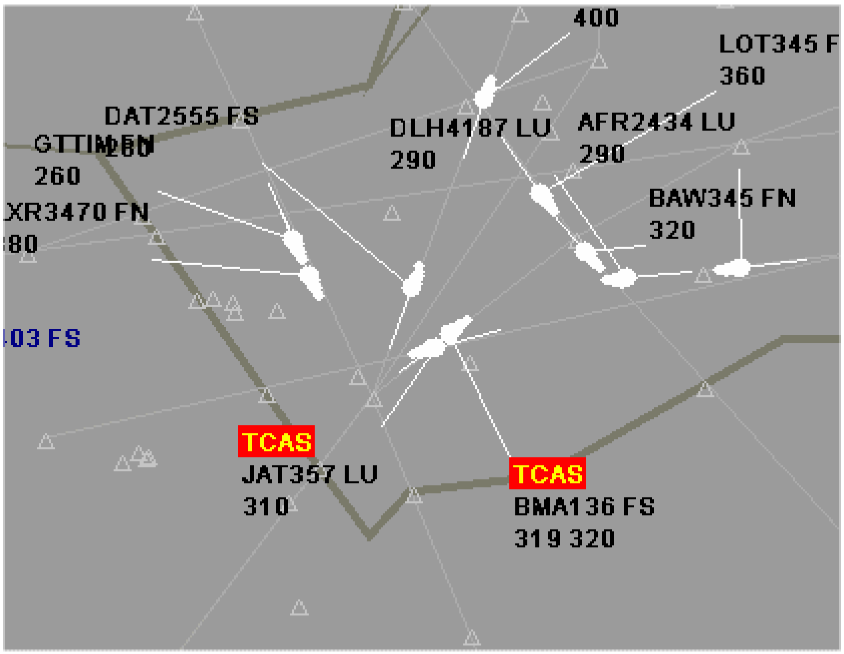

Figure 1: Minimum set interface

In the enhanced set interface, the RA indication on the label flashes (i.e. the alert is visible for 900 ms and not visible for 100 ms) and there is also an auditory alert issued.

3.1.3 Downlink delay

“Downlink delay” refers to the interval between the RA being generated in the cockpit and the display of the RA on the radar screen. For the purpose of the experiment, it was assumed that two technical solutions of RA downlink are available, both associated with a specific delay:

- Mode S radar: RA information will be displayed on the controller screen with a delay of 5 seconds,
- Network of omni-directional antennas (experimental technology): RA information will be displayed on the controller screen with no delay.

Note that the variable “downlink delay” cannot be completely crossed with the variable “HMI solution”. This means that the two downlink delays cannot be combined with all possible HMIs. Downlink delays can only be realised for those HMIs that include RA information, but not for the status quo HMI.

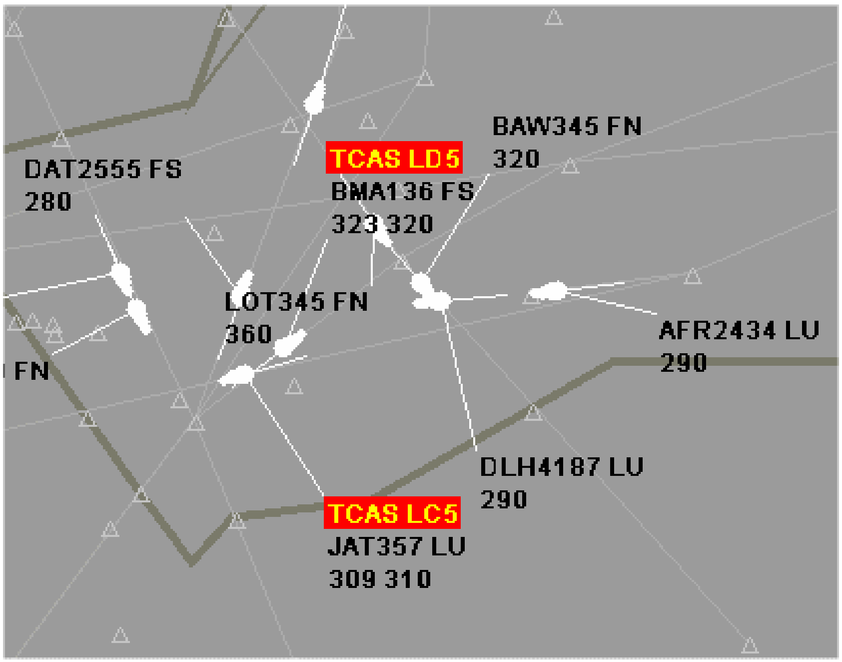

Figure 2: Intermediate and enhanced set interface

3.2 Dependent variables

The data collected in the experiment pertain to the following topics: Controller attitudes and acceptance, situational awareness, allocation of attention, and visual workload.

3.2.1 Controller attitudes

Controller attitudes were collected on a number of topics, including the general acceptance of RA downlink, the assessment of different HMIs, the benefits and drawbacks of RA downlink in different operational scenarios, and issues of technical implementation (for a more comprehensive list of topics see Chapter 5.4). In order to gather controllers' feedback, questionnaires were used and a de-briefing was carried out.

3.2.2 Situational Awareness

Situational Awareness refers to the "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (cf. Endsley, [4, 5]). Situational Awareness was measured on the basis of

- *A memory test on details of the traffic situation.* The memory test served to assess whether the controller fully understood the situation that led to the RA, as well as the type of RAs issued and the pilot's response to it. In this way, the memory test can be considered an objective (i.e., performance-based) measurement of situation awareness similar to the Situation Awareness Global Assessment Technique (SAGAT) proposed by Endsley [4, 5]. The well-known problems of this technique (in particular, its intrusiveness) does not apply to the present experiment, as the memory test did not yield any additional disruption of the exercise.

- *A Situation Awareness Self-rating scale.* The self-rating scale is a modified and shortened version of SASHA (Situation Awareness for SHAPE), EUROCONTROL's questionnaire for self-assessment of situation awareness. The scale consists of a set of questions on different aspects of situational awareness that need to be answered on a 5-point rating scale.

3.2.3 Allocation of attention

Some of the potential benefits of RA downlink, such as a better planning of the post-conflict situation, should be reflected in differences in the allocation of attention to certain items of information on the radar screen. For instance, if RA downlink facilitates planning, then the controller should scan surrounding traffic potentially conflicting with the aircraft's resolution manoeuvre earlier or more extensively. It is usually assumed that the controller's scanning behaviour is a valid indicator of the controller's focus of attention. In order to measure scanning behaviour (e.g., scanning entropy, number of fixations) eye-point-of-gaze measurements were carried out.

3.2.4 Visual workload

Visual workload will be measured on the basis of a controller's eye blink rate. Differences in the blink rate before and after the incident yielding the RA will be taken as indicators for changes in the level of visual workload. These changes in visual workload can be compared for the different HMI designs.

3.3 Assignment of independent variables to participants

Ideally, every participant would be presented with every possible combination of experimental variables. This, however, requires 35 experimental runs for every participant, as there are a total of 35 possible combinations of experimental variables: Five ACAS themes displayed with 3 different RA HMIs in two different delay conditions (i.e., 5x3x2 = 30) plus five ACAS themes shown with the HMI without advisories (i.e. 5x1 = 5). Therefore, a complete within-subjects design is not feasible.

Alternatively, one of the experimental variables could have been manipulated between subjects. That is, specific levels of the experimental variables could only be shown to a subset of participants. Nevertheless, as the purpose of the experiment is to obtain as much feedback as possible on the different HMIs, delay conditions, and traffic situations, it was decided to present all participants with all different levels of the experimental variables.

Because a complete crossing of experimental variables on the level of a single individual was not possible, a decision was made as to what variables were not fully crossed. For the experimental design, it was chosen not to completely cross ACAS theme and the HMI solution. This means that a specific individual does not see every ACAS themes with all of the four different HMIs.

The experimental design can be found in 0. It has the following characteristics:

- Every controller is exposed to every ACAS theme, once without RA, once with an RA in the “no delay” condition, and once with an RA in the “5 seconds delay” condition.

- Every controller is exposed to every of the possible HMIs (one without RA, three with RAs)
- Within an ACAS theme, experimental HMI versions are held constant for an individual participant, which means that there is only one HMI with an RA shown to a particular participant in a particular ACAS theme.
- Every participant is exposed to 15 different experimental runs.
- Over all participants, each HMI solution is presented with every ACAS theme and every delay condition equally often.

3.4 Assignment of traffic samples to independent variables and participants

In order to prevent participants from recognising a conflict situation, every traffic sample was only shown once to a particular participant. Because a single participant is exposed three times to a specific class of situations (i.e. the ACAS themes), three different traffic samples for every ACAS theme are required.

The assignment of participants to experimental conditions and traffic samples can be found in 0. In this assignment, it is ensured that

- every participant sees a particular traffic sample only once, and
- over a set of nine participants, every traffic sample is used equally often with each HMI version, each delay, and each ACAS theme. Because the sample size in the present experiment was not a multiple of nine, there is a slight imbalance in the usage of traffic samples. However, this is not considered as compromising the interpretation of the results.

3.5 Presentation order

Each controller was exposed to 15 different runs. In order to control for training effects, the order of presentation was randomised. Randomisation was done by generating ten different random lists of numbers between 1 and 15 that were used as presentation orders for the experimental runs. The ten presentation orders were then assigned to Participants 1 to 10, 11 to 20, and 21 to 30. The specific presentation order of traffic samples for each participant is provided in Appendix F.

3.6 Specific procedure for the eye-tracking runs

Due to the effort involved in the collection and analysis of eye-tracking data and the limited availability of the eye-tracker[2], it was decided to use eye-tracking only for a subset of the controllers. Eye-tracking data were collected during the second week of the experiment with six controllers. Furthermore, “eye-tracking runs” were only carried out for three out of the five ACAS themes (ATC error, pilot error, and combined ATC/pilot error), and only one delay condition (a delay of one second). In this way, only six eye-tracking runs per participant were required. The reason for this restriction was that six measured runs per participant could still be fitted into the normal experimental schedule (by using two blocks of three experimental

[2] The eye-tracker was used in a different experiment during the first week of RADE1.

runs), with the eye-tracker calibration procedure being carried out in one of the scheduled breaks (see Chapter 5.1). The experimental conditions realised in the eye-tracking runs are displayed in Table 1.

The proposed design allowed for investigating the following questions:

- Are there any differences with respect to scanning pattern and blink rate between a condition with RA downlink and a condition without RA downlink?
- Is the influence of RA information on the scanning pattern and the blink rate modified by the specific HMI solution chosen?

It should be noted that, in the RA downlink experiment, eye-tracking data are only used for exploratory purposes (i.e., to get a first indication of the impact of RAs) rather than for strict hypothesis-testing purposes.

	ACAS theme					
	Theme A		**Theme B**		**Theme C**	
No.	**No RA**	**RA**	**No RA**	**RA**	**No RA**	**RA**
1	HMI0	HMI1	HMI0	HMI2	HMI0	HMI3
2	HMI0	HMI2	HMI0	HMI3	HMI0	HMI1
3	HMI0	HMI3	HMI0	HMI1	HMI0	HMI2
4	HMI0	HMI1	HMI0	HMI2	HMI0	HMI3
5	HMI0	HMI2	HMI0	HMI3	HMI0	HMI1
6	HMI0	HMI3	HMI0	HMI1	HMI0	HMI2

Table 1: Experimental conditions in the eye-tracking runs

The procedure for the eye-tracking runs was as follows. From every controller group arriving in the second week (i.e. from participant 17 on), two participants were selected. The selection criteria were (a) that participants did not wear contact lenses, and (b) were willing to participate in the eye-tracking. One of the two selected participants was measured during the afternoon of Day 1, the other one was measured during the morning of Day 2. This means that there were 8 slots for eye-tracking sessions (from Monday afternoon to Friday morning). The additional two sessions were used in order to allow for repetitions of trials in case this was considered necessary.

Controllers taking part in the eye-tracking runs were subjected to a specific presentation order of experimental runs (and thus, did not follow the presentation order of runs as outlined in Appendix F). This special presentation order served to ensure that all target runs (as specified above) could be carried out within a slot of 2:20 hrs (including a break), either in the afternoon of Day 1 or the morning of Day 2.

4. EXPERIMENTAL ENVIRONMENT

4.1 Area Control Centre and airspace

The setting for the experiment was Cottam Centre, which was described to the participants as “a fictitious facility located somewhere in Europe”. During the experiment, participants were working in the Cottam Upper Sector (FL245 and above).

The following regulations in Cottam Upper Airspace apply

- Cottam airspace is RVSM airspace. This means that the minimum vertical separation below FL410 is 1000ft. Horizontally, the minimum separation is 5 NM.
- Even levels are used for westbound traffic, odd levels are used for eastbound traffic (semi-circular rule). Occasionally, reciprocal levels are allowed to facilitate traffic.

4.2 Experimental scenarios

For the simulation, 15 different traffic scenarios were used. All scenarios lasted between 3 and 9 minutes, and they were built based on real incidents. The radio-telephony (RT) used in the scenarios were simplified recreations of the original RT.

Table 2 provides the list of traffic scenarios used in RADE 1. Note that the first digit indicates the ACAS theme and the second digit indicates the particular traffic sample within the theme.

In some of the scenarios, STCA was working (and detected the potential conflict situation before an RA was issued); in other scenarios, STCA was not enabled (and thus, no STCA was issued prior to the RA).

	Traffic Scenario	ACAS theme	Conflict a/c	Duration (approx.)	STCA enabled[3]
	11	ATC Error	BAL504A BAW254	9 min.	Y
	12	ATC Error	FIN311 BMA204 BMA106	5 min.	N
	13	ATC Error	LAZ957 DLH4180	3 min.	Y
	21	Level-off	BAW323 RYR3240	4 min.	Y
	22	Level-off	LAZ175 RYR2317	4 min.	N
	23	Level-off	BAW461 AFR2510	6 min.	Y
	31	False ACAS	BAW586	4 min.	N
	32	False ACAS	SAS569	5 min.	Y
	334	False ACAS	SWR836	4 min.	Y
	41	ATC Error + Pilot Error + Pilot ACAS Error	MAH507 RYR2207	5 min.	N
	42	Level Bust + Pilot ACAS Error	BMA136 JAT357	5 min.	Y
	43	ATC Error + Pilot ACAS Error	RYR1016 GTTIM	7 min.	Y
	51	Pilot Error	BAW785 DAT44J	8 min.	N
	52	Pilot Error	VIR200 DLH4180	4 min.	Y
	53	Pilot Error	ROT960 EZY199	6 min.	Y

Table 2: List of traffic scenarios used in the RA downlink experiment

4.3 Types of Resolution Advisories

Resolution Advisories as issued by ACAS can be categorised (a) according to the direction, and (b) according to the type [8].

Direction of RAs. There are two different directions for suggested resolutions: upward and downward.

- An upward RA is either a climb or a limit descend.
- A downward RA is either descend or limit climb.

[3] STCA used in the Experiment did not take into account the Cleared Flight Level, it was based only on the Actual Flight Level.

Types of RAs. RAs are either given for a single direction or for multiple directions.

- Single direction RAs limit vertical speed only in one direction (i.e., either upward or downward). Single direction RAs can be
  - corrective – meaning that the pilot is required to *change* the current vertical rate, or
  - preventive – meaning that the pilot is not required to change the vertical speed, but is advised not to exceed a certain vertical rate.
- Multiple direction RAs limit vertical speed in both the upward and the downward direction.

It is possible that more than one RA is issued to an aircraft. In this case, the subsequent RAs can be strengthening (e.g., “increase descend” after “descend”), weakening (e.g., “limit climb 500 ft per minute” after “limit climb 1000 ft per minute”), or they can reverse their sense (e.g., “descend” after “climb”).

In the simulation, only single direction RAs were issued. In some scenarios used in the simulation, more than one RA was given to one aircraft. Subsequent RAs could then be weakening, strengthening, or reversing their sense. A list of the RAs used in the simulation along with their abbreviations can be found in Appendix C.

4.4 Controller working positions

There were four controller working positions in the experimental room. Each of the controller working positions consisted of a LINUX workstation with a Barco LCD display. A computer mouse served as input device for the participants. Note that due to the restricted system interaction in the experiment, the mouse was only used for setting up the radar screen (zoom and centre), selecting a label (to access further information), de-conflicting labels, and displaying aircraft trajectories.

In the experiment, EUROCONTROL’s basic EATMP interface was employed. In the experimental conditions (with RA downlink), this interface was enhanced with RA information. One of the main characteristics of the EATMP interface is that all relevant flight data are accessible through the radar labels and are displayed on the radar screen. Thus, all relevant information on the traffic in the sector was displayed on the Barco screen. Except for the auditory information described below, there were no other sources of flight information (such as paper flight strips or additional information displays) provided to the participants.

Controllers were also provided with a headset that enabled them to listen to the R/T communication between ATC (i.e., the ‘trainee’) and aircraft in the sector as well as to the co-ordination with adjacent sectors. Figure 3 displays a controller working position with the Barco LCD display, the mouse and the headset.

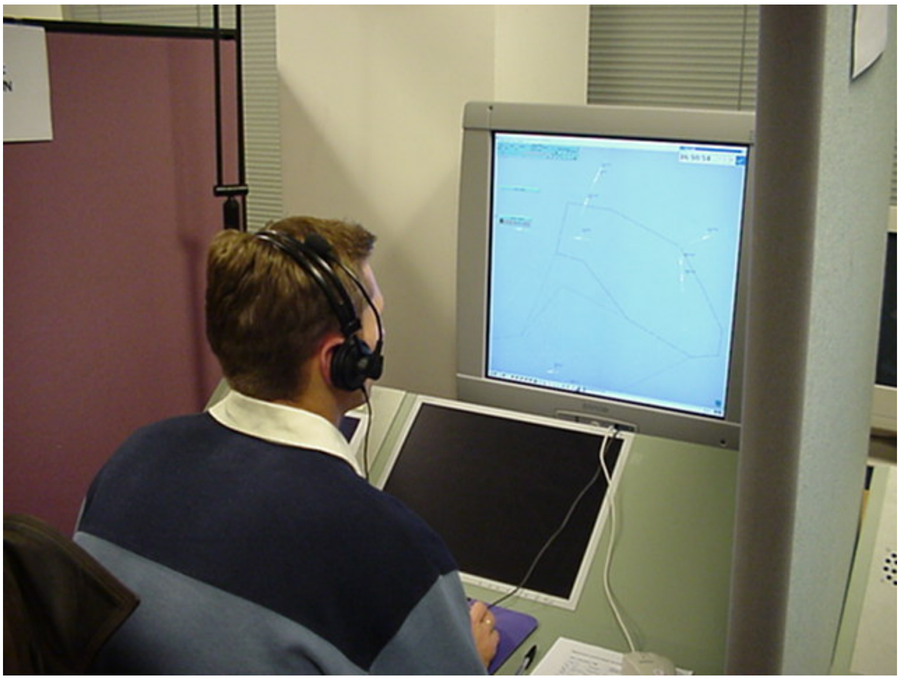

Figure 3: Controller working position with Barco LCD display, mouse, and headset

5. CONDUCT OF THE EXPERIMENT

5.1 Structure of the experiment

The RA downlink experiment consisted of three main parts:
1) a briefing session
2) the experimental scenarios, and
3) the de-briefing.

1. The briefing session. In the briefing session, controllers attended a number of presentations covering the following topics:
- The purpose of the experiment,
- The controller's task during the experiment,
- The Human-Machine Interface used in the experiment,
- The ACAS algorithm and RA advisories.

Before the presentations, a pre-experimental questionnaire was handed out (see 5.4.1).

2. The experimental scenarios. Each controller was exposed to 15 different traffic scenarios which lasted between 3 and 9 minutes. The procedure for running a scenario was as follows: A member of the experimental team started up the traffic scenarios for every participant in a specific order, and with a specific HMI version and delay condition. The scenario was then frozen and the controller was instructed to build up an understanding of the traffic situation (similar as to when taking over a position), by scanning the information displayed on the radar screen. As soon as the controller indicated to have an understanding of the situation in the sector, the scenario was run. At the end of a scenario, a recorded voice announced the end of the exercise and instructed the participant to fill in the questionnaires. One questionnaire was on details of the traffic situation, the other was a self-rating scale for situational awareness. The screen was switched off by a member of the experimental team, before participants filled in the questionnaires.

3. The de-briefing. Controllers feedback on RA downlink and the different HMIs used in the experiment were collected on the basis of a post-experimental questionnaire and in a final discussion. For a more detailed description of the post-experimental questionnaire and the topics discussed in the de-briefing, see Chapter 5.4.3.

5.2 Time schedule

The RA downlink experiment took place at EUROCONTROL Experimental Centre at Brétigny from 17 November 2003 to 28 November 2003. Controllers were invited to the simulation in groups of 2 and 4 controllers. Every group of controllers participated in the experiment for two days (referred to as Day 1 and Day 2 below). Table 3 shows the generic time schedule for each group on the two days of the experiment.

Day 1	Day 2
Briefing and introductions **9:00 – 9:20** – Welcome & pre-trial questionnaire **9:20 – 10:20** – Experiment, team, and HMI **10:20 – 10:40** – Break **10:40 – 11:40** – ACAS and ATC, types of RA **11:40 – 12:40** Lunch **Experiment – Part 1 (each scenario is followed by a questionnaire)** **12:40 – 13:00** – Lab and HMI familiarisation **13:00 – 13:20** – Scenario 1 **13:20 – 13:40** – Scenario 2 **13:40 – 14:00** – Scenario 3 **14:00 – 14:20** – Break **14:20 – 14:40** – Scenario 4 **14:40 – 15:00** – Scenario 5 **15:00 – 15:20** – Scenario 6 **15:20 – 15:40** – Break **15:40 – 16:00** – Scenario 7 **16:00 – 16:20** – Scenario 8 **16:20 – 16:40** – Scenario 9 **16:40 – 17:00** – Spare run or break	**Experiment – Part 2 (each scenario is followed by a questionnaire)** **9:00 – 9:20** – Scenario 10 **9:20 – 9:40** – Scenario 11 **9:40 – 10:00** – Scenario 12 **10:00 – 10:20** – Break **10:20 – 10:40** – Scenario 13 **10:40 – 11:00** – Scenario 14 **11:00 – 11:20** – Scenario 15 **11:20 – 11:40** – Break **11:40 – 12:00** – Spare run or lunch **12:00 – 12:20** – Spare run or lunch **12:20 – 13:20 –** Lunch break **Debriefing** **13:20 – 14:20** – Final questionnaire **14:20 – 15:20** – Debriefing **15:20 – 15:25** – Farewell

Table 3: Time schedule for the RA downlink experiment.

Except for the last day of the simulation (i.e., Friday 28 November 2003), one group of controllers (i.e., 2 or 4 participants) arrived every weekday. As a consequence, there were overlapping groups during most of the experiment.

5.3 Participants

A total of 30 air traffic controllers from ten European ACCs participated in the experiment. All but one of the participants were active area controllers; the remaining participant had been an active controller but works presently in the R&D department of a national service provider. Figure 4 provides a breakdown of the experimental participants as a function of the ACC they are employed at (in brackets the number of participants from a specific centre).

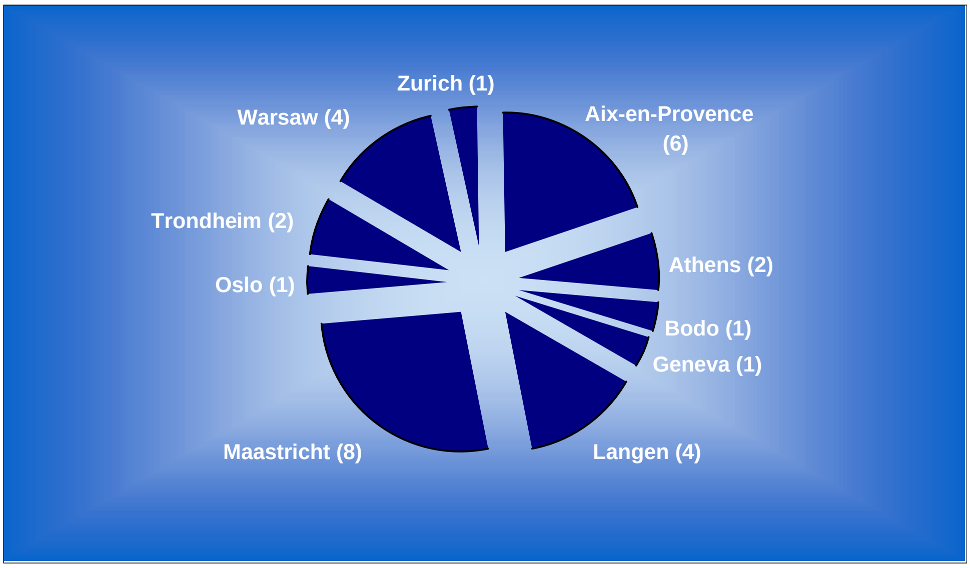

Figure 4: Home ACCs of the participants in the RA downlink experiment.

For controllers from Maastricht UAC, the location of the home ACC and the controller's nationality did not always correspond. Therefore, a breakdown of the experimental participants according to their nationality is given in Figure 5 (in brackets the number of participants with a specific nationality). As can be seen from the figure, there were ten different nationalities in the controller sample, with the largest groups being French and German.

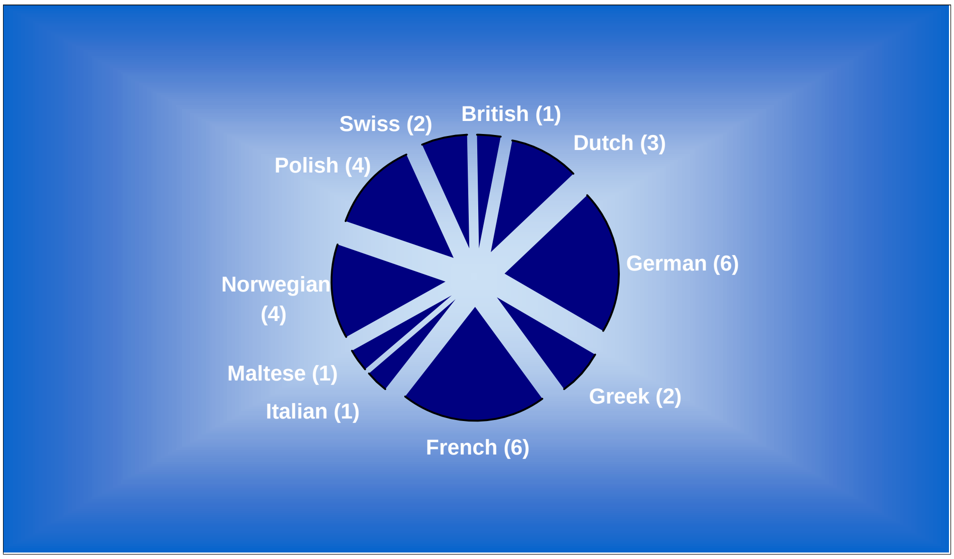

Figure 5: Nationality of participants in the RA downlink experiment

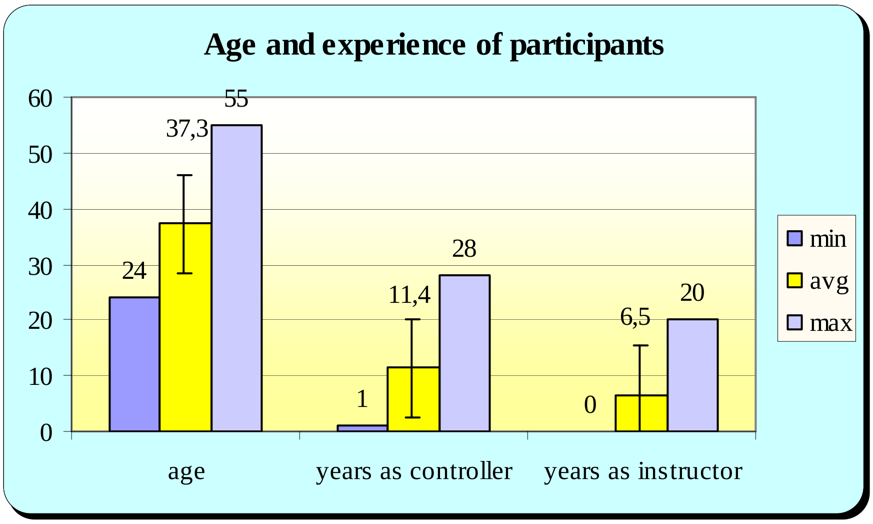

Figure 6: Age and experience of participants in the RA downlink experiment

The mean age of participants was 37 years (Standard Deviation, SD = 8.8, ranging from 24 to 55 years). On average, participants worked as licensed controllers for 11 years (SD = 8.0), ranging from 1 to 28 years of working experience. Of the 30 controllers, 26 had been working as instructors (including On-The-Job Training), with a mean experience as instructor for 7.5 years (SD = 5.6), ranging from 2 to 20 years. Figure 6 provides information on the age and the experience of the experimental participants.

5.4 Data collection techniques

5.4.1 Pre-experimental questionnaire

At the beginning of the experiment (i.e., before the presentations and the simulation runs), a pre-experimental questionnaire was handed out to the participants. This questionnaire served to obtain information on

- Controllers' background (biographical information and experience as ATCo),
- Knowledge of ACAS,
- Pre-conceptions on the display of RAs to the controller.

The pre-experimental questionnaire can be found in Appendix A.

5.4.2 Post-exercise questionnaire and test

Following a simulation run, the participants were requested to fill in a memory test and a self-rating scale. Both the memory test and the self-rating scale served to assess the controller's understanding of the traffic scenario that was displayed to them and, thus, can be used as measurements for the controllers' situational awareness. In this way, subjective measures of situation awareness (i.e., controllers' self rating) can be compared with objective measures of situation awareness (i.e., knowledge of certain critical items of information). The modified

SASHA questionnaire and the memory test used in the RA downlink experiment can be found in Appendix A.

By handing out the questionnaire and test after each experimental run (i.e., 15 times for every participants), measurements of situational awareness can be compared between the different experimental conditions.

5.4.3 Post-experimental questionnaire

After the experimental runs, controllers were requested to fill in a post-experimental questionnaire. This questionnaire focused on the following topics:

- General assessment of ACAS and RA downlink
- Impact of RA downlink in different situations
- Human-Machine Interface
- Procedural issues related to the introduction of RA downlink
- Evaluation of the experiment.

Some questions in the post-experimental questionnaire were identical to questions in the pre-experimental questionnaire. In this way, the changes in controllers' attitudes and opinions as a consequence of participation in the experiment can be investigated. The post-experimental questionnaire can be found in Appendix A.

5.4.4 De-briefing

Following the post-experimental questionnaire, a de-briefing was held with each controller group consisting of 2 or 4 participants. The following topics were addressed in the de-briefing:

- Thought experiments on RA downlink malfunction: The effect of RA downlink malfunction on safety was discussed. The situations discussed include a false downlink of an RA (i.e., an RA that is shown on the controller screen although there was no RA issued in the cockpit) and a missed RA (i.e., an RA that is issued in the cockpit but not shown on the controller screen).
- Legal consequences. In the de-briefing, controllers were asked whether they see any problems related to legal issues and liability and, if so, whether there are any solutions to these problems.
- Technical implementation. It was asked whether some of the RAs should be filtered for information display and what the maximum acceptable downlink delay is.
- Procedural changes. It was discussed whether the introduction of RA downlink required the change of current operational procedures. For instance, it was inquired whether the phrase "Follow ACAS" should be introduced.
- HMI issues. Controllers were asked to give their opinion on the various RA displays, including the voice and vibration alerts.
- Experimental issues: Controllers were requested to indicate whether they experienced the simulation as realistic. Also, controllers should indicate which step should be taken next in the investigation of RA downlink.

During the de-briefing, comments were noted in real-time and displayed to the participants on a screen. This served to ensure that the participants' comments were understood and noted down correctly by the experimental team.

The list of questions to be asked in the de-briefing can be found in Appendix B.

5.4.5 Eye tracking

The participants' directions of gaze on a number of predefined surfaces of interest as well as the eye-blink rate were measured with an eye-tracker[4]. Data recording and analysis were done with equipment and software from Applied Science Laboratories - ASL (eye-tracker model 501, analyses software package Eyenal [12]). Both are property of the Human Factors Laboratory at EUROCONTROL Experimental Centre.

The ASL model 501 eye tracker is based upon the "pupil corneal reflection", also known as "bright pupil", principle. The head-mounted equipment (see Figure 7) consists of a headband, a 50 Hz black and white eye camera, a visor and a sensor for the magnetic head tracker and a colour camera to film the scene in front of the controller.

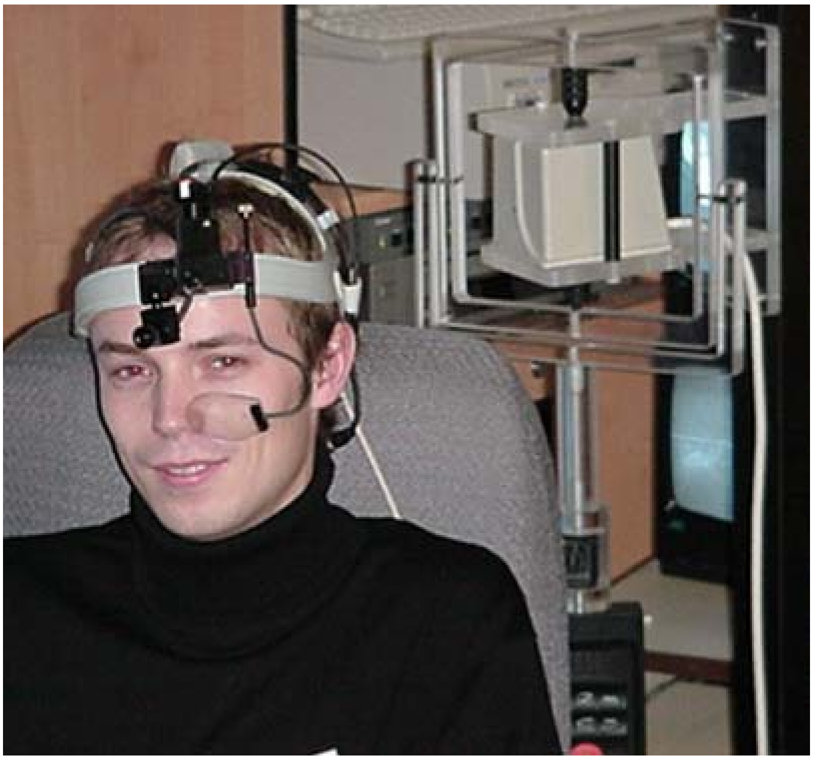

Figure 7: ASL 501 equipment used in the experiment

[4] An eye tracker just records eye movements; in the current study, eye movements and head movements were recorded. The product of eye- and head-movements was used to establish the subjects' direction of gaze. "Eye tracker" in the current report refers, thus, to a combined unit for eye and head tracking.

The ASL model 501 is designed to measure a participant's direction of gaze (eye-line of gaze with respect to the head). The direction of gaze was displayed as a cursor superimposed on the image from the scene camera. A videotape of this image was created as a permanent record. For the analysis, digitally recorded data (i.e., time, x- and y-co-ordinates of the eye position, and pupil diameter) were used. External data events (markers) were recorded in order to identify certain critical times during the data analysis. These included the start and end of a scenario and the onset/offset of an RA display on the screen.

Every 20 ms the eye tracker recorded the current status of the pupil diameter and the direction in which eye and head were aimed. After data recording, the analysis software allowed for the deduction of the following parameters:

- the scanning pattern,
- the amount of fixations,
- the dwell time,
- the pupil diameter, and
- the eye-blink activity (which permits blink rate and duration to be derived).

In the current study, a number of these measures were used as indicators of mental and visual workload (for the relationship between these measurements and workload see [13, 14, 15, 16, 17, 18]). In particular, two relationships are important. First, eye-blink rate is usually considered a negative indicator for (visual) workload: the higher the visual workload, the lower the eye-blink rate. Second, the scanning behaviour is considered an indicator of the controller's focus of attention. The assumption is made that if a controller looks at a particular area of interest he or she is paying attention to that area.

6. RESULTS AND DISCUSSION

6.1 Previous experiences

A number of items in the pre-experimental questionnaire addressed controllers' operational experiences with incidents and ACAS RAs. These items were not thought to deliver objective measurements for the frequencies of incidents and RAs at different European ACCs. Rather, they aimed at obtaining information on the participants' *individual experiences* with RAs and their role in incidents, which might have influenced their preconceptions about the utility of RA downlink.

Of the 30 participants, 24 participants indicated that they had witnessed at least one incident where a serious violation of separation minima has occurred or could have occurred. These incidents either concerned traffic under their responsibility or under responsibility of adjacent sectors or colleagues. Those participants who had witnessed at least one incident were asked to specify the number of witnessed incidents. Three participants did not provide an indication; the indications of the remaining participants ranged between 1 and 15 incidents. The mean rating (M) was 4.1 with a Standard Deviation (SD) of 3.9.

Six of the participants who had witnessed one or more incidents stated that there were no ACAS RAs generated in these situations. Eighteen participants, in contrast, had experienced RAs in at least one of the witnessed incidents. For this latter group of participants, the indicated numbers of incidents with RAs ranged from 1 to 5 (M = 2.08, SD = 1.5), amounting to 20 to 100 percent of all witnessed incidents (M = 55.6, SD = 22.3).[5]

Participants who had experienced incidents (with or without RAs) were asked to indicate on a 5-point scale ranging from "not at all" to "absolutely" whether RAs had helped to solve the conflict situations. Figure 8 provides the controllers' responses to this question. The mean rating (M) was 3 (corresponding to a neutral assessment), with a Standard Deviation (SD) of 2. Only 19 of the 24 controllers who had witnessed one or more incidents responded to this question; most of the missing answers originate from those controllers who had not witnessed incidents with RAs. Possibly, these incidents without RAs concerned aircraft not equipped with TCAS II and, thus, cannot be interpreted as (negative) experiences with RAs.

Eighteen of the 30 participants reported that they were at least once informed by a pilot about a nuisance RA (e.g., an RA that was due to fast climbing or fast descending aircraft before levelling off). Numerical estimates of the number of reported nuisance RAs ranged from 1 to 10 (M = 4.39, SD = 3.4); two participants described the number of nuisance alerts as "plenty" or "a lot".

[5] The indicated frequencies of incidents and RAs should be interpreted with some caution. First, not all participants who had witnessed incidents with or without RAs provided exact frequencies of the events. Second, the indicated numbers reflect controllers' *recollections* of the incidents and, thus, may be potentially biased.

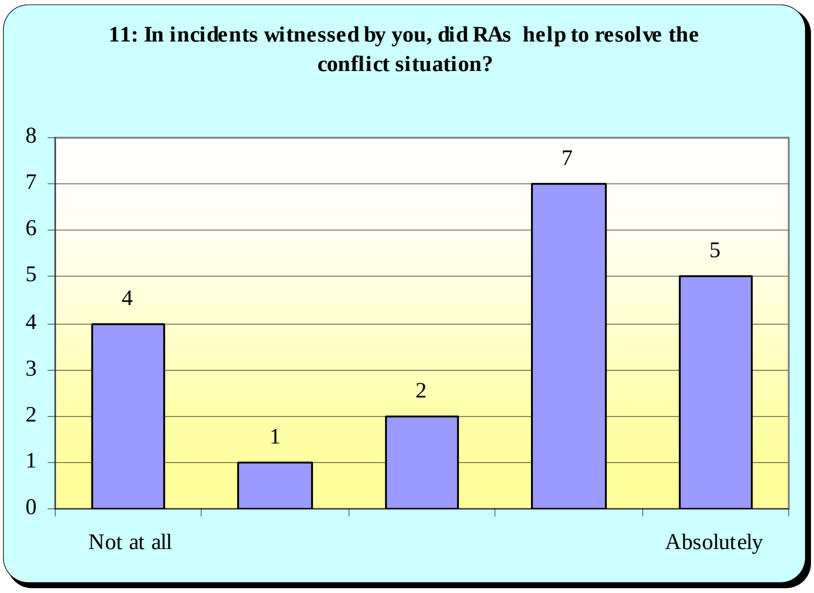

Figure 8: Experience with RAs in witnessed incidents

Thirteen of the 30 participants were at least informed once by a pilot about a false RA (i.e., an RA occurring without any other traffic in the vicinity). Numerical estimates of the number of reported false RAs ranged from 2 to 5 (M = 1.8, SD = 1.17); again, two participants provided only qualitative estimates ("few" and "a lot" respectively).

6.2 Knowledge of ACAS and RA downlink

Both in the pre- and in the post-experimental questionnaire, participants were asked to rate their knowledge of TCAS II on a scale from poor to very good. Figure 9 and Figure 10 show the distribution of the ratings.

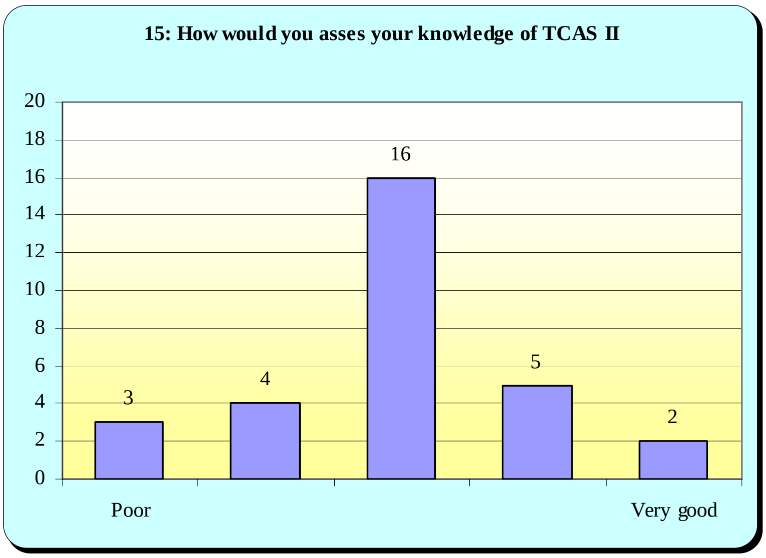

Figure 9: Knowledge of TCAS II before the experiment

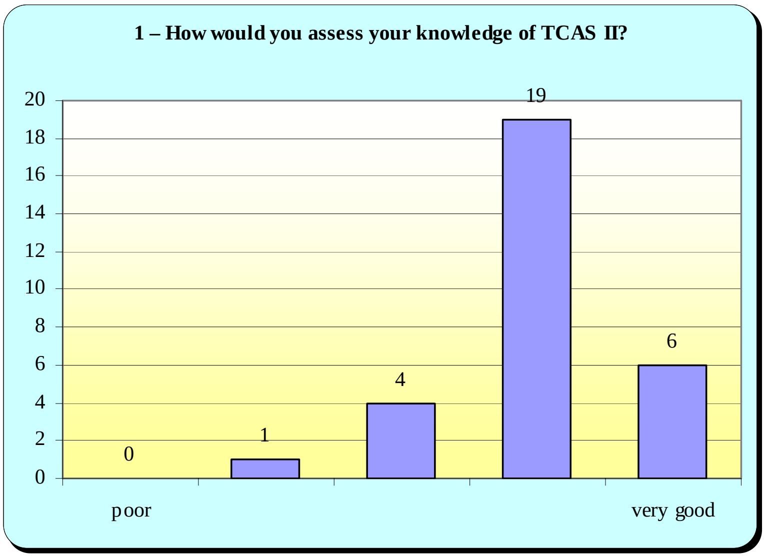

Figure 10: Knowledge of TCAS II after the experiment

The mean rating of TCAS II knowledge was 2.97 (*SD* = 1.0) before the experiment (in the pre-experimental questionnaire) and 4.0 (*SD* = .70) after the experiment (in the post-experimental questionnaire). According to a t-test, the differences between the pre- and the post-experimental ratings are significant ($t(30) = 6.66$, $p = .001$). This means that controllers perceived their knowledge of TCAS II as substantially better after having participated in the RA downlink experiment.

Like with TCAS II knowledge, controllers were requested to rate their level of knowledge on RA downlink before and after the experiment (see Figure 11 and Figure 12).

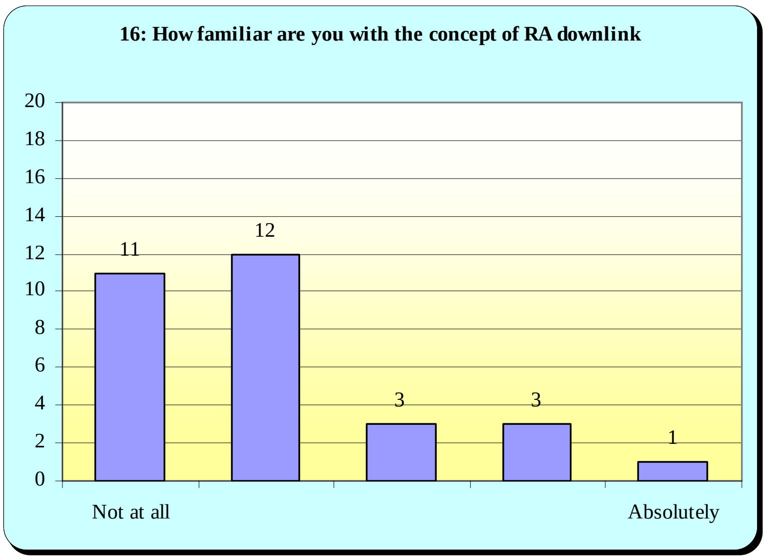

Figure 11: Familiarity with RA downlink before the experiment

Before the experiment (in the pre-experimental questionnaire), the mean rating of knowledge on RA downlink was 2.03 (*SD* = 1.1); after the experiment, the mean rating was 3.7 (*SD* = .84). Again, this difference was highly significant ($t(30) = 7.53$, $p < .001$). This indicates that controllers perceived a substantial improvement in their knowledge of RA downlink after having participated in the experiment.

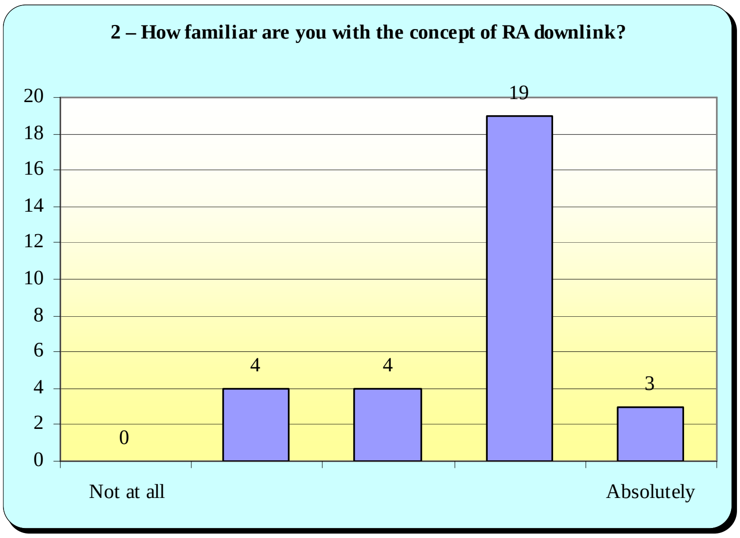

Figure 12: Familiarity with RA downlink after the experiment

At the end of the experiment, participants were asked whether air traffic controllers in general would benefit from additional TCAS training. As Figure 13 shows, the majority of controllers considers additional TCAS training as "absolutely" beneficial. Only two controllers do not see a need for additional training, one controller is unsure about it.

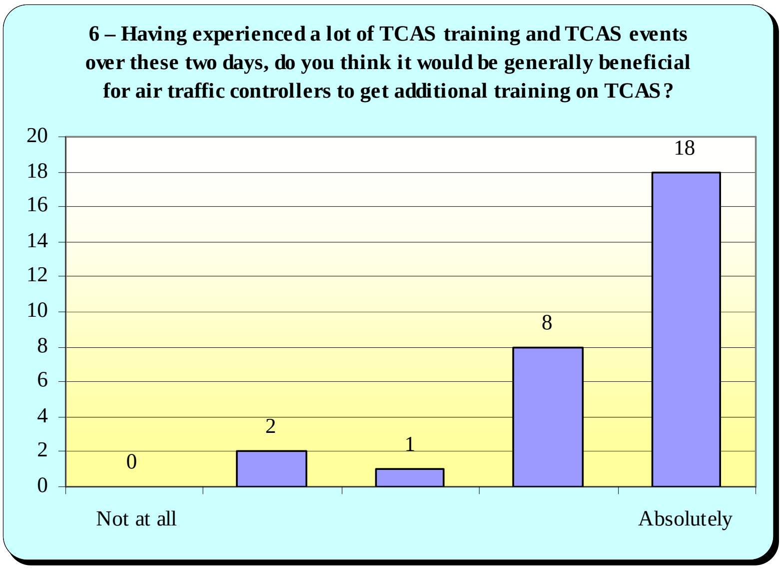

Figure 13: Necessity of additional TCAS training for controllers

6.3 Controllers attitudes on RA downlink

6.3.1 General acceptance

In order to assess controller's general acceptance of RA downlink, participants were asked to indicate how useful in their opinion the display of RAs to the controller is. This question was asked at the beginning of the experiment as well as at the end. Figure 14 and Figure 15 show the distribution of answers.

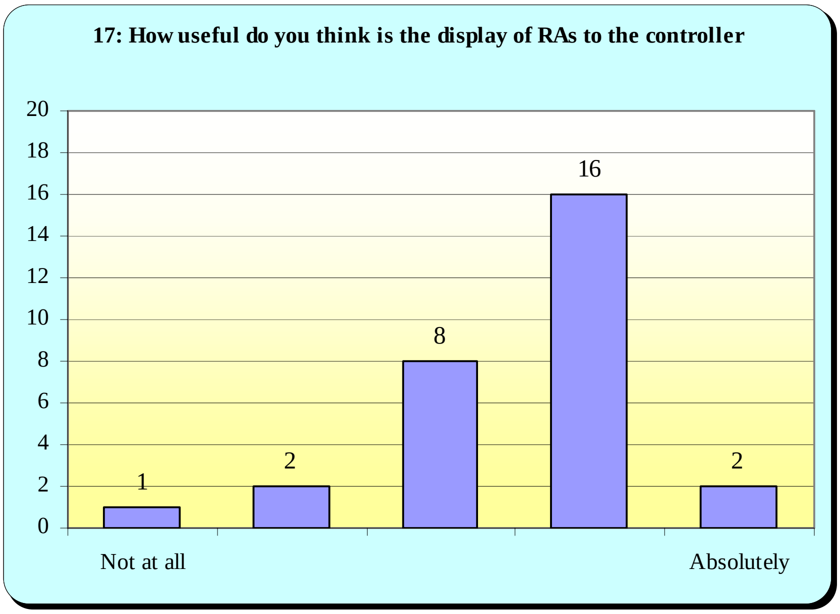

Figure 14: Rated utility of RA downlink before the experiment

The mean rating before the experiment is 3.55 (SD = .87); after the experiment, the mean rating is 3.59 (SD = .73). Both ratings reflect a moderately positive assessment of RA downlink. The difference between the pre- and the post-experimental ratings are negligible, as shown by the results of a t-test for dependent samples ($t(28) = .20$, $p = .85$).

Thus, controllers' attitudes did not become more positive with more information on and exposure to RA downlink. When interpreting this finding, though, it needs to be taken into account that controllers' initial assessments were already positive. Also, the initial attitude on RA downlink was based on fairly limited knowledge of RA downlink (as indicated by low ratings for knowledge on RA downlink before the experiment). This suggests that the initial ratings reflected more an attitude of openness within the participant group than a well-founded opinion. The post-experimental ratings, in contrast, are based on a much sounder knowledge of RA downlink. Thus, although the pre- and post-ratings do not differ quantitatively, the quality of the answers does.

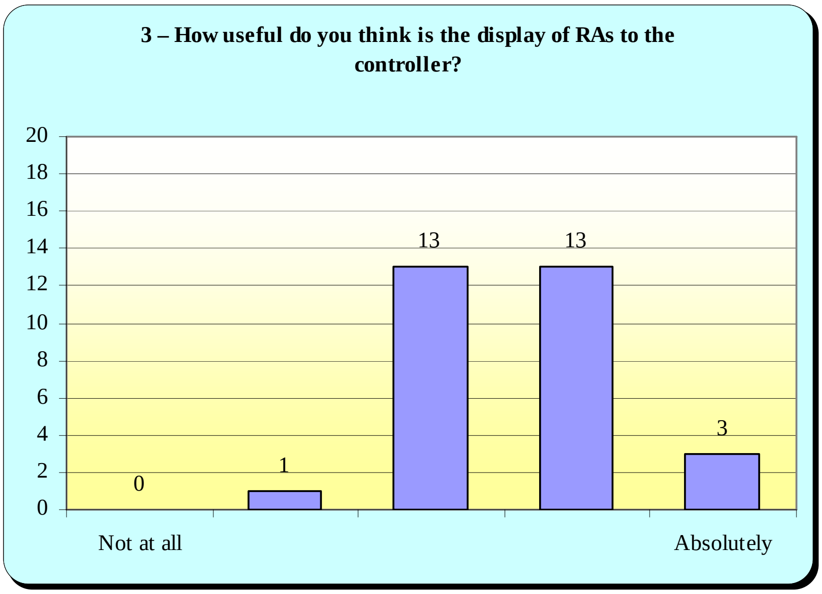

Figure 15: Rated utility of RA downlink after the experiment

6.3.2 Operational advantages and disadvantages of RA downlink

In the pre- and post-experimental questionnaires, controllers were asked to indicate what, in their opinion, the operational advantages and disadvantages of displaying RAs to the controller are. Answers were given in an open format and were analysed using the method of content analysis [e.g. 9]. The procedure for the content analysis was as follows: On the basis of the controllers' responses, a list of categories of potential advantages and disadvantages was produced. Controllers' responses were then coded for frequency, that is, it was counted how often a specific category was mentioned. For this coding process, a fairly general level of analysis was used. This means, that coding was based on concepts and ideas rather than on specific wordings.

Operational advantages. Table 4 provides a list of operational advantages (ordered according to categories), the frequency with which they were named, and the different aspects mentioned.

ID	Category	Frequency	Specific aspects mentioned
1	Improves anticipation of pilot manoeuvres	16	• Better comprehension of the traffic situation • Better anticipation of the traffic situation • Reduces the surprise factor
2	Potentially faster and more reliable than pilot report	14	• Pilot might not report at all • Pilot might report late • Busy frequency can delay pilot report
3	Directs the controller's attention to the problem	7	• Controller can be alerted to an unnoticed problem • Controller can adjust his conflict scanning
4	Prevents the controller from issuing contradictory clearances	6	• Controller is less likely to issue a contradictory clearance • Controller can retract previous clearance • Controller knows that it is up to the machine to decide and the pilot to act
5	Helps to give traffic information	4	• Earlier traffic information to concerned aircraft • More accurate traffic information to concerned aircraft • Traffic information to third party aircraft
6	Provides a further safety net	2	• In case STCA does not work • In case STCA does work
7	Facilitates planning of the post-conflict situation	2	
8	Decreases time pressure	2	• Controller can identify situation earlier • Controller has more time for situation assessment and action planning
9	Helps to reduce stress	1	
10	Gives opportunity to check consistency of RAs	1	
11	Reduces R/T in conflict situation	1	

Table 4: Potential operational advantages of RA downlink

Category 1 (improved anticipation of pilot manoeuvre) was defined fairly broadly and includes both the comprehension of the current traffic situation as well as the projection of the traffic situation into the near future (anticipation). In this way, the category captures the concept of "situation awareness" as defined by Endsley [e.g. 4, 5].

Operational advantages were also discussed during the final de-briefing. The opinions expressed in the de-briefings largely mirror the results from the post-experimental questionnaire. There was one additional benefit of RA downlink not mentioned in the questionnaires: in case of high traffic load, the RA information on the screen can help the controller to change the priority of tasks.

Operational disadvantages. Like for advantages, controllers were asked to indicate what, in their opinion, the operational disadvantages of RA downlink were. Table 5 gives an overview of the controllers' responses to this question.

As the above list shows, controllers main concern is that the analysis of RA information draws too much on their attention (see Category 1). As a consequence, controllers might fail to monitor other aspects of the traffic situation, either with respect to the conflict situation detected by ACAS or with respect to conflicts elsewhere in the sector (Category 2). This concern, however, is seen as highly dependant on the design of the HMI, and thus often expressed conditional to the way the RA information is displayed. The following statements were made: "if the display is too 'aggressive' – too much information and an audio signal – it could be distracting for the controller and sometimes confusing"; "it depends how it is displayed - in the label it could be distracting"; "might lead to information overload, especially with an extreme HMI". Issues related to the HMI will be further discussed in Chapter 6.5.

There are also some concerns that are more conceptual in nature. Out of these more conceptual concerns, the dominant one is related to the fact that the RA and the subsequent pilot action can diverge. With RA downlink, the controller might falsely assume that the pilot is following the RA. In addition to the potential inconsistency between RA and pilot action, there is also the possibility of inconsistency between the RA and the pilot report. In this situation, the controller has to determine which of the two information sources is trustworthy.

The potential disadvantages of RA downlink were also discussed in a group setting during the de-brief. The disadvantages named in the de-briefing reflect the ones listed in the questionnaire, and were mostly concerned with the potential information overload when displaying RAs to the controller. In addition to concerns expressed in the questionnaire, it was pointed out that "if you get too many alerts or too much information with them, you will tend to ignore the alerts".

ID	Category	Frequency	Specific aspects mentioned
1	Increases amount of information to be analysed	19	• Information overload, especially in complex situations • Analysis of information is time-consuming • Analysis of information to be done under time pressure • Integration of information difficult, especially with several RAs • Radar screen is cluttered • Risk of misinterpretation is increased • Unnecessary RAs should not be displayed
2	Distracts controller from other problems	10	• Controller should not interfere, no reason to alert him • Narrows attention down to a single problem (tunnel vision) • Observing changes in RAs distracts controller from general conflict analysis • If conflict was already identified or reported, RA draws on attention unnecessarily. • Distracting if RA is displayed in label with no possibility to switch-off • Distracting if HMI is too eye-catching or aggressive
3	Can mislead the controller to expect a/c manoeuvres	5	• Pilot might not follow RA • Pilot might initiate the reverse manoeuvre • Controller can falsely believe situation is sorted out
4	Introduces possibility of false RA downlink	3	• Induces new safety problems • Creates stress for the controller • False RAs need to be filtered out
6	Renders responsibility for a/c separation unclear	2	• When to pass on responsibility to pilot (RA vs. pilot report)? • When to regain responsibility ("clear of conflict" vs. pilot report)?
7	Changes pilots' reporting behaviour	1	• Pilots might not report RAs any more
8	Changes controllers' style of control	1	• Controllers will use RA downlink as separation tool
9	Makes controller more likely to interfere in case of an RA	1	• Controllers know what the pilot is supposed to do
10	Has technical restrictions	1	• Slow and not yet established

Table 5: Potential operational disadvantages

6.3.3 RA downlink in different situations

In the post-experimental questionnaire, controllers were asked to rate the benefits of RA downlink in specific operational scenarios. These scenarios referred to different causes for the RA being issued (such as pilot error, ATC error, false ACAS alert, and high vertical rate before level off) as well as to different pilot reactions following the RA (such as pilot does not report the RA, or does not follow the advisory). In the questionnaire, controllers were not requested to give reasons for their answers. During the de-briefings, though, participants provided additional explanations why certain types of RAs should or should not be filtered. Hence, if a motivation is given for a certain answer, this motivation is taken from the responses in the de-briefing.

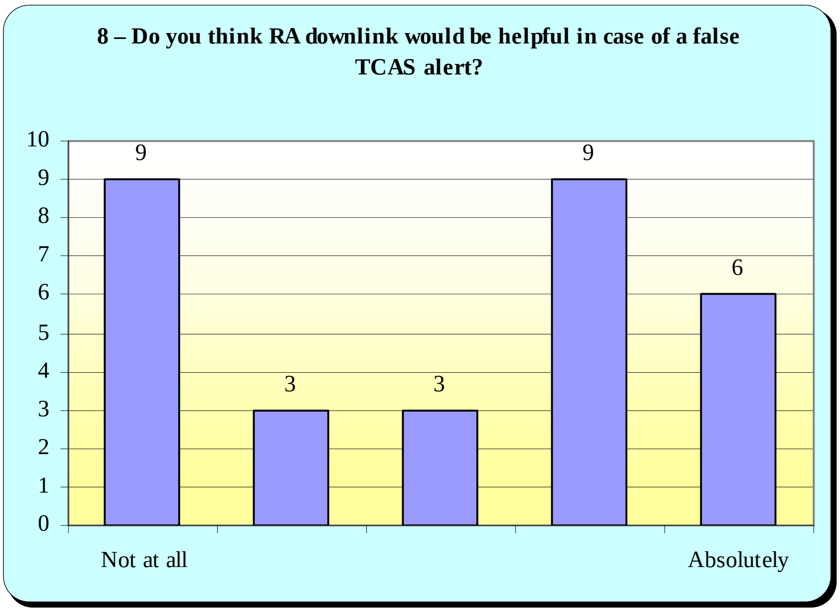

Figure 16: Utility of RA downlink in case of a false alert

Participants' opinions diverge as to whether RA downlink is helpful in case of a false ACAS alert (see Figure 16). Out of the 30 participants, 12 do not see a benefit in displaying a false alert (i.e., their ratings are on the negative side of the dimension); whereas 15 do see a benefit (i.e., their ratings are on the positive side of the dimension). The average rating in the group is neutral (*M* = 3.0, *SD* = 1.6). The argument against displaying a false ACAS alert is that it is irrelevant for the controller as it does not indicate a conflict situation; the argument in favour of displaying a false ACAS alert is, that although the ACAS alert might be false, the pilot could still follow the advisory.

Similarly, controllers have different opinions on whether RA downlink is helpful in case the RA has been triggered by a high vertical rate before level off (see Figure 17). Fourteen participants consider such an RA as relevant for the controller, ten participants do not consider such an RA as relevant. As a consequence, the average rating in the group is fairly neutral (*M* = 3.1, *SD* = 1.4). The argument against showing these 'nuisance' RAs to the controller is that they do not point to a real conflict situation and do not imply a deviation from the ATC clearance. Arguments for displaying nuisance alerts are that (a) pilots might overreact to ACAS RAs (thereby deviating from the ATC clearance) and (b) even if they do not overreact it is comfortable for the controller to know that pilots are alerted not to bust their level.

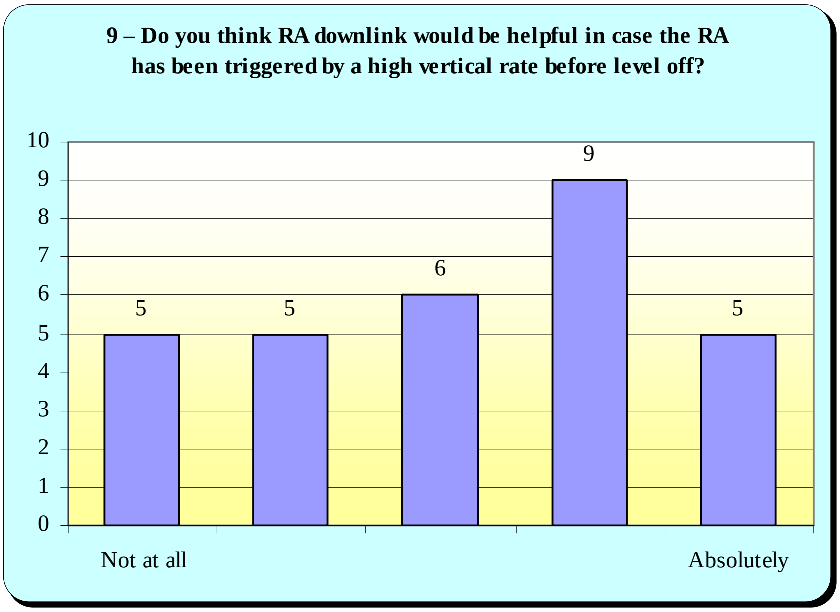

Figure 17: Utility of RA downlink in case of level-off

As regards RAs that are due to a pilot error or an ATC error (and, thus, point to a real conflict situation), participants' opinions are more consistent (see Figure 18 and Figure 19). Most of the controllers think that RA downlink is beneficial in case of an ATC error (*M* = 4.2, *SD* = 1.0) and a pilot error (*M* = 4.2, *SD* = 1.0).

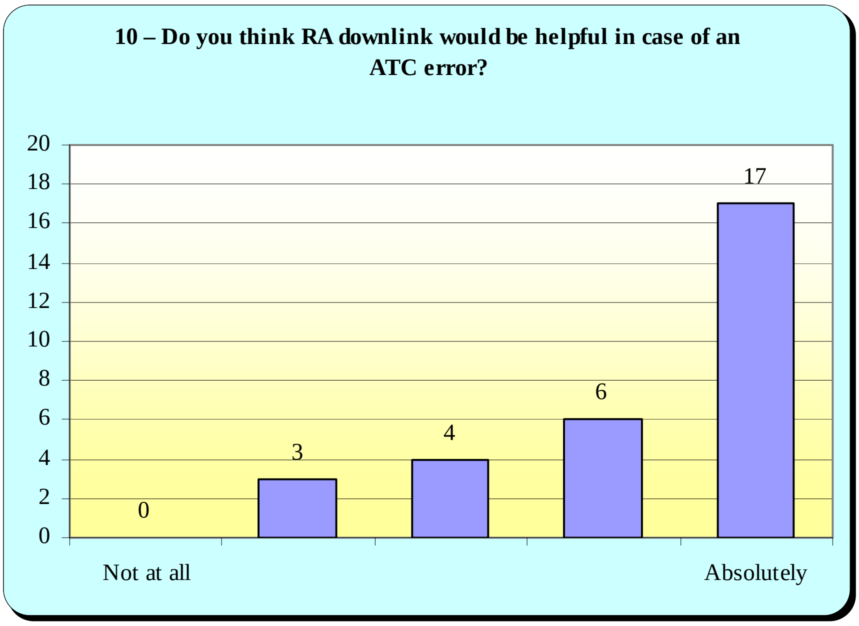

Figure 18: Utility of RA downlink in case of an ATC error

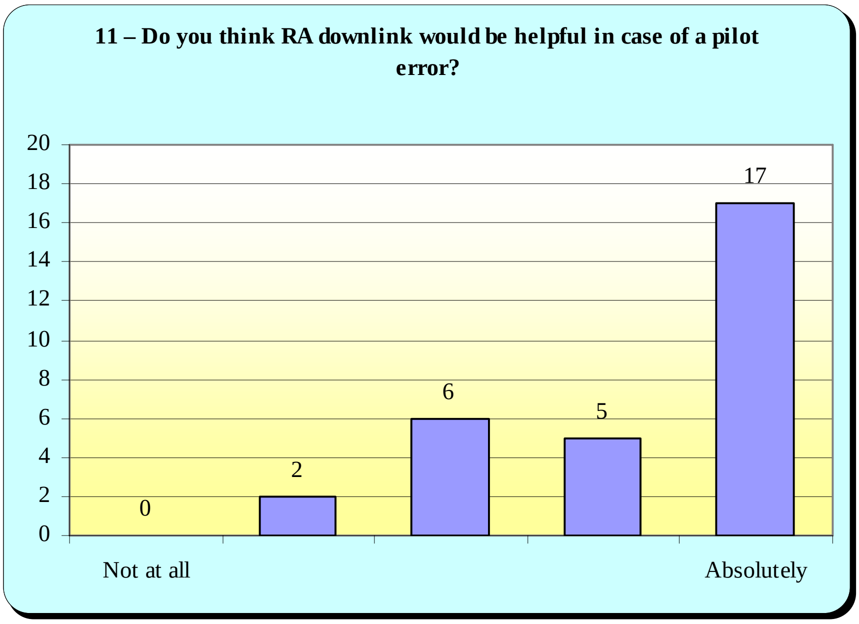

Figure 19: Utility of RA downlink in case of a pilot error

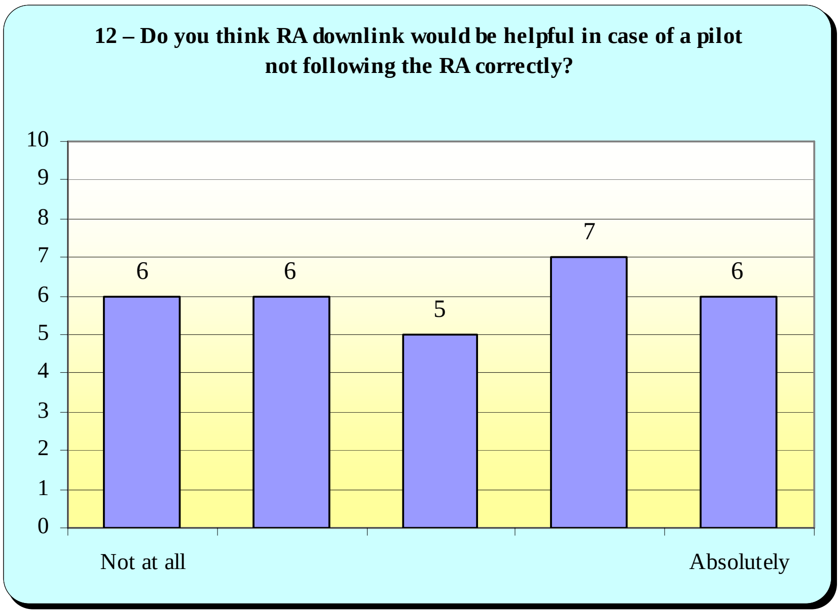

Figure 20: Utility of RA downlink in case of pilot not following the RA

For a situation in which the pilot does not follow the RA, the utility of RA downlink is less clear to the participants (see Figure 20). Answers are distributed almost evenly across the range of possible answers (*M* = 3.0, *SD* = 1.4). The argument against displaying RAs not followed by the pilot is that the pilot manoeuvre is relevant for the controller, rather than the RA itself. The argument for displaying such RAs is that even if an RA is not complied with, it can increase the controller's understanding of the situation, for instance, by alerting the controller to a conflict situation.

Controllers are also not convinced about the utility of RA downlink in case of complex situations (e.g., more than two aircraft involved in the conflict situation). Across participants, the rated utility of RAs in complex situations is neutral (*M* = 2.9, *SD* = 1.2). This might have to do with the fact that, especially in more complex situations, participants sometimes felt overloaded with the interpretation of the (perhaps quickly changing) RA information.

All but one participant consider RA downlink as helpful in case the pilot fails to notify ATC about RA by R/T (*M* = 4.6, *SD* = 0.6, see Figure 22). In this case, RA downlink is the only source of information for the controller to know that responsibility for separation has been passed on to the pilot and the pilot is likely to make an evasive manoeuvre.

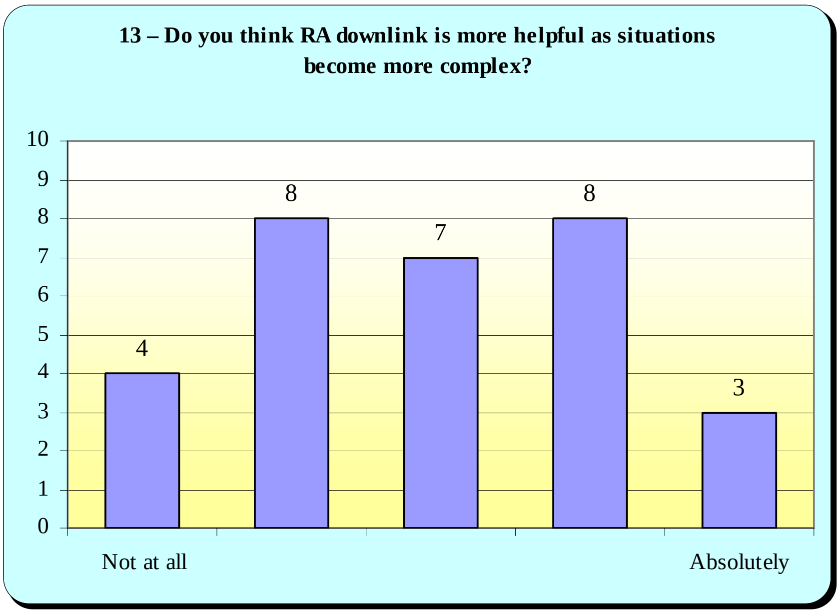

Figure 21: Utility of RA downlink in complex situations

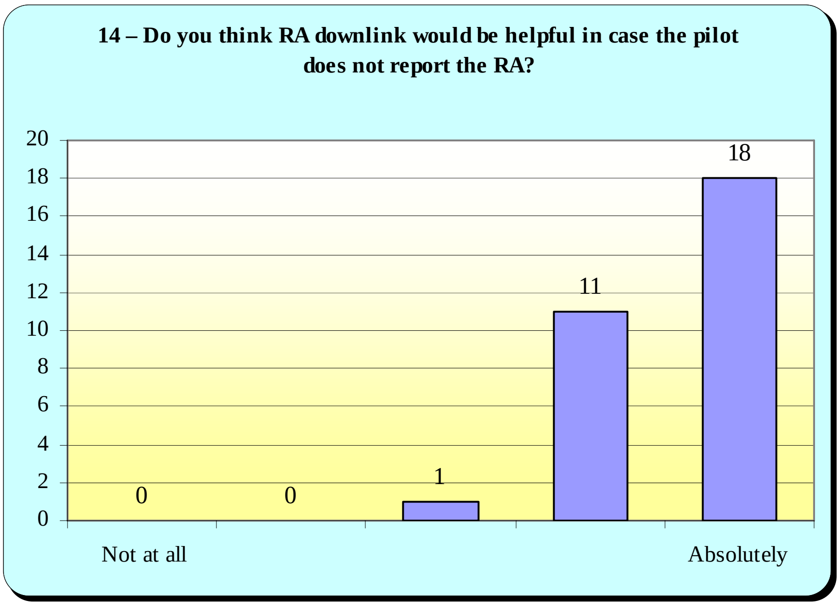

Figure 22: Utility of RA downlink in case of pilot not reporting RA

Finally, controllers were asked to assess whether RA downlink is helpful in case the pilot reports the RA (see Figure 23). Note that, in this case, the RA information might be redundant with the pilot report (depending on the timing and the level of detail). Consequently, controllers only see a smaller benefit in comparison with a situation in which the pilot fails to report the RA (M = 3.3, SD = 1.3). However, the rating is still positive, possibly because the RA information can be more precise or faster than the pilot report.

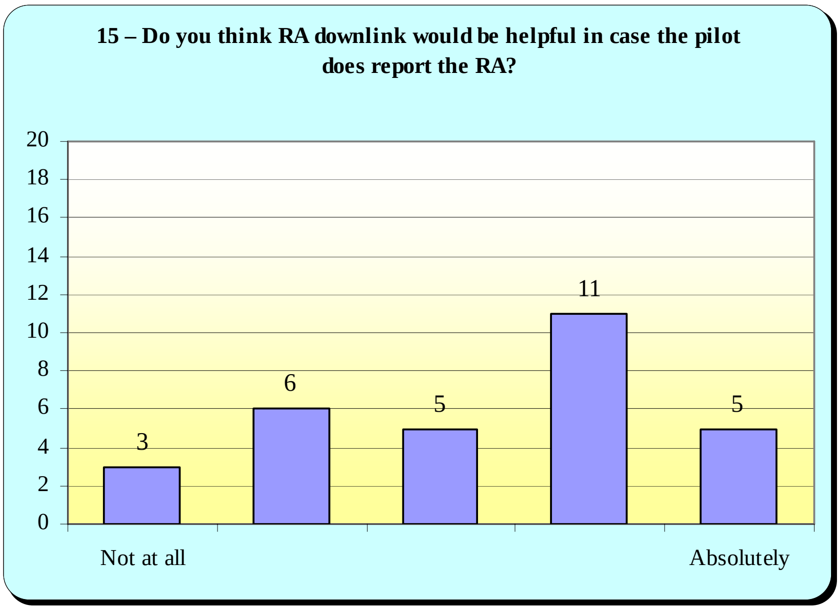

Figure 23: Utility of RA downlink in case of pilot reporting RA

6.3.4 Technical implementation

6.3.4.1 Downlink delay

In the experiment, two different downlink delays were realised: a delay of 0 seconds (i.e., no delay), and a delay of 5 seconds. Although participants were informed about the delay conditions, only nine of the 30 controllers stated that they had noticed differences in the speed of RAs being shown. The other participants did not notice any differences in the downlink delay.

Controllers were also asked what, in their opinion, the maximum acceptable delay between the RA generated at the aircraft and the display on the controller screen is. Five controllers found it difficult to answer this question and did not provide a number. The answers obtained from the rest of the participants ranged from 1 second to 10 seconds, with a median of 5 (see Figure 24).

It has to be taken into account that the majority of the controllers failed to notice any differences between a delay condition of 0 and of 5 seconds. At the same time, some of these controllers do not consider a delay of 5 seconds or less as acceptable. This seems to indicate that the participants have a stricter criterion in their abstract judgements on downlink delays than in their experience of these delays. Independently of whether controllers notice the downlink delay or not, the expected benefits of RA downlink (in particular, the prevention of contradictory clearances and the facilitation of traffic information) get lesser with a longer downlink delay[6].

[6] It has to be taken into account that the information on the radar is also displayed with a delay. It does not seem desirable to have RA information displayed faster than Mode S information either.

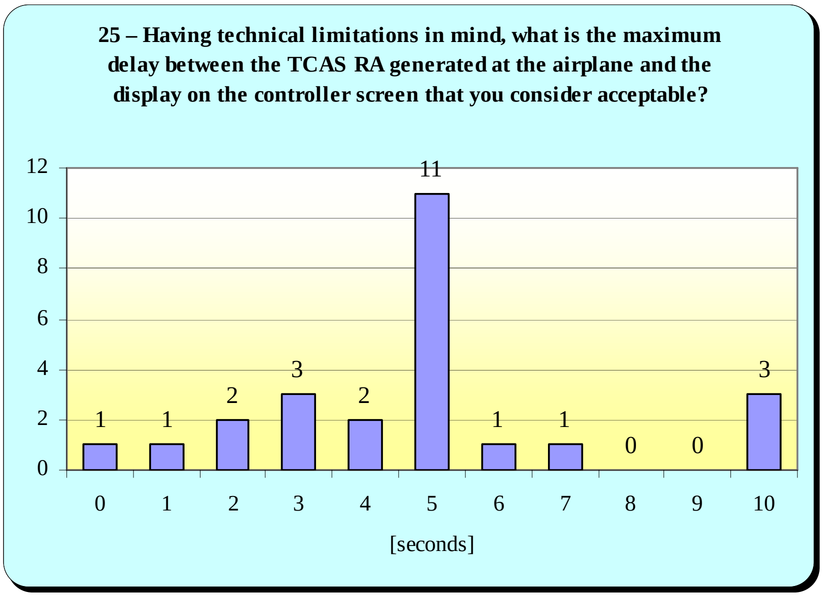

Figure 24: Maximum acceptable delay for RA downlink

6.3.4.2 Filtering of RAs

In the post-experimental questionnaire, participants were asked whether certain RAs should be suppressed from being shown on the radar screen. Out of the 30 participants, five did not answer this question or indicated that they did not know how to answer the question. Four participants stated that they would not want to have any RAs filtered but want to have all RAs displayed on the radar screen. The remaining 21 controllers would prefer to have some RAs filtered out. Table 6 provides a summary of the participants' answers.

ID	Answers	Frequency
1	Do not filter any RAs	4
2	Filter false alerts (i.e., no other aircraft in the vicinity)	9
3	Filter RAs that will not result in a deviation from the ATC clearance	4
4	Filter RAs that are due to high vertical rates before level off[7]	7
5	Filter RAs that are not complied with by the pilot	4
6	Filter RAs that were reported correctly by the pilot	3
7	Filter situations with several RAs for the same aircraft within a short period of time (i.e., strengthening/weakening RAs)	2
8	Filter situations involving too many aircraft	1

Table 6: Controllers' opinions on filtering RAs

Some participants suggested to filter out RAs that are not complied with by the pilot. The argument was made that the controller wants to "know what the pilot is doing", rather than

[7] This category is actually tightly connected to the previous one.

what ACAS tells the pilot to do. As experienced in the simulation, “pilots sometimes do the reverse thing”, thereby deviating from the RA. Furthermore, “as soon as the controller recognises that there is an RA, he will watch the mode C of the concerned aircraft, waiting for the pilot’s reaction” which – in case of a pilot not following the RA – means that the controller just loses time.

Other comments made by the participants referred to the interface for displaying RAs and the level of detail shown to the controller, rather than to a general filter for certain situations. One controller mentioned that “the RA display function should come with an on/off switch”, another controller reckons that “the specific manoeuvre [*the sense of the RA*] should not be displayed to the controller”. Another controller thinks that detailed RA information should be displayed in a separate window or on a separate screen, with only the letters “TCAS” or “ACAS” in the label on the radar.

Filtering of RAs was elaborated on in the de-briefings. Note that the terminology used by the controllers (both in the de-briefing and in the questionnaires) often did not correspond fully with the ACAS terminology. Participants used the term “preventive RA” in order to refer to an RA that does not yield a deviation from the cleared level. “Corrective RA” on the other hand was used in order to denote an RA that yields a deviation from the cleared level. According to the ACAS terminology, however, a “corrective RA” requires the pilot to change the vertical rate. A preventive RA, on the other hand, is an advisory not to change the vertical rate above a certain specified value. Thus, a “limit climb” or “limit descend” advisory (that is corrective in the ACAS terminology), was experienced as preventive by the participants, because it does not yield a deviation from the ATC clearance.

Participants’ opinions on filtering RAs as expressed in the de-briefings are listed below.

- *Filtering of false alerts.* Although some of the controllers indicate that the “display of false alerts is “not desirable”, the majority of controllers see a benefit in downlinking false alerts because “they explain why an aircraft is climbing or descending”.
- *Filtering of RAs that do not result in a deviation from the ATC clearance.* A number of controllers indicate that RAs should not be shown to the controller unless they yield a deviation from the ATC clearance. Examples for such RAs are “Limit Descend” or “Limit Climb”, and they were often referred to as “preventive” by the controllers. These “preventive” alerts were frequently experienced as irrelevant for the controller. However, it was also pointed out that the display of such RAs can be helpful in some situations. For instance, if both aircraft are in vertical movement approaching each other, it might be helpful for the controller to know that the pilots have been alerted to the consequences of a flight level bust. Furthermore, it was stated that, especially after the mid-air collision over the Lake Constance, pilots are more likely to overreact to RAs. Thus, even if the RA itself might not involve a deviation from the clearance, the pilot’s response to it might do. The display of “preventive” RAs from the cleared flight path might therefore help to anticipate on pilot’s overreactions.
- *Filtering of RAs not followed by the pilot*. A small number of controllers expressed that RAs should only be displayed if the pilot follows the RA. The reasoning is similar to filtering of preventive RAs: The controller only needs to be informed about an RA if it yields a deviation from the original ATC clearance.

Like in the questionnaires, some of the controllers explicitly stated that they do not want to have any RAs filtered: “as long as the pilot gets the RA, I want to get it too”. Furthermore, it was expressed that RAs are not likely to be frequent events so there is no need to filter out specific situations.

6.3.5 Legal issues

Potential legal implications of RA downlink (i.e., liability) were discussed with the controllers in the de-briefing at the end of the experiment[8]. Controllers’ attitudes ranged from very strong concerns of increased liability to not anticipating any new legal problems (especially, if controller/pilot responsibilities are not changed in comparison to current procedures). Generally, the number of participants anticipating on legal problems was by far smaller than the number of participants without any substantial concerns. The arguments and points made by the controllers are listed below:

A safety-critical scenario: the pilot does not follow RA. Concerns about legal consequences of RA downlink were mainly illustrated on the basis of the following situation: There is a conflict situation that cause the ACAS of the subject aircraft to issue RAs. These RAs are also displayed on the controller screen. At least one of the pilots involved in the situation, though, does not follow the RA, which eventually yields an accident. It was assumed that the controller – knowing about the RA and seeing that the pilot does not follow it - is held responsible for not prompting the pilot to comply with the RA. These concerns were expressed as follows by controllers: “The judge will say – you had this information so you could have done extra things.” Even though the controller might not be strictly responsible for the pilot following the RA “you could be asked in the court: why didn’t you do something.”

Nevertheless, not all of the participants see legal difficulties with the above scenario. The following points were made by other participants when being presented with the above scenario:

- The situation described above does not differ qualitatively from a situation in which a pilot reports an RA by R/T, but does not follow it. If this yields an accident, the controller could be asked in the same way why he or she did not remind or prompt the pilot to follow the RA.
- If the responsibilities are kept as in the ICAO document 4444 (PANS-ATM) [10], there are no legal consequences for the controller. “The ICAO rules say clearly that RAs have priority over controller clearances”. “The pilot is responsible at the end of the day - you can’t force him to do something.”
- If there were new regulations and procedures to be defined, then it needs to be assured that responsibilities between the pilot and the controller are not changed. This was expressed as follows: “If new rules are implemented, they should exclude controllers liability – RA downlink is supplementary information only. Controllers should not act on this information.” Or: “We should have immunity from prosecution for using the RA downlink information. We cannot be responsible that the pilot reports the RA and follows it!”

[8] In this chapter, “rules” and “regulations” denote any material that interprets, implements, or makes specific a certain law. “Procedures” denote the prescribed or established mode of enforcing a law.

Criterion for transfer of responsibility. The argument about pilot/controller responsibility evoked a discussion on when exactly the responsibility for maintaining separation has to be passed from the controller to the pilot. According to current procedures, the controller needs the pilot's report of the RA in order to know that it is not his or her task anymore to provide separation[9]. As the pilot's report is currently the only source of RA information for the controller, there is no ambiguity as to when the controller is obliged to take his or her hands off the aircraft (provided that the pilot only reports an RA that causes him to depart from his clearance). With RA downlink, in contrast, there are two sources of information: the pilot's report and the RA information on the screen. The vast majority of the controllers think that, even with RA downlink, responsibility for collision avoidance should only be transferred from the controller to the aircrew following the pilot report of the RA. The reason given was that "RA information on the screen does not mean that the pilot will follow". A pilot report of an RA, on the other hand, is experienced as a much stronger indicator of a pilot's intention to follow the RA ("The pilot's report is a stronger argument to transfer responsibility"). Note that the phrase "TCAS climb" or "TCAS descend" (as described in [10]) is not only a report of the RA, but includes the pilot's compliance with the advisory. Only a few controllers think that "there should not be a difference in weight between the downlink and the pilot report", and thus, whatever information comes first should trigger the controller to pass responsibility on to the pilot.

Definition of new procedures. One point made in the de-briefings was that the introduction of RA downlink requires the definition of operational procedures, on the basis of which responsibility will be clearly defined. Legal consequences cannot be fully anticipated unless those regulations and procedures are known. With respect to how these new procedures should be formulated, one controller group stated that legal issues are "questions for the management and the lawyers: If the new procedures are clear, we will follow the new procedures". Most of the controllers, though, did have clear preferences for a certain definition of rules and regulations. With respect to liability issues, it was advocated that liability should be unchanged: it is the pilot's responsibility to follow the RA, once an RA has been issued. With respect to operational procedures, it was suggested to incorporate RA downlink into the existing operational procedures (as defined in [10]). RA downlink related procedures should be an amendment to the existing procedures, rather than causing a change of the current procedures.

Operational procedures with respect to RA downlink should especially address the following questions:

- What should the controller do if there is only one RA displayed on the controller screen?
- When is responsibility for separation passed on to the pilot and the controller has to stop issuing clearances?
- What does the controller have to do if there is an RA downlink but no pilot report? Is it the controller's task to confirm the RA and the pilot's intention to follow it?
- Does the controller have to write a report if the pilot does not follow an RA that is displayed on the controller screen?

Miscellaneous. A further perspective on controller responsibility and liability was expressed in two of the de-briefing sessions. According to this perspective, "you [*as a controller*] have the moral responsibility to do everything in your power to sort things out, and if you have the RA

[9] Strictly speaking, the controller ceases to be responsible "once an aircraft departs from the current ATC clearance in compliance with an RA" (Document 7030).

downlink you should use this to help sort out the situation. I do not care about legal issues then – I just want to sort out the situation". In addition, it was pointed out that the controller "is likely to be guilty anyway, if he has set up the situation" that led to the RA.

Taken together, the majority of the controllers do not see any liability issues that are inherent to the concept of RA downlink and cannot be tackled by the definition of appropriate procedures. Such procedures should preserve the current responsibilities of pilots and controllers. Authority for separation should preferably be passed to the pilot following the verbal report of the RA, rather than the RA downlink. RA downlink should only be used for informational purposes; no obligations for further controller actions and responsibilities should arise from the display of RA information. A few controllers, though, find it difficult to believe that the RA information will not result in new responsibilities (and thus liability) for the controller.

6.3.6 Procedural changes

An issue tightly connected with the legal consequences of RA downlink concerns the procedural changes associated with RA downlink. Controllers were asked whether they see a need for procedural changes if RA downlink is introduced.

Possibility of horizontal clearances. One question asked referred to the possibility of issuing (horizontal) instructions to an aircraft that had received an RA. Most of the controllers do not see a need for changing the current procedures that govern the controller/pilot authority once a (corrective) RA has been issued. It was pointed out that on the basis of the current procedures, controllers can already suggest horizontal manoeuvres. Whether such horizontal "instructions" have and should have the status of a clearance or an advisory, seemed to need further clarification.

A number of controllers generally questioned the use of horizontal clearances in a situation in which an RA was issued. The following points were made against the use of horizontal clearance:

- If the aircraft turns at the same time the evasive vertical manoeuvre is initiated, this can lead to a 'stick shaker' and the maximum rate of climb can be reduced.
- In case of a (corrective) RA, the workload in the cockpit is already high. The controller should therefore avoid giving additional clearances to the aircraft.
- If an RA has already been issued, it is usually too late to give a horizontal avoiding action to achieve standard separation. In this situation, the rules of the air should be applied (i.e., evade to the right).

However, there are some controllers who do advocate a split of responsibility in the different planes once an RA was issued: In the vertical plane, responsibility is and should be transferred to the pilot, whereas in the horizontal plane it should be kept with ATC. These controllers state that they "would like to be able to give horizontal clearances during the RA", for instance, "to avoid third-party aircraft".

Incorporating RA downlink into existing procedures. Although the majority of participants do no consider substantial changes to the existing procedures as necessary, controllers do see a need for defining European wide procedures for RA downlink if it was to be implemented. It was suggested that these RA related procedures should amend the existing operational procedures as defined in [PANS-ATM] (see above), thus retaining for instance the pilot's responsibility to report the RA as soon as possible to ATC. The newly amended procedures should clarify when the responsibility for aircraft separation is passed on to the pilot (on RA display or on pilot report), and how to behave in case of an RA downlink but no pilot report. Furthermore, controllers would like to be informed not only about the RA itself, but about the pilot's intention to follow the RA. Only a small number of participants suggested a change in the operational procedures so as to "act on the RA downlink in the same way as if informed by the pilot".

Generally, it was emphasised that operational procedures should be strengthened and monitored, so that no deviations from the procedures should be allowed. In particular, it should be ensured that pilots report RAs in a timely and reliable manner.

"Follow TCAS". Participants were asked to consider the introduction of a new ATC phrase "Follow TCAS". This phrase could be transmitted to the aircraft for which an RA was displayed on the screen. In this way, the controller could indicate to the pilot that he or she is aware of the RA and that previous instructions are retracted.

The majority of the participants, however, do not see clear benefits of the phrase "Follow TCAS". The following points against such a phrase were made:

- The pilot is obliged to follow the RA anyway, so the phrase is unnecessary.
- If the controller is informed about the RA, he or she will not give a contradictory clearance. Thus, there is no added value to the phrase.
- By introducing this phrase, R/T and, thus, the information to be processed by the pilot increases. This is particularly bad in a situation in which workload in the cockpit is high.
- The controller tells the pilot to carry out a manoeuvre the consequences of which he or she might not be able to predict (e.g., in case of GPWS or a stall warning).
- Depending on the status of this phrase (clearance/instruction or just information), it might require a pilot acknowledgement.
- The phrase indicates too clearly that the controller has made a mistake and the situation is out of his or her hands. For this reason, it will not be accepted by controllers.
- The phrase might yield confusion as regards responsibility: It seems to suggest that the controller is still responsible for separation.

Concerning the problem of responsibility, a corrective RA in current procedures entails that responsibility for aircraft separation is passed on to the pilot. For this reason, the controller cannot issue any clearances or instructions any more. Therefore, the phrase "Follow TCAS" cannot have the status of a clearance. Rather, it can only serve to inform the pilot that ATC is aware of the RA and previous instructions are invalid. The wording of the phrase, nevertheless, seems to suggest that an ATC instruction was given.

Furthermore, given the pilot's responsibility to report an RA as quickly as possible, the phrase "Follow TCAS" only makes sense if it is transmitted before the pilot report. This requires a very quick downlink and display of the RA information on the controller screen. Once the pilot has reported the RA, it is sufficient for ATC to respond "Roger" to the report.

There were a few participants who saw potential advantages in the phrase "Follow TCAS". These participants indicated that the phrase can help to ensure that the pilot in fact follows the RA ("it might be helpful for pushing the pilot in the right direction").

TCAS observed. One of the participants suggested the phrase "TCAS observed" instead of "Follow TCAS". The advantage of the former over the latter is that it is clearly an information to the pilot, rather than a clearance or an instruction. Thus, a number of the problems with the phrase "Follow TCAS" would be overcome. This suggestion was discussed with three subsequent participant groups in the debriefing. In these participant groups, there was some limited support for the suggestion: it is "nice to have the option – it is a clear way of saying that the controller has seen the pilot has got an RA". However, it was also stated that the phrase only makes sense if the pilot does not report the RA in a timely manner, and it might even increase the probability of the pilot not reporting the RA ("it could exempt the pilot from reporting"). Furthermore, if the phrase only serves for informing the pilot that ATC is aware of the RA, then this can also be achieved by issuing traffic information to the conflict aircraft in such a way that it is clearly based on an RA downlink.

Taken together, the majority of controllers do not think that RA downlink would require substantial changes to the existing procedures. This holds both for issuing clearances to an aircraft with an RA and for the introduction of new phraseology ("Follow TCAS" or "TCAS observed"). Nevertheless, if RA downlink was to be implemented, European wide procedures on how to use RA downlink information need to be defined.

6.4 System malfunction

Two scenarios related to malfunction of RA downlink were discussed in the de-briefing with all participants: a false downlink of an RA, and a missed RA. Two participant groups also wanted to discuss a further scenario: a downlink of a wrong RA sense.

6.4.1 Missed downlink of an RA

The scenario "missed downlink of an RA" was described as follows: RA downlink was to be used operationally. There is an RA issued in an aircraft under control, however, this RA is not displayed on the radar screen. Participants were requested to evaluate this scenario in terms of the disruption it would cause and in terms of possible safety issues.

On a general level, controllers' opinion diverged as to how they assess the scenario of a missed RA downlink. These general opinions reflect different attitudes on system failure and automation. On one side of the spectrum, there are controllers who do not tolerate any system failures and, thus, also no failures of RA downlink. This attitude is reflected in the following statements: "when RA downlink is implemented, it has to work perfectly"; "you have to rely on the system"; "I would feel unhappy – I would loose trust in the equipment"; "we as controllers must believe in the system".

On the other side of the spectrum, there are controllers who are more sceptical with respect to performance of technical systems and do have some tolerance for system failure; "equipment fails – why not RA downlink?"; "I should not be totally relying on one system. I have to be ready for small system failures." The crucial point for being able to deal with system failure seems to be that controllers are aware about system limitations: "I need to be aware that it might not work".

On a more specific level, controllers considered the consequences of a missed RA downlink on their task performance and on safety. The majority of the participants did not see a substantial problem with a missed RA downlink. This is especially true if procedures are not changed and pilots are required to report RAs by R/T even if RA downlink is in operation. Given such procedures, the case of a missed RA downlink is considered identical to the current situation, in which the only source of information on RAs is the pilot report.

Nevertheless, there are a few controllers who do think that the case “missed RA given RA downlink” differs from the case “no RA downlink”. These differences refer to the following aspects:

- First, it is suggested that pilots will be less likely to report an RA once RA downlink is in operation. Therefore, the probability of a timely pilot report will decrease in comparison to the current situation.
- Second, in case of a missed RA downlink and a pilot report of an RA, there is an inconsistency in information which needs to be resolved.

With respect to resolving the inconsistency in RA information, one controller indicated that he was “working to maintain separation, and not to handle TCAS information”. Another controller, though, pointed out that it would be straightforward to resolve the inconsistency: “I would trust the pilot – it is like with an altitude report”.

The predominant opinion within the participant group was that RA downlink is an additional source of information that helps the controller to understand a situation already beyond his or her control. Thus, RA downlink is considered “a bonus that will tell you why an aircraft does what it is doing” – “it is not a control tool but a safety net”. Even if this safety net fails occasionally, it is still preferable to have it: “every time we can see an RA, it helps. Anything is better than the current situation”.

To summarise: although there are some general concerns about system malfunctions, participants do not consider the scenario of a missed RA downlink as a safety-critical situation. The main argument is that a situation with a missed RA downlink is identical to the current situation in which no RAs are displayed. For this argument to be valid, though, it needs to be ensured that pilots continue to report RAs by R/T.

6.4.2 False downlink of an RA

The scenario “false downlink of an RA” was described as follows: RA downlink was to be used operationally. The controller sees an indication of an RA for a certain aircraft on the radar screen; however, in the aircraft in question, there was no RA issued. Given a certain known combination of transponder and ACAS equipment type, this scenario is in fact technically possible. Again, participants were requested to evaluate this scenario in terms of the disruption it would cause and in terms of possible safety issues.

A small number of participants think that any RA malfunction – such as the false downlink of an RA situation – is completely unacceptable as it takes away the controller’s confidence in the system. If RA downlink does not work 100% reliably, then they cannot base their actions on it.

Although this attitude is not shared by all controllers, the majority of controllers do see a potential safety issue associated with a false downlink of an RA. This safety issue consists in the fact that the (false) RA can yield the controller to believe that the pilot is responsible for aircraft separation, whereas the pilot assumes that the controller is responsible for separation. Nevertheless, as was pointed out by some controllers, such a “responsibility vacuum” can only arise if the responsibility for aircraft separation is transferred from ATC to the pilot at RA display rather than at pilot report.

Furthermore, most controllers think that they would be able to diagnose a false downlink of an RA. One reason is that a false downlink of an RA is unlikely to affect two aircraft at the same time that are close to each other. Nevertheless, if there is only one aircraft with RA displayed on the radar screen, it cannot be concluded straight away (i.e., without further situation analysis) that the RA has been downlinked falsely. For instance, an alternative explanation could be that the RA of the second aircraft could have been missed. In case the aircraft with the RA is surrounded by other traffic, this situation assessment requires the controller “to look carefully at the mode C information and the arrows (indicting vertical movement) to judge what is happening”. The controller can also figure out whether or not an RA has been downlinked correctly by contacting the pilot: “You could ask the pilot for confirmation“; “I would provide traffic information saying that I see an RA – the pilot would then respond by saying that he does not have an RA”.

However, it could take some time for the controller to figure out that the RA was false. During this time, the controller could be distracted from monitoring other traffic in the sector, which, especially in case of heavy traffic load, could have negative effects on controller performance.

In addition, the diagnosis of a false downlink of an RA could be impeded by the fact that in some ACCs, military aircraft are not (necessarily) displayed on the radar. In case there is only one RA displayed and – apparently – no other aircraft in the vicinity, this could point to a conflict situation with a military aircraft. In order to overcome this problem, it was suggested to force the display of the subject aircraft involved onto the radar screen.

Some participants pointed out that a false downlink of an RA would not qualitatively differ from current events with falsely displayed information, such as a false squawk ident or altitude reporting errors. In all of these situations, the controller needs to contact the pilot via R/T in order to confirm the information in question.

Informing controllers about the limitations of RA downlink was also seen as a way of minimising the negative effect of a false downlink of an RA: “as long as you know false downlink of an RA exists, this diminishes their negative impact”.

Taken together, controllers agree that a false downlink of an RA is an undesirable situation. However, the vast majority of the controllers do not consider a false downlink of an RA as a likely cause of a hazard. In order for a false downlink of an RA to develop into a safety-critical situation, a set of conditions need to be met simultaneously:

- Responsibility is transferred to the pilot upon RA display (rather than the pilot report)
- The controller does not diagnose the false RA on the basis of other information on the screen (i.e., there are potentially conflicting aircraft in the vicinity, and the controller does not check mode C information),
- The controller does not diagnose the situation by contacting the pilot (i.e., either to explicitly confirm the RA, or to implicitly confirm the RA by providing traffic information),
- The aircraft with the false RA is involved in a conflict situation with another aircraft.

Therefore, the safety-critical consequences of false downlink of an RA can be minimised by transferring responsibility only at pilot report and/or by training controllers on how to detect and handle incorrect RA information.

Although controllers do not think that a false downlink of an RA is likely to evolve into a hazardous situation, it may distract the controller from monitoring other traffic situations in the sector. This holds especially for a situation in which the false downlink of an RA is difficult to identify, and traffic load in the sector is high. As a consequence, the probability of a controller mistake can increase.

6.4.3 Downlink of a wrong RA sense

One controller mentioned a further situation worthwhile to discuss: the scenario in which a wrong RA sense (in particular, a climb instead of a descend and vice versa) would be downlinked and displayed on the radar screen. This situation was discussed with two controller groups in the de-briefing.

If a wrong direction of an RA was downlinked, it will be very likely that there is an inconsistency between the pilot report of the RA and the displayed RA (unless the pilot also mixes up the direction in the report). In this case, the controller would not know what information to rely on – the system or the pilot. As a consequence, the controller will temporarily loose situational awareness and will not be able to anticipate the traffic situation any more.

However, in case of an RA that yields a deviation from the clearance (as a “climb” or “descend” RA does), the controller is not supposed to issue any instruction to the aircraft any longer. For this reason, the only deteriorating effect on controller action refers to the controller issuing wrong traffic information. The effect of this, though, is not considered as directly affecting safety. One group of participants, though, pointed out that a situation in which two aircraft will seemingly initiate the same manoeuvre will be extremely stressful for the controller and make the controller intervene. Thus, there is a probability that the controller mixes up a situation that was perfectly sorted out by ACAS already.

6.5 Human-Machine Interface

6.5.1 Display of RA information

In both the post-experimental questionnaire and the de-briefing, participants were asked what kind of RA information they consider helpful and relevant. Figure 25 shows the controllers’ opinions on the relevance of certain bits of RA information.

The vast majority of controllers consider corrective RAs as relevant information for the controller. Again, it has to be pointed out that controllers’ notion of corrective RAs tended to be narrower than the technical definition of corrective RAs and excludes those (corrective) RAs that do not yield any deviation from the ATC clearance.

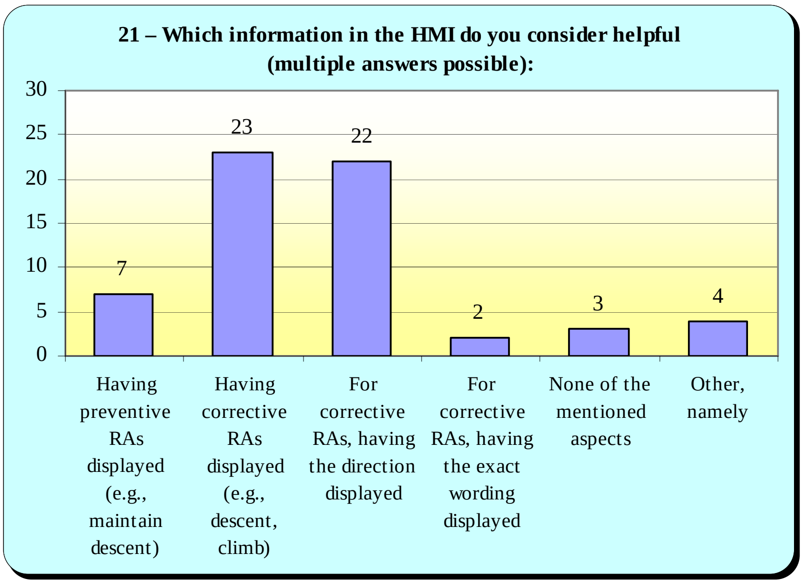

Figure 25: Relevance of different types of RAs

Only four out 30 controllers did not tick any of the three categories pertaining to the display of corrective RAs (i.e., “having corrective RAs displayed”, “for corrective RAs having the direction displayed”, and “for corrective RAs, having the exact wording displayed”). Of these four controllers, two indicate in the category “other” that they would like to have only “TCAS” (without any further description) displayed. These answers should, in fact, fall into the category “having corrective RAs displayed” and possibly also “having preventive RAs displayed”, as they imply that the participants would like to have (at least some) RAs displayed. One of them had also ticked the category “none of the mentioned aspects”. Thus, only two of the participants did not consider any sort of RA information as relevant for the controller.

Most of the participants also want to see the direction of the RA (i.e., 22). In contrast, only four participants consider the exact sense of the RA (including the direction and the exact wording) as relevant. The display of preventive RAs is only considered as helpful by seven out of 30 participants.

The following comments were made in the category “other” (in brackets the frequency of a comment):

- Only display of RA (2) (see above),
- Don’t want to have any additional signs, letters, etc. (1),
- Display of direction but in simplified wording (1).

The feedback on the display of RA information obtained during the de-briefings closely reflects the above results. Although most of the controllers considered the display of RA information (at least for corrective RAs) as helpful, they were not completely satisfied with any of the chosen implementations. The minimum HMI (which just gives an indication of the RA without specifying it), was considered as not providing enough information to the controllers. The intermediate and the enhanced HMI (which provide the exact sense of the RA) were considered as providing too much information to the controllers. With respect to the latter HMIs, two problems were perceived: First, a lot of the information was considered as irrelevant for the controller (i.e., the information that the pilot has to limit vertical movements to a specified value), and second, the abbreviations used were not intuitively understandable. Considering that RAs are a rare event and, thus, controllers would be only exposed to them infrequently, it is absolutely necessary that the abbreviations are intuitively understandable ("I can't spend the time decoding what it means, especially when they are so rare"). One group of controllers stated that the enhanced HMI even "forced you into a tunnel vision with everything changing so often – you were not looking at anything else".

The vast majority of the controllers agree that an optimal HMI would give an indication of a 'corrective' RA (meaning an RA that yields a deviation from the cleared flight path) together with its direction. This indication could be either given as symbols (i.e. arrows), or in a simplified wording. With respect to other bits of information, controllers' opinions diverged:
Some of the controller consider the message "clear of conflict" (COC) as superfluous ("it's up to the pilot to report", "RA could just disappear from the screen"); others consider this message as helpful.

Some controllers do not want to have 'preventive' RAs (meaning an RA that does not yield a deviation from the cleared flight path) displayed at all; other controllers think they should be displayed in a simplified form ("just show RA") or just in specific cases ("don't show preventive RAs, if both are preventive").

Some controllers also suggested to present details of the RA in a separate window, and only give the indication "TCAS" in the label.

6.5.2 Alerting

There were four different kinds of alerts for RAs used in the experiment

- A static visual alert, in which the RA was displayed in colour (i.e., yellow on red)
- A flashing visual alert, in which the RA was displayed in colour (i.e., yellow on red) with onset and offset phases of 900 and 100 ms respectively,
- An audio alert, in which a recorded human voice announced "TCAS TCAS".
- A vibration alert that consisted of a vibrating cushion mounted to a chair.

All controllers were exposed to the two visual alerts and to the audio alerts. The vibration alert, in contrast, was only demonstrated to a subset of controllers. This was due to the fact that (1) there was only one vibrating chair available, and (2) the vibration alert was only implemented some days after the start of the experiment. Figure 26 shows the controller ratings for the different types of alerts.

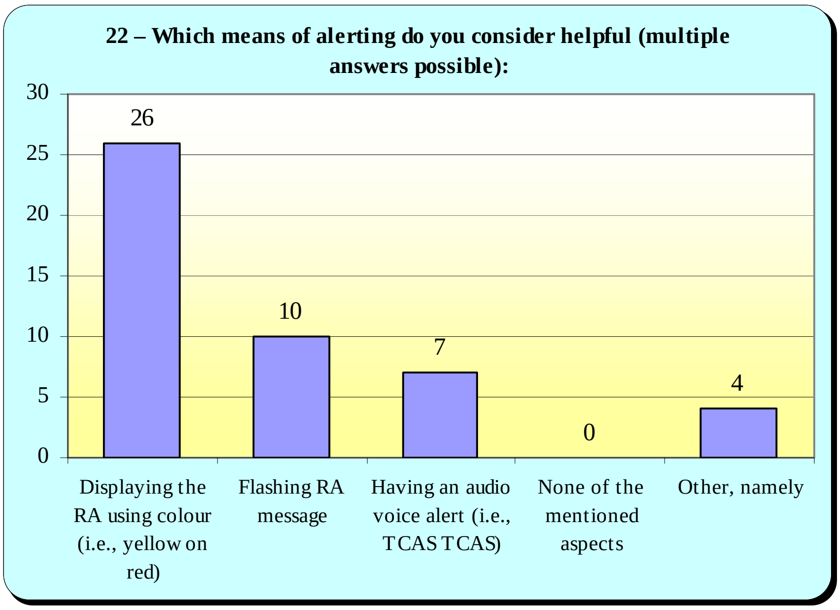

Figure 26: Evaluation of different kinds of alerts

The following comments were made in the category "other" (in brackets the frequency of a comment):

- Different colours should be used for the visual alert (1)
- Tone or signal instead of voice in case of an aural alert (2)
- Definitely not a vibrating chair (1).

6.5.2.1 Visual alerts

The majority of participants (i.e., 26 out of 30) think that using colour to display RAs is helpful for attracting attention. Also, the specific choice of colours (i.e., yellow on red) was appreciated by most of the controllers.

Nevertheless, there was one major complaint with respect to the visual alert. In the simulation, there was also an STCA that used the same means of alerting (yellow text on red background). Almost all participants reported that it was difficult to distinguish between the STCA and the ACAS alert (RA). The potential for confusion between the alerts could have been limited by using a different way of displaying the two kinds of alerts (for instance, by using different colours). One suggestion made was to display the STCA by turning the aircraft label red, whereas the RA could still be displayed as an additional line in the label, displayed in yellow on red.

An easy distinction between STCA and RA is especially important, because the implication of the two alerts for the controller is completely different. The STCA alerts the controller to a situation that (in case it is not a nuisance alert or a false alert) requires immediate action from the controller's side. In contrast, the RA alerts the controller to a situation in which no control actions should be taken any more (provided the RA yields a deviation from the clearance).

Most of the controllers did not appreciate the flashing alert. Controllers who did like the flashing stated that “in a screen with many colours [*such as the EATMP interface*] you need flashing”. Controllers who did not like the flashing alert pointed out that “the flashing alert is disturbing and distracting”, and it makes the controller assume “that something has changed in the information display”. With the flashing alert, the controller also does not have a precise indication of the end of the RA any more: If the RA disappears, it might either indicate the end of the conflict or it might be part of the flashing. This comment, however, only applies to the minimum interface in which the end of the ACAS detected conflict situation is not indicated by the message “clear of conflict” (COC). One participant group suggested that flashing should only be used in case the RA changed its sense.

6.5.2.2 Voice alert

Voice alert for RAs were only considered as adequate by a minority of participants (i.e. 7 out of 30, see Figure 26). Those participants who did not appreciate the audio alert experienced it as “annoying”, “distracting”, and increasing their stress level. Furthermore, the voice alert can overlap with the R/T transmission, so that information provided by the pilot is lost. In some of the cases, participants had mistaken the voice alert for a pilot report of the RA (“I thought it came from the cockpit”); and participants who did not mistake it for a pilot response could easily imagine confusion with a pilot report. The confusion was could have been at least partially caused by the fact that, in the experiment, the voice used for the RA alert was the same as used for one of the pilots. In addition, participants feared an overload with auditory information, particularly because, in case of an RA, “there is too much happening in the headset anyway”.

Another argument made against an aural alert was based on the following reasoning: If the controller fails to detect the conflict situation and the visual RA alert (as well as a possible STCA), then he or she is not attending the traffic situation. In this case, the controller will neither be likely to issue a contradictory instruction to the conflict aircraft nor experience a sudden breakdown in situational awareness due to the unexpected RA manoeuvre. Thus, the potential benefits of alerting the controller to the RA (e.g., preventing contradictory instructions and helping to maintain situational awareness) are very restricted.

Participants who liked the voice alert mentioned that “it gives information through a different channel, which can be helpful because your eyes are not always fixed on the screen”. It was argued by other participants, though, that even in case a controller does not look at the screen, the benefit of a voice alert is limited: “there is usually more than one controller looking at the screen – so there is little chance to miss a visual RA alert”. This is especially true if the conflict situation had been already detected by STCA (possibly with voice alert) before the RA was issued.

Voice vs. other audio alerts. A number of participants reckon that, if an audio alert is to be used, it should be a simple tone (such as a beep or a bell), rather than a voice alert. Furthermore, there should be a possibility to either turn down the volume or switch the alert off. For an audio alert, some potential benefits were seen, for instance, in quiet situations such as during a night shift.

Combination with aural STCA alert. The participants’ evaluation of the RA voice alert needs to be seen in the context of the STCA used in the simulation: the STCA also made use of a voice alert (a female voice announcing “conflict”). In some cases, it was difficult for the participants to identify whether the audio alert was part of the RA downlink or part of the STCA. Furthermore, the STCA audio alert probably contributed to the participants' experience of an auditory information overload during the conflict situations. Thus, the evaluation of the RA voice alert might have been more positive in a context of an STCA without voice alert than in the present context of an STCA with voice alert.

6.5.2.3 Vibration alert

The participants who were exposed to the vibration alert in the seat experienced the alert as "unpleasant", "uncomfortable", "awful", and "annoying". The above comments, though negative, could be taken as arguments in favour of a vibration alert: The strong controller reactions make it apparent that it is very difficult to miss or neglect the vibration alert, indicating that vibration is, in fact, a powerful stimulus for attracting immediate attention.

However, participants did not appreciate where their attention was drawn to. By attending to the haptic information conveyed by the vibration alert, participants felt distracted from processing visual stimuli on the screen. This was expressed as follows: the vibration alert is "distracting – it takes your focus away from the screen and of what is of importance". In the same line, controllers did "not see the link between the vibration and the situation, as the vibration draws your attention to the stimulated body parts".

Furthermore, the added benefit of the vibration alert in addition to a visual - and possibly an auditory alert - was not recognised ("it doesn't give me any important information that I did not get elsewhere before"). Only a few participants appreciated the fact that the vibration alert can trigger the controller to look at the screen in case s/he has missed the other alerts (visual and/or aural) before. These participants did not completely dismiss the concept of a vibration alert. One controller stated that a vibration alert might be useful if the controller "had the head set off and was looking elsewhere". Another controller said that one advantage of the vibration alert was "that you might get it even if there are other noises around (e.g. talking on the phone)".

During the de-briefing, participants were also requested to abstract from the specific implementation of a vibration alert (using a chair), and assess the potential of any vibration alert in general. As an example for an alternative implementation, a vibrating device around the wrist was suggested (i.e., a vibrating wristwatch). This suggestion, however, did not change the controllers' attitudes towards the vibration alert. "Even a wristwatch would be distracting – I would not wear it if it was optional".

It has to be taken into account that the technical implementation of the vibration alert in the simulation was not perfect. First, the onset of the vibration was not synchronised with the onset of the RA information on he screen. Second, vibration was triggered with any change in the display of the RA, therefore, also to indicate a "clear of conflict". Third, the vibration persisted for too long. With a better implementation of the vibration alert, the controllers' judgements might have been more positive. Furthermore, it could be argued that the experienced intrusiveness of the vibration alert is at least partially due to its novelty. Once the controller has learned the link between the vibration and the RA information on the screen, the vibration might distract the controller to a lesser extent from processing information on the screen. Because RAs will be an infrequent event, though, this argument is not convincing.

6.5.3 Assessment of the three different interfaces

In the post-experimental questionnaire, participants were asked to evaluate the three different HMIs (minimum, intermediate, and enhanced) on a scale ranging from “poor” to “very good”.

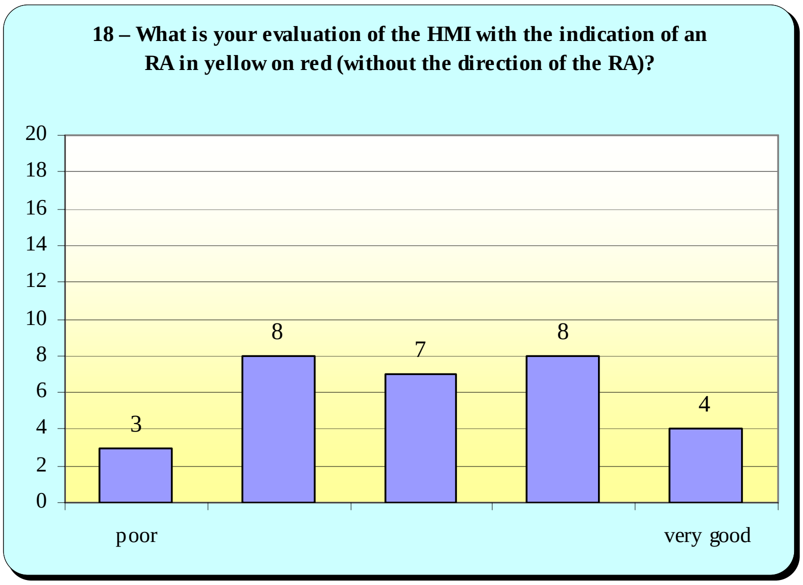

Figure 27: Evaluation of the minimum HMI

Figure 27, Figure 28, and Figure 29 show the distribution of ratings for the minimum, intermediate and enhanced interface. The mean rating for the minimum HMI was 3.1 (SD = 1.2); the mean rating for the intermediate HMI was 3.6 (SD = 1.1), and the mean rating for the enhanced set HMI was 2.5 (SD = 1.2).

Thus, among the three different HMIs used in the experiment, the intermediate HMI is the preferred one. In spite of this, the intermediate HMI is still considered far from being perfect by the participants (see above discussion). Potential for improvement concerns both the level of detail of the RA information and the alerting. These problems affect the enhanced HMI in the same way; in addition, the enhanced HMI contains a flashing visual alert, an aural alert, and – for some participants – a vibration alert, which were both not appreciated. The minimum HMI, on the other hand, lacks information on the sense of an RA, which was considered relevant by the majority of controllers.

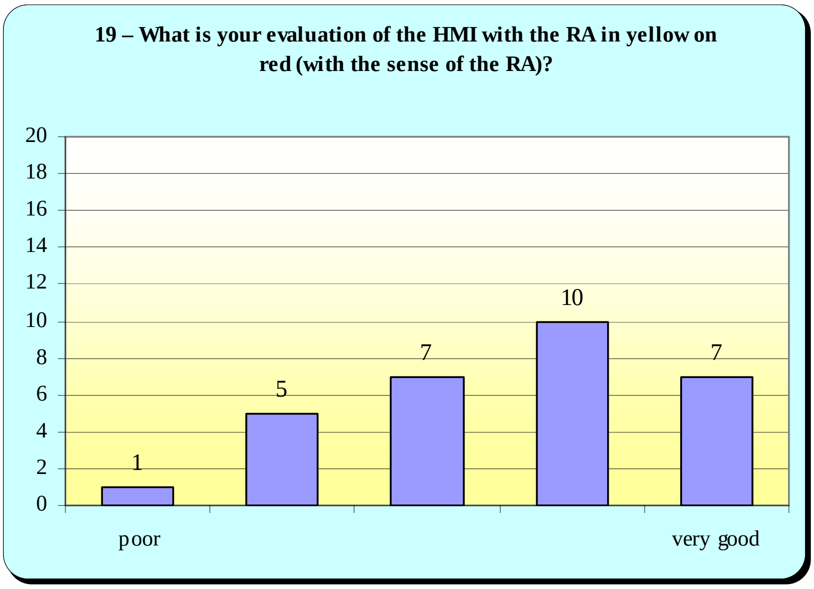

Figure 28: Evaluation of the intermediate HMI

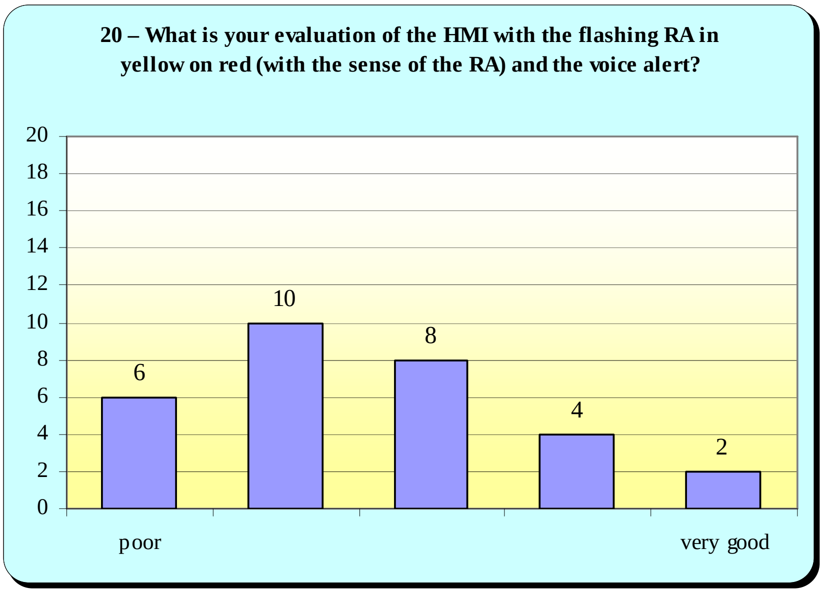

Figure 29: Evaluation of the enhanced set HMI

6.6 Situational awareness

6.6.1 Memory test

After each simulation run, participants were requested to fill in a memory test on the conflict situation they had just witnessed. This memory test comprised questions

- on the conflict situation (callsign of conflict aircraft, cleared FL, heading, and vertical movement),
- on the RA issued (type of RA, reversal in sense),
- on the source of RA information (pilot's report, display on the screen), and
- on the events following the RA (pilot's compliance, follow-up conflicts).

The complete memory test can be found in Appendix A.

Knowledge of the conflict geometry. Four of the items in the memory test referred to the situation that triggered the RA. These items were

- Aircraft involved in the RA situation (callsign or airline 3-letter code),
- Cleared level of aircraft,
- Climb/level/descend prior to RA/incident,
- Approximate Heading.

Note that for the ACAS themes II, IV, and V, the conflict situation involved two aircraft. Accordingly, the maximum number of correct answers to the four questions was eight. For the ACAS theme III (false alert), the situation only involved one aircraft, which means that the maximum number of correct answers was four. For ACAS theme I, two conflict scenarios involved two aircraft, and one involved three aircraft. The maximum number of correct answers for ACAS theme I is therefore higher than for the other ACAS themes (i.e., averaged over the three traffic scenarios 9.33).

Figure 30 shows the mean number of recollected items as a function of ACAS theme and RA condition (no RA, RA with datalink delay, and RA with radar delay. A 5 (ACAS theme) x 3 (RA condition) repeated measurements ANOVA yielded a highly significant effect of the ACAS theme ($F(4, 116) = 320.6$, $p < .001$).This effect is due to the differences in the maximum number of to be recollected items. In particular, the mean number of recollected items is lower for ACAS theme 3, in which only details of one aircraft had to be remembered. More importantly, there was no effect of the RA condition (i.e., no RA, RA with datalink delay or RA with radar delay) on the amount of recollected information. The interaction between ACAS theme and RA condition also did not achieve significance. This means that, for none of the ACAS themes, the recollection of the conflict geometry is influenced by the provision of RA information. Further, it also does not depend on whether RA information is provided without delay or with a delay of 5 seconds.

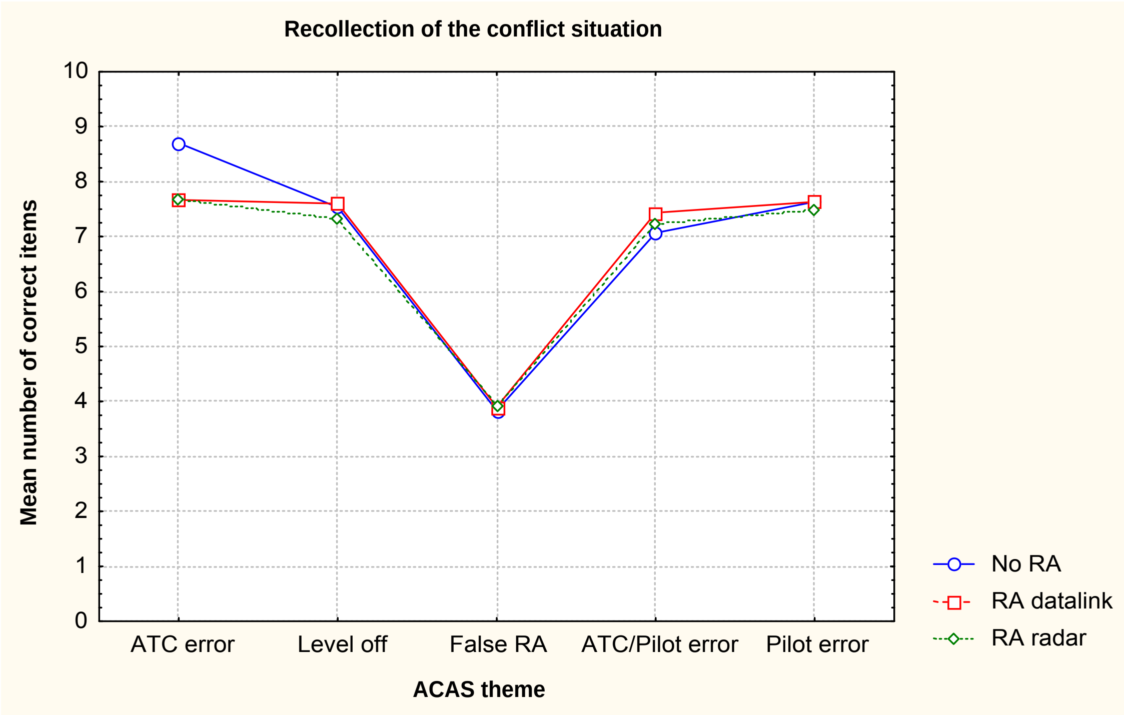

Figure 30: Situation recollection as a function of ACAS theme and RA condition

So far, the analysis has not taken into account the specific RA HMI. That is, measurements in the RA datalink and RA radar conditions were averaged over the minimum, the intermediate, and the enhanced HMI. In order to investigate whether there are any differences between the three RA HMIs, analyses with the independent factors “HMI versions (minimum, intermediate, enhanced)” and “downlink delay (datalink, radar)” were calculated, separately for each of the five ACAS themes. None of these ANOVAs yielded a significant effect. This means that, for none of the five ACAS themes, there was a statistically significant relationship between the recollection of the RA situation (in terms of callsign, cleared level, heading and vertical movements) and the type of RA HMI (minimum, intermediate, and enhanced). Similarly, there was no effect of the downlink delay on the recollection of the traffic situation.

Knowledge of RA related information. Three items in the memory test requested the participants to recollect RA related information. These items were:

- What was the type of RA issued to the aircraft?
- Did the aircraft follow the RA?

For the baseline condition (i.e., EATMP: no RA), the only source of information on the type of RA was the pilot report. However, the pilot in some cases did not report the type of RA properly. This means that there was either no report, or the report was incomplete (i.e. without the sense of the RA) or incorrect (i.e., the reported sense was incorrect). This also affected the participants’ knowledge in the minimum HMI, as there was no indication of the sense of the RA given on the screen. In the intermediate and the enhanced HMIs, in contrast, information on the type of RA could be obtained from the screen.

Figure 31 provides the mean number of correct responses on the RA types issued by ACAS[10]. A 5 (ACAS theme) x 3 (RA condition) ANOVA revealed significant main effects of the ACAS theme ($F(4,116) = 5.54$, $p < .001$) and the RA condition ($F(2,58) = 42.86$, $p < .001$) as well as a significant interaction between the two factors ($F(8,232) = 5.56$, $p < .001$). This means that there are more correct answers in the RA conditions than in the no RA condition. However, this is only true for certain ACAS themes but not for others.

Figure 31: Mean number of correct recollections of RA type

For instance, there is no difference in correct answers for the False RA condition, in which all pilots reported the RA correctly. The extent to which the frequency of correct answers differs in the other ACAS themes mainly reflects the number of incomplete or incorrect pilot reports.

Figure 32 provides the mean number of correct responses to the question of whether the pilot followed the RA. A 5 (ACAS theme) x 3 (RA condition) ANOVA revealed significant main effects of the ACAS theme ($F(4,116) = 6.40$, $p < .001$) and the RA condition ($F(2,58) = 29.32$, $p < .001$) as well as a significant interaction between the two factors ($F(8,232) = 3.81$, $p < .001$). This means that there are more correct answers in the RA conditions than in the no RA condition. However, this is only true for certain ACAS themes (e.g., ATC/Pilot error) but not for others (e.g., False RA). This probably again reflects the fact that, in some ACAS themes, pilot reports were more reliable than in others.

[10] This number excludes the reconstruction of the type of RA on the basis of the RA manoeuvre. That is, correct answers were only counted as such if the participant was informed about the RA type.

Figure 32: Mean number of correct recollections of pilot manoeuvres

In order to investigate whether there are any differences between the three RA HMIs, analyses with the independent factors "HMI version (minimum, intermediate, enhanced)" and "downlink delay (datalink, radar)" were calculated. Analyses were calculated separately for each of the five ACAS themes, and they were calculated for both the recollection of the RA type and the recollection of the pilot's compliance with the RA. None of these ANOVAs yielded a statistically significant effect. Thus, the HMI version (minimum, intermediate, enhanced) did not have a significant effect on the recollection of the RA type and the recollection of the pilot's compliance with it.

Follow-up conflicts. The last item in the memory test asked participants to indicate whether the RA and the resulting pilot manoeuvre yielded any new conflicts. If so, they were asked to specify the conflict. An incorrect answer to this item was scored as 0, and a correct answer was scored as 1. Figure 33 shows the mean frequency of a correct response depending on the ACAS theme and the RA condition (no RA, RA with datalink delay, and RA with radar delay). Note that incorrect answers were predominantly due to the participants seeing a potential follow-up conflict that, in fact, was not a problem, rather than to a failure to detect a problem.

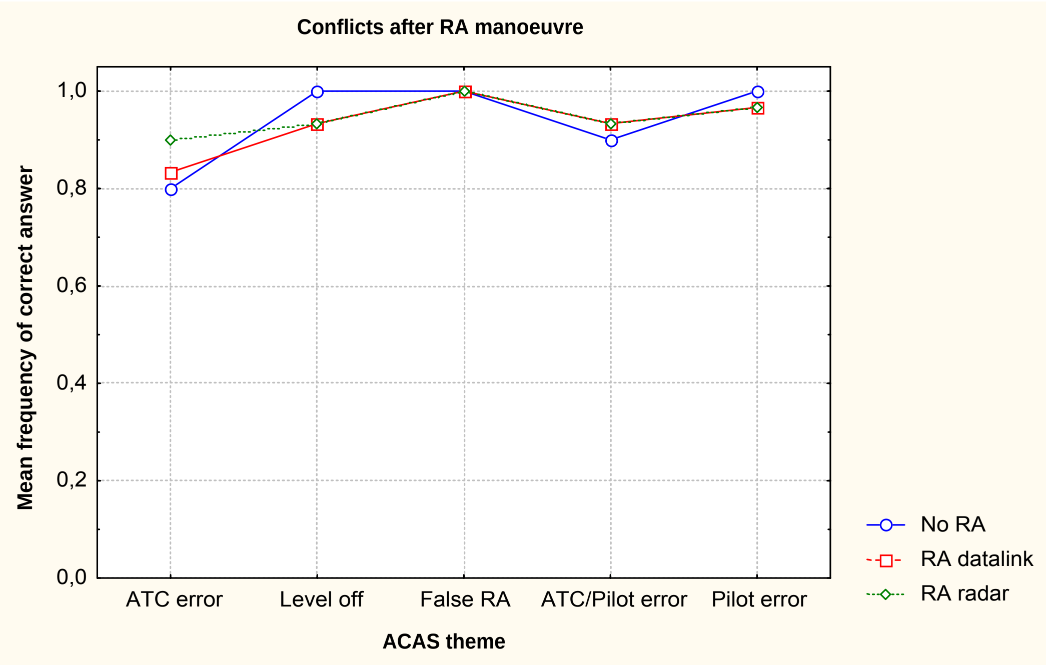

Figure 33: Recollection of conflicts following the pilot manoeuvre

A 5 (ACAS theme) x 3 (RA condition) repeated measurements ANOVA showed a significant effect of the ACAS theme on the frequency of a correct answer ($F(4, 116) = 7.19$, $p <. 001$): Correct answers were less frequent with some ACAS themes (i.e., ATC error) than in others (false alert and pilot error). This effect is most probably due to the specific traffic samples used within a certain ACAS theme. The effect of the RA condition as well as the interaction between RA condition and ACAS theme did not achieve significance. The latter means that the participants' ability to correctly remember follow-up conflicts did not depend on whether RA downlink was provided or not.

6.6.2 Self-rating scale

The situational awareness self-rating scale that had to be filled in after each simulation run is a modified and shortened version of SASHA (Situation Awareness for SHAPE), EUROCONTROL's questionnaire for self-assessment of situational awareness. The last item of this scale requires the participants to give an overall estimate of the level of situational awareness during an exercise ("How would you rate your overall situation awareness during this exercise?"). Answers are given on a 5-point scale ranging from "poor" (1) over "quite poor" (2), "okay" (3), "quite good" (4), to "good" (5).

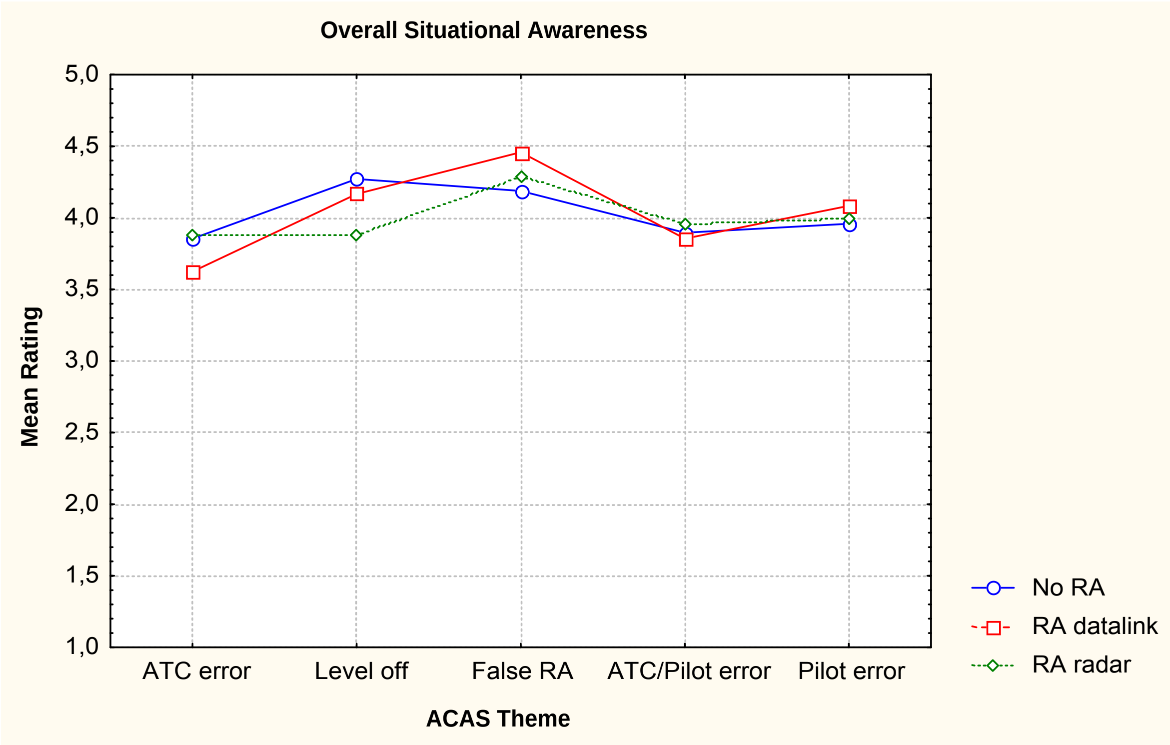

Figure 34: Situational Awareness as a function of ACAS theme and RA condition

Figure 34 provides the mean ratings for situational awareness depending on the ACAS theme and the RA condition (no RA, RA with datalink delay of 0 seconds, an RA with radar delay of 5 seconds).

According to a 5 (ACAS theme) x 3 (RA condition) repeated measurements ANOVA, there is a significant effect of the ACAS theme on the rated situational awareness ($F(4,92) = 7.64$, $p < .001$): ratings are higher for some ACAS themes (such as False RA) than for others (such as ATC error). Neither the main effect of the RA condition nor the interaction of ACAS theme and RA condition yield any significant results. The latter means that the rated situational awareness does not depend on whether RA downlink is presented or not.

The analysis above has not taken into account the specific RA HMI. Measurements in the RA datalink and RA radar conditions were averaged over the minimum, the intermediate, and the enhanced HMI. In order to investigate whether there are any differences between the different RA downlink HMIs, a further set of analyses was calculated. These were ANOVAs with the independent factors “HMI versions (minimum, intermediate, enhanced)” and “downlink delay (datalink, radar)”, calculated separately for each of the five ACAS themes.

The only significant effect was found for the ACAS theme I (i.e., ATC error). For ACAS theme I, ratings differed significantly between the two delay conditions ($F(1, 27) = 4.56$, $p < .04$): situational awareness was rated higher for the radar delay condition than for the datalink delay condition. The effect of the HMI version, in contrast, was not significant. For the other four ACAS themes, neither the effect of the HMI version nor the effect of the delay was found to be significant.

This means that the participants did not experience a difference in their situational awareness between the three different RA downlink HMIs. Further, except for one ACAS theme (i.e., ATC error), there was no difference in the experienced situational awareness between the two delay conditions.

6.7 Eye-tracking

Filtering of data files. The collection of eye-tracking data was carried out by EUROCONTROL. These data were passed on to the NLR for data analysis. Before analysing the data, the quality of the recorded data was evaluated. In order to do so, the following steps were carried out:

1. Check whether eye and head tracker were both functioning during the experimental runs. In case the eye tracker or the head tracker was not working properly during the experimental run, the data file was excluded from data analysis.
2. Calculate the percentage of recorded fixations per run. If this percentage was less than 60% of the total scenario run time, the data file was excluded from further analysis.
3. Check the accuracy of the calibration. At the beginning and the end of a scenario, participants were instructed to look at the corners of the monitor. In case the position of the fixations differed between these two recording points, the data file was excluded from further analysis. A difference indicated a shift of the (head mounted) equipment during the experimental run and, thus, unreliable data.

Only data that had passed at least the second filter were used for eye-blink frequency analysis, and only data that had passed all three filters were used for the analysis of the direction of gaze. Unfortunately, the filtering process yielded a substantial reduction in the number of eye-tracking data. For instance, for the enhanced HMI condition, only one data file passed all three filters. For details about the outcome of the filtering process, see Appendix D.

Data were then pre-processed with the Eyenal software package. After that, in-house software developed by the NLR in combination with MS-Excel was used for further analysis.

Definitions used in the data analysis. Eye blinks were defined as all events in which the pupil diameter was zero for longer than 20 ms and shorter than 240 ms (default settings of the Eyenal software package). The blink frequency is the number of blinks divided by the sample duration in seconds. For the definition of a fixation, the ASL default settings were used, except that the minimum duration for a static focus to be identified as a fixation was increased from 100 ms to 150 ms.

6.7.1 Eye-blink activity

The eye-blink frequency was calculated for each run from the moment the scenario started until its end. Note that the eye-blink rate is usually taken as a (negative) indicator for visual workload: the higher the blink rate, the lower the visual workload. Figure 35 and Figure 36 show the mean eye-blink frequency for each HMI version (EATMP, minimum, intermediate, and enhanced) and the traffic scenarios used in the eye-tracking runs. The error bars in the graphs indicate the standard deviation.

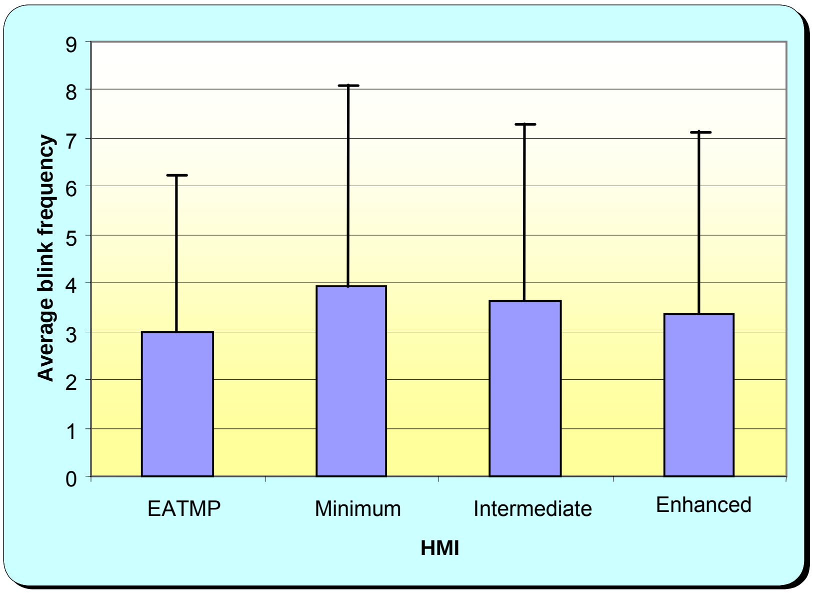

Figure 35: Mean blink frequency depending on the HMI

The differences in eye-blink frequency between the four different HMIs are minor. Furthermore, the standard deviation (as visualised by the error bars) is relatively large, so that possible differences in the eye-blink frequency did not become significant.

Note that for the eye-tracking runs, only a subset of ACAS themes (i.e., themes I, IV, and V) and only two out of three traffic scenarios per ACAS theme were used. The first digit of the traffic scenario indicate the ACAS theme, the second indicates the particular traffic sample (e.g., Scenario 11 and 12 are both used within the ACAS theme I “ATC error”).

The differences in the eye-blink frequency between scenarios were numerically larger than the differences between HMI versions. However, they also did not achieve significance. This is probably due to the large standard deviations.

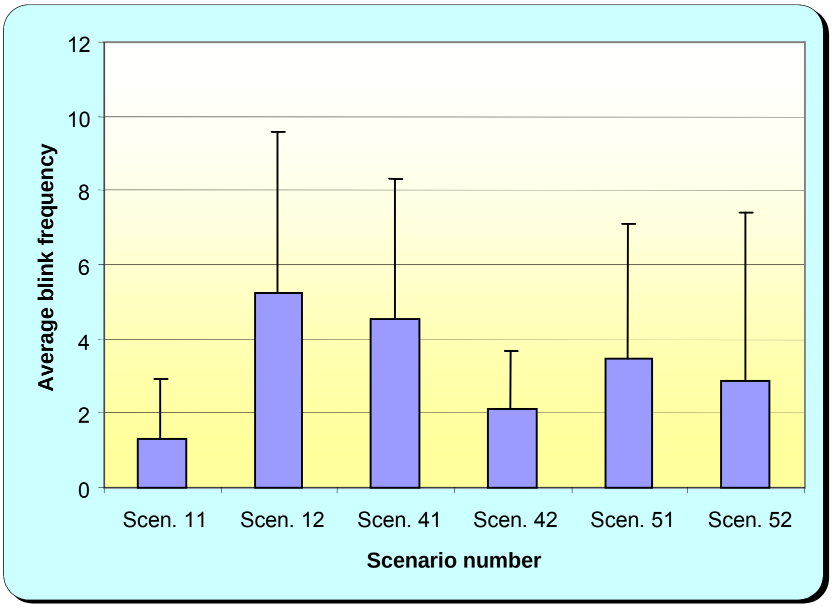

Figure 36: Mean blink frequency depending on the scenario number

The large standard deviations in the eye-blink frequencies suggest that there are large differences within the different HMIs and the different scenarios which could, for instance, be created by differences between participants. However, for the present set of data, it seems more likely that the large standard deviations are due to artefacts or measurement problems.

If the eye tracker cannot identify a pupil, it records the pupil diameter as zero. This information is used as the input for the calculation of an eye blink. Nevertheless, a closed eyelid is not the only possible cause of a pupil diameter of zero. An extreme illumination, reflections, and half-opened eyes can all prevent the equipment from recognising a pupil. Given the unlikely high eye-blink frequencies in a large number of runs, it seems likely that the amount of artefacts is relatively high.

During data analysis, it is extremely tricky to separate the true blinks from artefacts. Therefore, only those data files that have passed the first quality filter were used for the analysis of eye blinks. Even after this filter, though, there was still a number of data files with unlikely high eye-blink frequencies. Since there is no objective criterion for further filtering data files, it was decided to include them in the data analysis.

A further restriction of the eye-blink analysis needs to be mentioned: Eye-blink frequencies vary between individuals. Therefore, comparisons should only be made within individuals or, if comparisons are made between individuals, with standardised scores. Given the huge variance in eye-blink frequencies that is very likely due to artefacts, it was decided to abstain from any further analysis.

6.7.2 Focus of attention

In order to analyse participants' focus of attention during a conflict situation (and thus, during the potential display of RA information), the time spent focussing on the conflict area during the conflict divided by the time spent on other areas was calculated. The definition of a conflict area in this context is as follows: The conflict area is the smallest rectangle on the controller's screen that covers the conflict aircraft (including their target symbols and labels) during the entire conflict period. For all scenarios except scenario 5.1, conflicts lasted about one minute. The conflict in scenario 5.1 lasted about half a minute.

Figure 37 shows the mean percentage of time spent on the conflict area as a function of the HMI version. Also shown is the mean percentage of time spent on the same area when no conflict was present. Note that for the enhanced HMI, the data are based on one experimental run (with one participant) only. For this reason, no error bars are displayed.

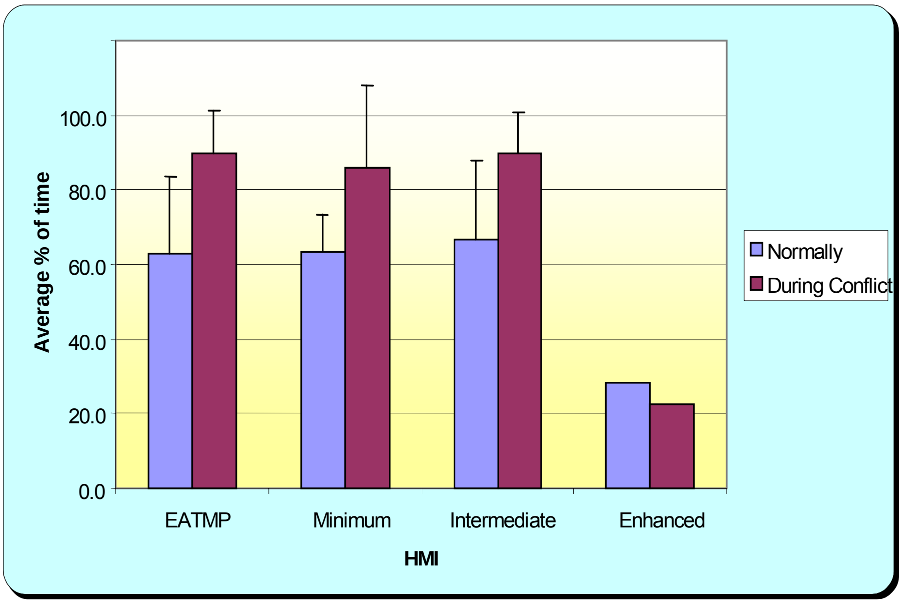

Figure 37: Mean percentage of time spent on conflict area depending on HMI

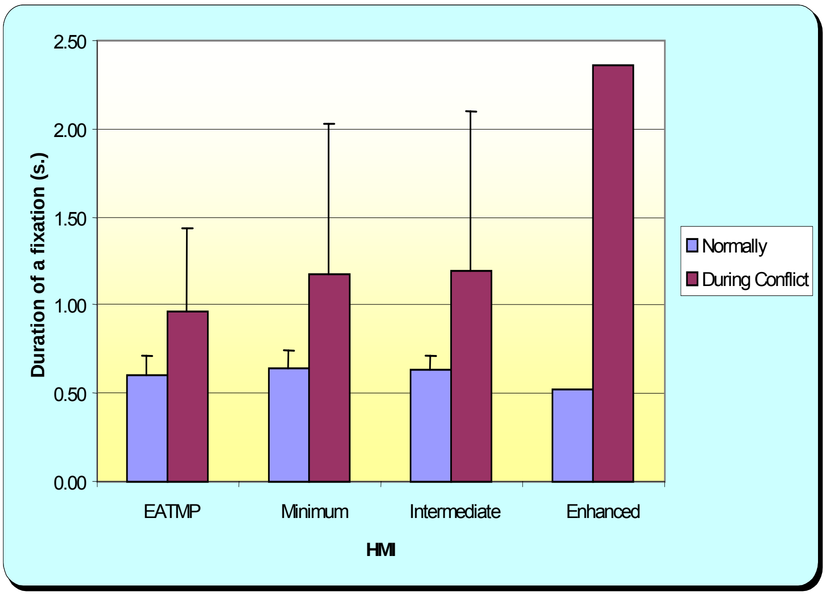

Figure 38: Mean duration of fixations (in sec.) on conflict area depending on HMI

Figure 38 shows the mean duration of fixations on the conflict area as a function of the HMI version. Also shown is the mean duration of fixations on the same spot when no conflict was present. Again, data for the enhanced HMI are only based on a single run.

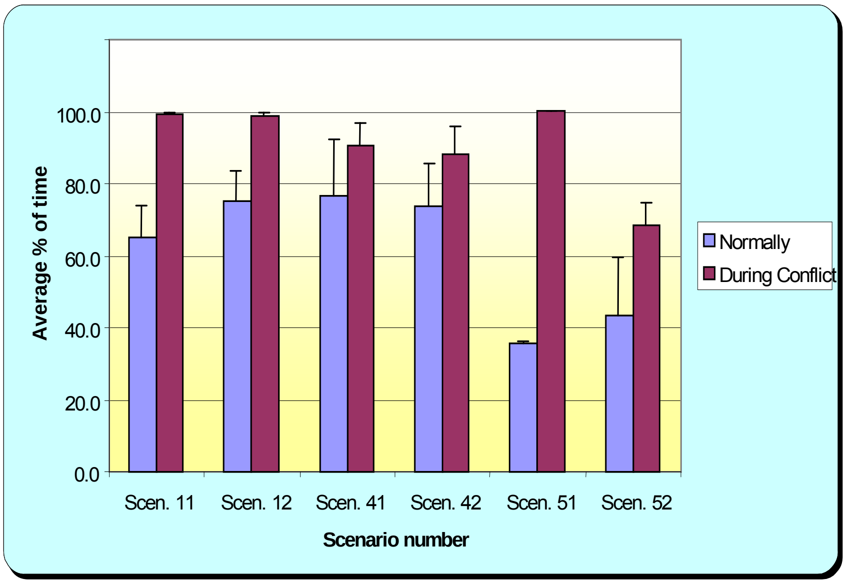

Figure 39: Mean percentage of time spent on conflict area depending on scenario

Numerically, both the time spent on the critical area as well as the duration of a fixation is longer in case of a conflict in the area than in case of no conflict. This corresponds to the expectation. The differences between the HMI versions, in contrast, are negligible. Numerical differences can only be observed for the enhanced HMI, however, these data are based on a single experimental run. For this reason, differences can be due to the particular participant, the specific traffic sample, the HMI version, or just random variation.

Figure 39 shows the mean percentage of time on the conflict area during the conflict depending on the traffic scenario. The figure also shows the percentage of time on this area if no conflict was present. Note that in 3 out of 6 traffic scenarios, the participants spent all time looking at the conflict area during the conflict.

Unfortunately, the amount of data that remained after filtering and the quality of the data in general does not allow for drawing statistically valid conclusions. On the basis of the eye-tracking data, it seems as if there are no differences in the allocation of attention for the different HMI versions. However, it requires high quality data to identify the subtle differences that one may expect as a result of different HMIs. Therefore, it can not be concluded that there is no effect of the different HMIs on the allocation of attention (as well as on the visual workload). Rather, the eye-tracker data were not suitable for identifying potential differences between the HMIs versions.

6.8 Assessment of the experiment

A further set of questions to be investigated concerned the evaluation of the RA downlink experiment and, in particular, the validity of the experimental approach. The evaluation of the experiment was done on the basis of participants' feedback provided both in the post-experimental questionnaire and the de-briefing.

All participants think that the RA downlink experiment helped them to acquire a better understanding of ACAS and RA downlink (*M* = 4.6, *SD* = 0.5, see Figure 40).

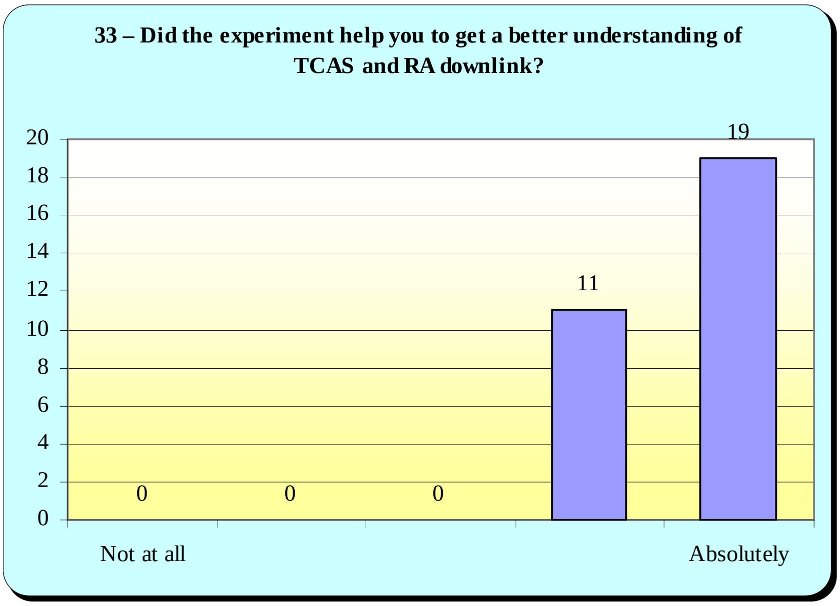

Figure 40: Understanding of ACAS and RA downlink

One limitation of the RA downlink experiment was a rather restricted participant role: participants did not actively control traffic by issuing instructions, but had the role of an observer (mimicking an instructor in an OJT situation). In order to assess the impact of this limitation, participants were asked whether they were able to form a profound opinion of RA downlink by just observing traffic samples (see Figure 41). On average, controllers have a fairly balanced opinion on the adequacy of the observer role (Mean = 3.3, *SD* = 1.1). Six of the participants think that the observer role restricted their ability to evaluate RA downlink (i.e. ratings are on the negative end of the scale). Twelve participants give a neutral assessment; the remaining twelve participants think that they were able to form a profound opinion by observing traffic samples.

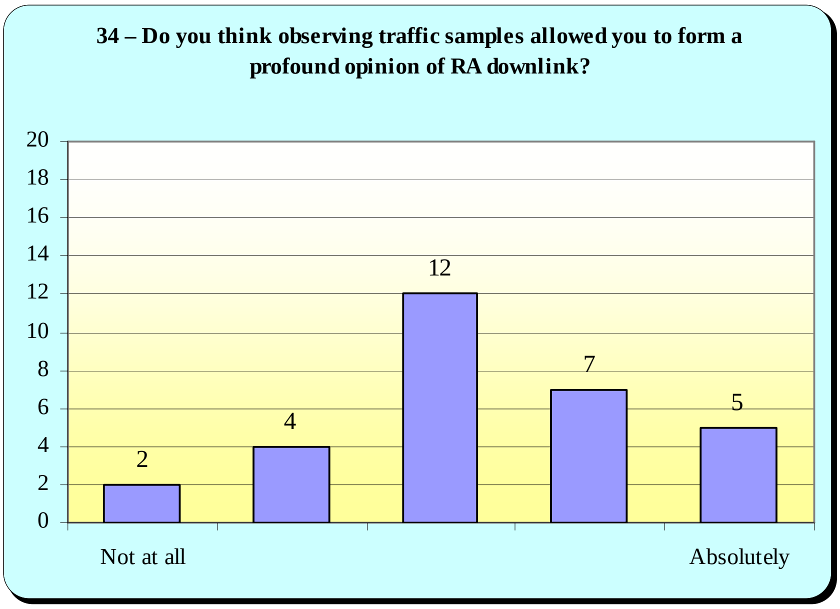

Figure 41: Appropriateness of the observer role

This result is consistent with the feedback obtained in the de-briefings. A small number of controllers had the impression that the participant role in the experiment was too remote from a realistic controller task, thereby severely hampering their ability to form an opinion on RA downlink. The majority of participants, though, did see clear restrictions of the chosen experimental approach, but did not consider the restrictions as compromising the validity of the experimental results. These participants considered the approach chosen in the experiment as adequate for obtaining - at least initial - feedback on RA downlink.

Most of the controllers experienced the traffic situations shown in the simulation as realistic (M = 3.8, SD = 0.9, see Figure 42). Only three out of the 30 participants judged the traffic samples as fairly unrealistic. Twenty-one participants considered the traffic samples as (fairly or absolutely) realistic; six participants made a neutral assessment.

In spite of this fairly positive evaluation, some suggestions for improving the traffic samples were made:

- Increase traffic load,
- More aircraft on direct routes or headings,
- More vertical movements,
- Larger variability in ground speed,
- Higher number of R/T contacts per aircraft,
- Adverse weather conditions,
- Include emergency situations,
- Include military or restricted areas in the sector.

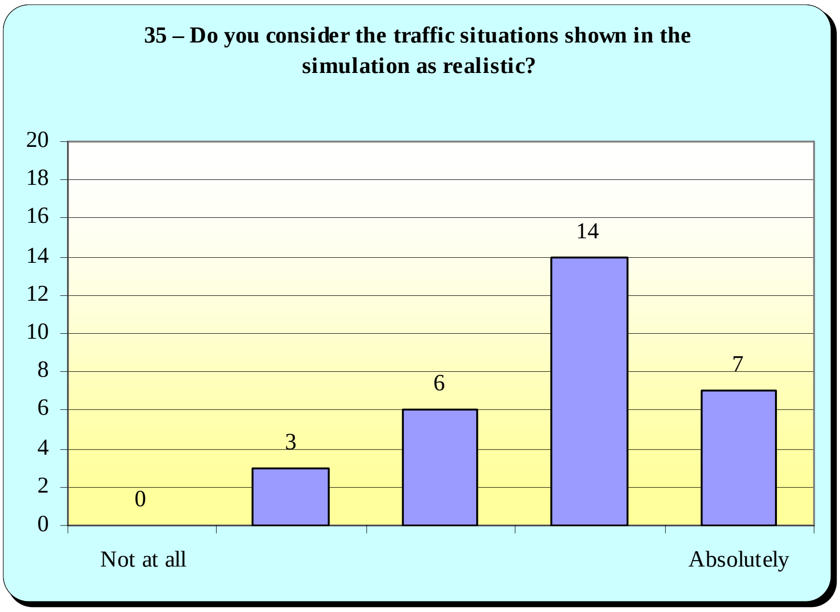

Figure 42: Realism of the traffic samples

All of the suggested improvements should serve to decrease the predictability of the conflict situation. With the current traffic samples, most controllers had the impression that there were able to identify the problem area well in advance. This reduced the "surprise factor" and, therefore, also the potential benefits of the RA downlink.

7. CONCLUSIONS

7.1 Objective 1: Evaluate controllers' acceptance of RA downlink

Operational advantages and disadvantages. Most of the controllers participating in the experiment think that RA downlink will be beneficial for the controller. The main advantages seen are:

1. RA downlink is experienced as more reliable and often faster than a pilot's report of an RA via R/T,
2. it can help to direct the controllers' attention to a problem and to support the anticipation of unexpected pilot manoeuvres (thereby improving situational awareness),
3. it prevents the controller from issuing contradictory clearances to the conflict aircraft, and
4. it facilitates the provision of traffic information, either to the conflict aircraft or to third-party aircraft.

These operational advantages of RA downlink are, to a certain extent, countered by some operational disadvantages.

1. RA downlink increases the amount of information to be processed by the controller,
2. it might narrow the focus of attention down to a single problem on the screen,
3. it provides the controller with information about what the pilot is supposed to do rather than his actual action; in case of discrepancies between RA and pilot manoeuvre, RA downlink can be misleading for the controller.

For most of the controllers participating in the study, the disadvantages do not outweigh the expected advantages of RA downlink. Furthermore, the majority of the concerns on RA downlink are related to an inappropriate interface (i.e., too much and detailed information provided, frequent changes in information, aggressive alerting), and thus, can be minimised by careful design choices.

Legal issues related to RA downlink. The majority of participants do not see any liability issues that are inherent to the concept of RA downlink and that cannot be tackled by the definition of appropriate procedures. Such procedures should preserve the current responsibilities of pilots and controllers. Authority for separation should be preferably transferred to the pilot at the verbal report of the RA, rather than at the RA downlink. RA downlink should only be used for informational purposes; no obligations for further controller actions and responsibilities should arise from the display of RA information. A few controllers, though, find it difficult to believe that the RA information will not result in new responsibilities (and thus liability) for the controller.

Necessity of procedural changes. Most participants do not think that RA downlink would require substantial changes to the existing procedures. This holds both for issuing clearances to an aircraft with an RA and for the introduction of new phraseology ("Follow TCAS" or "TCAS observed"). Nevertheless, if RA downlink is implemented, European wide procedures on how to use RA downlink information need to be defined. These RA related procedures should preferably amend the existing operational procedures as outlined in [10]. The newly amended procedures should clarify, among others, when the responsibility for aircraft separation is passed on to the pilot (at RA display or at pilot report), and how to behave in case of an RA downlink but no pilot report.

7.2 Objective 2: Evaluate RA downlink in different operational scenarios.

The participating controllers see the clearest benefits of RA downlink in a situation in which the RA was caused by either a pilot error or an ATC error. For both nuisance alerts and false alerts, controllers' opinions diverge as to whether a display of RAs provides the controller with useful information or not. A false alert does not point to a real conflict situation and, therefore, is less relevant for the controller. However, downlink of a false alert can provide an explanation why a pilot initiates a manoeuvre that is not in line with the clearance. A nuisance RA (i.e., an RA that is due to high vertical rate of the aircraft involved) does not yield a deviation from the cleared flight path and, thus, is less relevant for the controller. There are some controllers, though, who see advantages in downlinking nuisance alerts: first, the pilot could overreact to the RA, thereby deviating from the original clearance, and second, it could reduce stress for the controller to see that the pilots are aware of the other aircraft (for instance, in case of two aircraft in vertical movement approaching each other). With respect to the pilot's behaviour following the RA, RA downlink is thought to have the biggest benefit in case the pilot does not report the RA by means of R/T. In this case, the RA downlink is the only source of information for the controller to know that an RA has been issued in the cockpit and the pilot will probably deviate from the cleared flight level.

7.3 Objective 3: Evaluate the impact of RA downlink malfunction.

False downlink of an RA. A false downlink of an RA refers to a situation in which an RA is displayed on the radar screen, although no RA was issued by ACAS. All participants consider a false downlink of an RA as a highly undesirable situation. However, the vast majority of the controllers do not regard a false downlink of an RA as a likely cause of a hazard. In order for a false downlink of an RA to develop into a hazardous situation, a set of conditions need to be simultaneously met:

- Responsibility is transferred to the pilot upon RA display (rather than the pilot report),
- the controller does not diagnose the false RA on the basis of other information on the screen (i.e., there are potentially conflicting aircraft in the vicinity, and the controller does not check mode C information),
- the controller does not diagnose the false RA by contacting the pilot (i.e., either to explicitly confirm the RA, or to implicitly confirm the RA by providing traffic situation), and
- the aircraft with the false RA is involved in a conflict situation with another aircraft.

Therefore, the safety-critical consequences of a false downlink of an RA can be minimised by transferring responsibility only at pilot report and by training controllers on how to detect and deal with incorrect RA information.

Missed downlink of an RA. A missed downlink of an RA refers to a situation in which no RA is displayed on the radar screen, although there was an ACAS RA in the cockpit. There are some general concerns about system malfunctions (i.e., malfunction would compromise controllers' trust in RA downlink), however, the participants do not consider the scenario of a missed RA downlink as the likely cause of a safety-critical situation. The main argument is that a situation with a missed RA downlink is identical to the current situation in which no RAs are displayed. For this argument to be valid, though, it needs to be ensured that pilots continue to report RAs by R/T and, thus, the likelihood of a missing pilot report does not increase with the introduction of RA downlink.

7.4 Objective 4: Evaluate the technical implementation of RA downlink.

Downlink delay. Most of the participants consider 5 seconds as the maximum acceptable delay for RA downlink, with controllers' responses varying from 1 to 10 seconds. However, the majority of participants did not notice a difference between the two implemented delay conditions of 0 and of 5 seconds. This could be taken as evidence that there is not any noticeable difference in the understanding of the conflict situation and the ability to plan the post-alert situation. Furthermore, the discrepancy between the controllers' experience of delays and their abstract judgements seems to indicate that the participants apply a fairly strict criterion in their judgements. Independently of whether controllers notice the downlink delay or not, it has to be stated that the expected benefits of RA downlink (in particular, the prevention of contradictory clearances and the facilitation of traffic information) get lesser with a longer downlink delay.

Filtering of RAs. With respect to filtering of RAs, controllers' opinions diverge. Some participants would like to see all RAs that are issued to the pilot, other participants want to have some RAs filtered. Obvious candidates for filtering are false alerts and RAs that do not yield a deviation from the cleared level. However, the majority of controllers appreciate the display of false alerts as the RA can provide an explanation of why a pilot initiates a certain manoeuvre and deviates from the clearance. RAs that do not result in a deviation from the cleared level, on the other hand, are experienced as less beneficial. In certain situations, such as two aircraft in vertical movement approaching each other, an RA might carry relevant information for the controller even if it does not mean an unexpected pilot manoeuvre. In any case, the main criterion for an RA being experienced as relevant for the controller or not is whether the RA involves a deviation from the cleared flight path. This also requires that the pilot follows the RA. For this reason, it was also suggested only to show an RA if the pilot initiates the corresponding manoeuvre.

7.5 Objective 5: Evaluate the different HMI versions for the display of RA information.

Comparison of the three HMIs for RA downlink. In the present study, three different HMIs for the display of RAs were used.

1. A minimum HMI that gives an indication of the RA (without its direction or sense) and uses a visual alert.
2. An intermediate HMI that gives an indication of the RA with its sense and uses a visual alert.
3. An enhanced HMI that an indication of the RA with its sense and uses a visual, auditory and (for some participants) a vibration alert.

Among the three different HMIs, the intermediate HMI is the preferred one. The minimum HMI was judged as lacking information on the sense of an RA, which was considered relevant by the majority of controllers. The enhanced HMI was not fully appreciated because of its flashing visual alert, the aural alert, and the vibration alert. In spite of its superior assessment, the intermediate HMI is not considered optimal either, both with respect to the level of detail of the RA information and the alerting (see below).

Display of RA information. Although most of the controllers considered the display of RA information (at least for those RAs that imply a deviation from the cleared level) as helpful, they were not completely satisfied with any of the chosen implementations. The minimum HMI (which just gives an indication of the RA without specifying it), was considered as not providing enough information to the controllers. The intermediate and the enhanced HMI (which provide the exact sense of the RA) were considered as providing too much information to the controllers. With respect to the intermediate and the enhanced HMIs, two problems were perceived: First, a lot of the information was considered as irrelevant (i.e., limit descent to a certain rate), and second, the abbreviations used were not intuitively understandable. Considering that RAs are a rare event and, thus, controllers would be only exposed to them infrequently, it is absolutely necessary that the abbreviations are intuitively understandable.

RA downlink alerts. The majority of controllers think that using colour to display RAs (i.e., a visual alert) is helpful for attracting attention. Also, the specific choice of colours (i.e., yellow on red) was appreciated by most of the controllers. Nevertheless, there was one major criticism concerning the perceptual similarity between the display of the RA and the display of an STCA: Because of the use of the same colour scheme, it was difficult to distinguish between the STCA and the RA.

In contrast, an audio alert is only appreciated by a minority of participants. Most participants see the advantages of an RA audio alert (i.e. it reduces the likelihood of the controller missing the RA) outweighed by its disadvantages (i.e., a potential information overload and interference with other auditory information). It was pointed out that audio alerts seem to be more suitable for STCAs (which should trigger the controller to take action), than for RAs.

Participants also did not like the concept of a vibration alert and experienced it as distressing and distracting. Only a couple of controllers see some benefit in a vibration alert if used in combination with a visual and an aural alert. With respect to the experienced distraction, it might be argued that this might wear off with more experience; again, however, it needs to be considered that RAs will be an infrequent event.

For both the aural and the vibration alert, it was maintained that, if the controller has failed to detect both the conflict situation as well as the STCA and the visual RA alert, the controller is not attending the traffic situation. In this case, the benefit of RA downlink is restricted anyway: neither is the controller likely to issue a contradictory instruction, nor will he or she be able to take full advantage of the RA information (with respect to post-planning the traffic situation or providing traffic information).

7.6 Objective 6: Assess the impact of RA information on controllers' situational awareness.

One of the expected benefits of RA downlink consists in an improvement of the controller's situational awareness. In the experiment, situational awareness was measured

- in terms of the recollection of the RA situation, and

- on the basis of participants' self-rating of their situation understanding.

With respect to the *self-ratings*, there was no effect of the RA information on the controllers' situational awareness. In particular, there was no significant difference in the controllers' understanding of the traffic situation whether or not RA downlink was present. Furthermore, there was negligible difference in the rated situational awareness between the two downlink delays (0 or 5 seconds), and the three different HMI versions for displaying RAs (minimum, intermediate, or enhanced) was implemented.

With respect to the *recollection of the RA situation*, there was also no clear effect of RA downlink on controllers' understanding of the situation. Within the recollection of the situation, three different aspects were distinguished: (a) the conflict description (aircraft involved and geometry), (b) the type of RA and the pilot's compliance with it, and (c) potential follow-up conflicts.

For both the conflict description and the follow-up conflicts, controllers' recollections did not differ, regardless of whether RA downlink was present or not. Further, there was generally no difference for the two downlink delays of 0 or 5 seconds (except for a single ACAS theme), and there was no effect of the HMI version (minimum, intermediate, or enhanced). In contrast, controllers' knowledge of the type of RA and the subsequent pilot manoeuvre was substantially better with RA downlink than without. This better RA related knowledge can be simply explained by the fact that participants in the RA downlink conditions (in particular, the intermediate and the enhanced HMIs) were provided with much more accurate information on the RA than in the condition without RA downlink.

The failure to find any effects of RA downlink on the controllers' situational awareness – in particular on the knowledge of the conflict geometry and follow-up conflicts – is potentially due to the experimental situation. Most of the participants reported that they were able to identify the problem area in the traffic scenarios well in advance. For this reason, they were not surprised by the RA and the subsequent pilot manoeuvre. It is likely that the high level of situational awareness throughout the simulation masked the potential benefits of RA downlink.

7.7 Objective 7: Assess the impact of RA information on visual behaviour.

Eye-blink frequency was analysed as an indicator of visual workload, and participants' direction of gaze on the screen was analysed as an indicator of the allocation of attention. Unfortunately, though, the amount of data that remained after a number of quality checks on the eye-tracking data as well as the quality of the remaining data does not allow for drawing statistically valid conclusions. On the basis of the available data, it seems as if there are no differences in the visual workload and the allocation of attention. This holds both for whether RA downlink is provided or not, and for the different RA downlink HMIs. However, it requires high quality data to detect the subtle effects one might expect for the manipulations carried out in the experiment. Therefore, it can not be concluded that there is no effect of the different HMI versions (with or without RA) downlink on visual workload and the allocation of attention. Rather, the eye-tracker data were not suitable for identifying potential differences between the HMIs versions.

7.8 Assessment of the experiment

All participants felt that the RA downlink experiment helped them to acquire a better understanding of ACAS and RA downlink. One limitation of the RA downlink experiment was a rather restricted participant role: participants did not actively control traffic (by issuing instructions), but had the role of an observer. A small number of controllers thought that these restrictions severely impaired their ability to form an opinion on RA downlink. The majority of participants, though, did see clear restrictions of the chosen experimental approach, but did not consider them as reducing the validity of the experimental results. Most of the participants experienced the traffic situations shown in the simulation as realistic. Nevertheless, it was suggested to increase the complexity of the traffic situations in order to make the conflict situations more difficult to anticipate. By increasing the 'surprise factor' the potential benefits of RA downlink might become more apparent.

8. RECOMMENDATIONS

On the basis of the results obtained in the RA downlink experiment, a number of recommendations for the future work on RA downlink can be formulated.

1. *Make the HMI as simple as possible.* One of the biggest concerns related to RA downlink is that controllers will be overloaded with information and, thus, could be distracted from other safety-critical information in the sector. For this reason, it is important to make the RA related HMI as simple as possible. Care should be taken that the information provided to the controller is (a) not too detailed and (b) intuitively understandable. With respect to the level of detail, the crucial question is whether a certain bit of information is relevant for the controller's task (including the situational awareness required to perform a task). In many cases, it is not appropriate to display the same level of detail to the controller as is provided to the pilot. For instance, an RA such as "limit descend to 500 ft per minute" has clear implications for the task of the pilot (i.e., to choose a specific vertical rate); however, for the controller there is only limited benefit to know what the specific restriction on the vertical rate is. Furthermore, if the level of detail is too fine-grained, the displayed RA information is more likely to change (for instance, from "climb" to "increase climb" or from "limit climb 2000 fpm" to "limit climb to 1000 fpm"). With respect to the understandability of the RA information, complex abbreviations should be avoided. This is especially important since controllers will only be exposed to the RAs very infrequently.

2. *Make clear whether an RA yields a deviation from the ATC clearance.* For the pilot, one of the crucial bits of information is whether the resolution advisory involves a change in the current (vertical) flight parameters, or whether the current flight parameters can be maintained. As a consequence, ACAS - that has been designed as a pilot support tool – distinguishes between corrective and preventive RAs. The distinction between preventive and corrective RAs, however, is not appropriate for the controller. According to ICAO Document 7030 EUR [11], the controller only ceases to be responsible for providing separation, if "an aircraft departs from the current ATC clearance in compliance with an RA". Thus, the crucial information for the controller is not whether ACAS has issued an RA or not, but whether the RA will yield a deviation from the ATC clearance (provided that the pilot complies with the RA). The fact that responsibility for separation is only transferred to the pilot if the aircraft deviates from the ATC clearance also rules out specific combinations of filtering and HMI decisions: In particular, a combination of not filtering any RAs and a minimum HMI (that does not give any indication of the sense of the RA), can be expected to yield confusion with respect to the pilot/controller responsibility. In order to make the distinction between RAs that yield a deviation from the ATC clearance and those who do not yield a deviation from the ATC clearance intuitively understandable, two approaches could be taken: either RAs not yielding a deviation of the ATC clearance are filtered from being displayed, or they are displayed in a different way than those that yield a deviation from the ATC clearance. However, there might be technical obstacles to the proposed approaches: if the automated system does not know

the current clearance, then it is impossible to display the RA depending on its relationship with the clearance.

3. *Show the direction of an RA.* Important benefits of RA downlink refer to the improvement of controllers' situational awareness, the facilitation of traffic information, and the planning of the post-alert situation. In order to realise these potential benefits, though, it is necessary that the controller is informed about the manoeuvre the pilot is likely to initiate. This means that the RA HMI should include the direction of the evasive manoeuvre, that is, whether the RA is to climb or to descend. Without such an indication, the controller is not able to anticipate on the future positions of the conflict aircraft, and the planning of the post-alert situation will be impaired.

4. *Make the RA alert perceptually dissimilar to the STCA.* In the current experiment, the RA and the STCA used similar means for visually alerting the controller to the conflict situation. Both the STCA and the RA were shown in the aircraft label, and they were displayed in yellow on a red background. The similarity between the two kinds of alerts rendered it difficult to distinguish them. Furthermore, the auditory RA alert issued in the enhanced HMI sometimes seemed to interfere with the auditory alert of the STCA. An easy distinction between STCA and RA is important, especially because the implications of the two alerts for the controller are qualitatively different. The STCA alerts the controller to a situation that (in case it is not a nuisance alert or a false alert) requires immediate action. The RA, in contrast, alerts the controller to a situation in which he or she should refrain from control actions – given that the RA implies a deviation from the ATC clearance. In general, the alerting mechanisms for RA downlink should be designed in the context of other kinds of alerts (such as STCA or MTCD) available at the controller working position.

5. *Propose operational procedures for the use of RA downlink.* The impact of RA downlink on the controller's task and performance cannot be fully investigated unless operational procedures for the use of RA downlink have been defined. For future studies (especially if they involve a higher degree of controller interaction), operational procedures need to be proposed. These procedures should clarify when the responsibility for aircraft separation is passed on to the pilot, what the controllers' actions following an RA are, and how to behave in case of inconsistency between different sources of information (e.g., pilot's report vs. RA downlink).

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Appendix A Questionnaires

Participant-ID:	Date:	Time:

Pre-experimental Questionnaire

Note: All data collected during this simulation will be treated with the ***strictest confidentiality***. Only member of the experimental team will have access to the questionnaires; data analysis and report will be done in such a way that responses cannot be traced back to any particular person.

ABOUT YOURSELF

1 – What is your age? ____________________

2 – What is your nationality? ____________________

ABOUT YOUR EXPERIENCE AS AN AIR TRAFFIC CONTROLLER

3 – In which ACC do you work? ____

4 – What other ratings do you hold or have held? ___________________________________

5 – How long are you licensed as a controller (in years)? __________________________

6 – How long are you licensed as an area controller (in years)?______________________

7 – Do you have experience as an instructor (including On-The-Job Training)?

❑ Yes, for ________ years
❑ No

8 – Have you ever witnessed any incidents where a serious violation of separation minima has occurred or could have occurred? (This can either concern traffic under your responsibility or under responsibility of adjacent sectors/your colleagues)?

- ❑ Yes, please indicate how many __________
- ❑ No

If you responded "yes", please proceed with Question 9. If you responded "no", please proceed with Question 12.

9 – In case you have witnessed (an) incident(s), were there any Resolution Advisories (RAs) generated in these situations?

- ❑ Yes, in ______ out of _______ cases
- ❑ No
- ❑ I don't know

10 – In case you responded "yes" to the previous question, how did you come to know about these RAs?

- ❑ Pilot reporting it on R/T
- ❑ Through an investigation
- ❑ Don't remember

11 – In the incidents witnessed by you, did RAs help to resolve the conflict situation?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

12 – In case your experiences with RAs differ (that is, in one incident it might have helped, in another, it might not), please specify.

13 – Have you ever been informed about RAs by a pilot that were nuisance alerts (e.g. due to fast climbing or fast descending aircraft)?

- ❑ Yes, please indicate how many ______
- ❑ No

14 – Have you ever been informed about RAs by a pilot that were false alerts (i.e., there was no other traffic in the vicinity)?

- ❑ Yes, please indicate how many _______
- ❑ No

ABOUT THE SIMULATION OBJECTIVES

15 – How would you assess your knowledge of TCAS II?

Poor ☐ ☐ ☐ ☐ ☐ Very good

16 – How familiar are you with the concept of RA downlink?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

17 – How useful do you think is the display of RAs to the controller?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

18 – What are – in your opinion – the operational advantages of displaying RAs to the controller?

19 – What are – in your opinion – the operational disadvantages of displaying RAs to the controller?

Thank you very much!

Situation Awareness Questionnaire

Participant-ID:	**Date:**	**Run-no.:**
HMI Version:	**Scenario no.:**	**Delay: DL/Radar**

Q1: - Did you have the feeling that you were ahead of the traffic and able to predict the evolution of the traffic?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Comments:………………………………………………………………………………………
…………………………………………………………………………………………………..
…………………………………………………………………………………………………..

(* to be answered only if RA information was displayed on the screen)

*Q2: - Did the RA information help you to have a better understanding of the situation?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Comments:………………………………………………………………………………………
…………………………………………………………………………………………………..
…………………………………………………………………………………………………..

*Q3: - Did you feel distracted by the RA information (from attending other relevant aspects of the traffic situation)?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Comments:………………………………………………………………………………………
…………………………………………………………………………………………………..
…………………………………………………………………………………………………

*Q4: - Did the RA information help you to focus on the safety-relevant aspects of the traffic situation?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Comments:……………………………………………………………………………………
………………………………………………………………………………………………..
………………………………………………………………………………………………..

Q5: - Finally, how would you rate your overall situation awareness during this exercise?

Poor ☐ Quite Poor ☐ Okay ☐ Quite good ☐ Very good ☐

Comments:……………………………………………………………………………………
………………………………………………………………………………………………...
………………………………………………………………………………………………..

Post-exercise questionnaire

Participant-ID:	**Date:**	**Run-no.:**
HMI Version:	**Scenario no.:**	**Delay: DL/Radar**

In your opinion, what was/were the reason/s for the RA/incident in the previous scenario? (Multiple answers possible)

❑ ATC error
❑ Pilot error
❑ TCAS error (that is, an alert without any aircraft in the vicinity)
❑ Fast climbing/fast descending aircraft
❑ Don’t know
❑ Other, namely ______________________________

Please describe the situation by filling in the table below.

<table>
<tr><td></td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td></tr>
<tr><td>Aircraft involved in the situation (Callsign or Airline 3-Letter Code)?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Cleared Level?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Climb/level/descend prior to RA/incident? (please mark)</td><td>↑</td><td>→</td><td>↓</td><td>↑</td><td>→</td><td>↓</td><td>↑</td><td>→</td><td>↓</td></tr>
<tr><td>Approximate Heading?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Did pilot report RA?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Was RA information displayed on the screen?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Type of RA issued to aircraft?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Did aircraft follow RA?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Did RA reverse its sense?</td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
</table>

Did pilot manoeuvre yield any new conflicts? If so, describe.	

Participant-ID:	Date:	Time:

Post-experimental Questionnaire

GENERAL ATTITUDE ON TCAS

After attending the experiment, we would like you to give us your opinion on the potential advantages and disadvantages of RA downlink again.

1 – How would you assess your knowledge of TCAS II?

Poor ☐ ☐ ☐ ☐ ☐ Very good

2 – How familiar are you with the concept of RA downlink?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

3 – How useful do you think is the display of RAs to the controller?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

4 - What are – in your opinion – the operational advantages of displaying RAs to the controller?

5 - What are – in your opinion – the operational disadvantages of displaying RAs to the controller?

6 – Having experienced a lot of TCAS training and TCAS events over these two days, do you think it would be generally beneficial for air traffic controllers to get additional training on TCAS?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

7 – If so, please specify concerning which topics:

TCAS IN DIFFERENT SITUATIONS

In this section, we are interested in the specific situations in which RA downlink might be helpful, and the situations in which it might be less helpful.

8 – Do you think RA downlink would be helpful in case of a false TCAS alert?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

9 – Do you think RA downlink would be helpful in case the RA has been triggered by a high vertical rate before level off?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

10 – Do you think RA downlink would be helpful in case of an ATC error?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

11 – Do you think RA downlink would be helpful in case of a pilot error?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

12 – Do you think RA downlink would be helpful in case of a pilot not following the RA correctly?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

13 – Do you think RA downlink is more helpful as situations become more complex?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

14 – Do you think RA downlink would be helpful in case the pilot *does not* report the RA?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

15 – Do you think RA downlink would be helpful in case of the pilot *does* report the RA?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

16 – If it was technically feasible to filter RA downlink in some situations and not show them to the controller, which situations should not be shown?

HUMAN-MACHINE INTERFACE

The questions below refer to the way in which the RA information was provided to you, that is, the human-machine interface.

17 – Generally, do you think do you like having RA information on the controller screen?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

18 – What is your evaluation of the HMI with the indication of an RA in yellow on red (without the direction of the RA)?

Poor ☐ ☐ ☐ ☐ ☐ Very good

19 – What is your evaluation of the HMI with the RA in yellow on red (with the sense of the RA)?

Poor ☐ ☐ ☐ ☐ ☐ Very good

20 – What is your evaluation of the HMI with the flashing RA in yellow on red (with the sense of the RA) and the voice alert?

Poor ☐ ☐ ☐ ☐ ☐ Very good

21 – Which information in the HMI do you consider informative and helpful (multiple answers possible):

❑ Having preventive RAs displayed (e.g., maintain descent)
❑ Having corrective RAs displayed (e.g., descent, climb)
❑ For corrective RAs, having the direction displayed
❑ For corrective RAs, having the exact wording displayed
❑ None of the mentioned aspects
❑ Other, namely ____

22 – Which means of alerting do you consider helpful (multiple answers possible):

❑ Displaying the RA using colour (i.e., yellow on red)
❑ Flashing RA message
❑ Having an audio voice alert (i.e., TCAS TCAS)
❑ None of the mentioned aspects
❑ Other, namely ____

23 – Do you have any suggestions for improving the Human-Machine Interface?

24 – Some RAs were shown with almost no delay, other RAs were shown with a delay of about 5 seconds. Did you notice any differences in the speed for RAs being shown?

- ❑ Yes
- ❑ No

25 – Having technical limitations in mind, what is the maximum delay between the TCAS RA generated at the airplane and the display on the controller screen that you consider acceptable?

_________________ seconds

PROCEDURES RELATED TO RA DOWNLINK

26 – Could controller's procedures be improved if RA downlink was implemented? If so, in which way?

27 – Could pilot's procedures be improved if RA downlink was implemented? If so, in which way?

28 –If you had RA info displayed on your screen, would you provide traffic information to (multiple answers possible):

- ❑ Aircraft involved in the conflict situation
- ❑ Surrounding traffic
- ❑ Difficult to say

29 – Based on your experience from the previous scenarios, do you think there would be enough time to provide traffic information?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

30 – Some people have suggested using the phraseology “Follow TCAS” when you get an RA downlink. Do you think this is an appropriate procedure for the situation?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

31 – In the situations, in which RA downlink was displayed, would an ATC clearance for a horizontal manoeuvre have helped the situation?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

32 – Would there be enough time to issue such an instruction?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

ON THE SIMULATION

In this section, we want your feedback on the content and the organisation of the experiment.

33 – Did the experiment help you to get a better understanding of TCAS and RA downlink?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Please indicate why:____

____

34 – Do you think observing traffic samples allowed you to form a thorough opinion of RA downlink?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Please indicate why: ____

____

35 – Do you consider the traffic situations shown in the simulation as realistic?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

Please indicate why: ____
____

36 – How do you assess the quality of the training (i.e. the presentations)?

Poor ☐ ☐ ☐ ☐ ☐ Very good

What could have been improved? ____
____

37 – How do you assess the organisation of the simulation, in terms of the travel and the accommodation?

Poor ☐ ☐ ☐ ☐ ☐ Very good

What could have been improved? ____
____

38 – How do you assess the organisation of the simulation, in terms of the daily schedule you had?

Poor ☐ ☐ ☐ ☐ ☐ Very good

What could have been improved? ____
____

39 – Are there any aspects of the simulation you particularly liked?

40 – Are there any aspects of the simulation you particularly disliked?

41 – Do you see a need for more research on RA downlink and further experiments?

Not at all ☐ ☐ ☐ ☐ ☐ Absolutely

42 – Are there any other comments on the simulation you would like to make?

Thank you very much for your co-operation and contribution!

Appendix B De-briefing Questions

Questions for the de-briefing

Thought Experiments

Several situations were not simulated during these experiments. Please think about the following theoretical situations:

1- What would be the effect if not all RAs were downlinked? In other words, an RA takes place on the aircraft but is not shown on the controller's screen – even though RA downlinking is on?

2 – What would happen if an RA was downlinked, but nothing was shown on the pilot's display?

3 – Are there any situations not shown in the experiment that we should consider that will have an effect on RA downlink to the controller?

Procedural changes

4 - You have observed a number of traffic situations. According to current procedures, you should not give any (vertical) instructions to an aircraft that receives an RA. Do you think these procedures need to be modified?

5- Do you think that RA downlinking would require procedures to be changed?

Liability

5 – What are the consequences of RA downlink for controller liability? Do you see any problems? For instance, what happens if RA is downlinked but the pilot does not follow it?

6 – Do you have any suggestions how these liability issues should be tackled?

Assessment of RA downlink and HMI

7 – What is your general feeling about RA downlink now?

8 – What do you think about the different ways in which RA were displayed to you in the experiment?

9 – Is there anything you would like to discuss that has not been addressed so far?

Appendix C List of RAs used in the Experiment

Abbreviation*	**Resolution Advisory**
LC5 / LC1 / LC2	Limit climb 500 / 1000 / 2000 feet per minute
DCL	Don't climb
DE	Descend (1500 fpm)
IDE	Increase descent (2500 fpm)
MDE	Maintain descent
CDE	Crossing Descend
RDE	Reverse descent
LD5 / LD1 / LD2	Limit descent 500 / 1000 / 2000 feet per minute
DDE	Don't descend
CL	Climb (1500 fpm)
ICL	Increase climb (2500 fpm)
MCL	Maintain climb
CCL	Crossing Climb
RCL	Reverse climb
COC	Clear of conflict

***only used in the intermediate and the enhanced set HMI**

Appendix D Eye-tracking run quality assessment

	PP	run	Scen		HMI	Dispatch		pp		scen	hmi		dl	processing status	filename
	17	7	1	1	EATMP		ra	17	s	11	h	0	n	head tracker malfunction	
	17	5	1	2	Minimum	DL	ra	17	s	12	h	1	D	head tracker malfunction	no
	17	6	4	1	EATMP		ra	17	s	41	h	0	n	head tracker malfunction	headtracker
	17	8	4	2	Intermediate	DL	ra	17	s	42	h	2	D	head tracker malfunction	
1	17	4	5	2	EATMP		ra	17	s	52	h	0	n	head tracker malfunction	
	17	9	5	3	Extreme	DL	ra	17	s	53	h	3	D	head tracker malfunction	
	20	11	1	1	EATMP		ra	20	s	11	h	0	n	head tracker malfunction	
	20	13	1	2	Intermediate	DL	ra	20	s	12	h	2	D	head tracker malfunction	no
	20	14	4	1	EATMP		ra	20	s	41	h	0	n	head tracker malfunction	headtracker
2	20	10	4	2	Extreme	DL	ra	20	s	42	h	3	D	head tracker malfunction	
	20	15	5	2	EATMP		ra	20	s	52	h	0	n	head tracker malfunction	
	20	12	5	3	Minimum	DL	ra	20	s	53	h	1	D	head tracker malfunction	
	21	5	1	1	EATMP		ra	21	s	11	h	0	n	only **7** % measured data	ra21s11h0n.pog
	21	6	1	2	Extreme	DL	ra	21	s	12	h	3	D	only **45** % measured data	ra21s12h3D.pog
	21	8	4	1	EATMP		ra	21	s	41	h	0	n	OK	ra21s41h0n.pog
	21	7	4	2	Minimum	DL	ra	21	s	42	h	1	D	only **27** % measured data	ra21s42h1D.pog
3	21	4	5	2	EATMP		ra	21	s	52	h	0	n	only **8** % measured data	ra21s52h0n.pog
	21	9	5	3	Intermediate	DL	ra	21	s	53	h	2	D	OK	ra21s53h2D.pog
	22	13	1	1	Minimum	DL	ra	22	s	11	h	1	D	OK	ra22s11h1D.pog
	22	11	1	2	EATMP		ra	22	s	12	h	0	n	only **0** % measured data	ra22s12h0n.pog
4	22	10	4	1	Intermediate	DL	ra	22	s	41	h	2	D	only **12** % measured data	ra22s41h2D.pog
	22	12	4	2	EATMP		ra	22	s	42	h	0	n	OK	ra22s42h0n.pog
	22	15	5	2	Extreme	DL	ra	22	s	52	h	3	D	only **21** % measured data	ra22s52h3D.pog
	22	14	5	3	EATMP		ra	22	s	53	h	0	n	OK	ra22s53h0n.pog
	23	8	1	1	Intermediate	DL	ra	23	s	11	h	2	D	OK	ra23s11h2D.pog
5	23	4	1	2	EATMP		ra	23	s	12	h	0	n	OK	ra23s12h0n.pog
	23	7	4	1	Extreme	DL	ra	23	s	41	h	3	D	only **53** % measured data	ra23s41h3D.pog
	23	5	4	2	EATMP		ra	23	s	42	h	0	n	OK	ra23s42h0n.pog
	23	6	5	2	Minimum	DL	ra	23	s	52	h	1	D	only **57** % measured data	ra23s52h1D.pog
	23	9	5	3	EATMP		ra	23	s	53	h	0	n	only **34** % measured data	ra23s53h0n.pog
	25	11	1	1	Extreme	DL	ra	25	s	11	h	3	D	head tracker malfunction	
	25	14	1	2	EATMP		ra	25	s	12	h	0	n	head tracker malfunction	no
	25	12	4	1	Minimum	DL	ra	25	s	41	h	1	D	head tracker malfunction	headtracker
	25	13	4	2	EATMP		ra	25	s	42	h	0	n	head tracker malfunction	
	25	15	5	2	Intermediate	DL	ra	25	s	52	h	2	D	head tracker malfunction	
6	25	10	5	3	EATMP		ra	25	s	53	h	0	n	head tracker malfunction	
	28	5	1	1	EATMP		ra	28	s	11	h	0	n	OK	ra28s11h0n.pog
	28	7	1	2	Intermediate	DL	ra	28	s	12	h	2	D	OK	ra28s12h2D.pog
	28	8	4	1	EATMP		ra	28	s	41	h	0	n	OK	ra28s41h0n.pog
hh 2	28	4	4	2	Extreme	DL	ra	28	s	42	h	3	D	stopped to early	ra28s42h3D.pog
	28	9	5	2	EATMP		ra	28	s	52	h	0	n	OK	ra28s52h0n.pog
	28	6	5	3	Minimum	DL	ra	28	s	53	h	1	D	OK	ra28s53h1D.pog
	30	13	1	1	Minimum	DL	ra	30	s	11	h	1	D	OK	ra30s11h1D.pog
	30	11	1	2	EATMP		ra	30	s	12	h	0	n	OK	ra30s12h0n.pog

hh 4	30	10	4	1	Intermediate	DL	ra	30	s	41	h	2	D	OK		ra30s41h2D.pog
	30	12	4	2	EATMP		ra	30	s	42	h	0	n	OK		ra30s42h0n.pog
	30	15	5	2	Extreme	DL	ra	30	s	52	h	3	D	OK		ra30s52h3D.pog
	30	14	5	3	EATMP		ra	30	s	53	h	0	n	OK		ra30s53h0n.pog
		total run of runs				48								19	usable	
					EATMP	24								11		
					Minimum	8								3		
					Intermediate	8								4		
					Extreme	8								1		

Appendix E Rotational scheme

Note: The table shows the assignment of ACAS themes (I-V), downlink delay (no RA, RA/D for a datalink delay of 0 second, RA/R for a radar delay of 5 seconds), and HMIs (0 – 3). In this table, traffic samples are denoted by T and two digits, with the first digit indicating the ACAS theme and the second digit indicating the particular traffic sample within a theme.

	ACAS theme														
	Theme I			**Theme II**			**Theme III**			**Theme IV**			**Theme V**		
ATCo	**No RA**	**RA/D**	**RA/R**	**No RA**	**RA/D**	**RA/R**	**No RA**	**RA/D**	**RA/R**	**No RA**	**RA/D**	**RA/R**	**No RA**	**RA/D**	**RA/R**
1.	HMI0 T1.1	HMI1 T1.2	HMI1 T1.3	HMI0 T2.1	HMI2 T2.2	HMI2 T2.3	HMI0 T3.1	HMI3 T3.2	HMI3 T3.3	HMI0 T4.1	HMI1 T4.2	HMI1 T4.3	HMI0 T5.1	HMI2 T5.2	HMI2 T5.3
2.	HMI0 T1.1	HMI2 T1.2	HMI2 T1.3	HMI0 T2.1	HMI3 T2.2	HMI3 T2.3	HMI0 T3.1	HMI1 T3.2	HMI1 T3.3	HMI0 T4.1	HMI2 T4.2	HMI2 T4.3	HMI0 T5.1	HMI3 T5.2	HMI3 T5.3
3.	HMI0 T1.1	HMI3 T1.2	HMI3 T1.3	HMI0 T2.1	HMI1 T2.2	HMI1 T2.3	HMI0 T3.1	HMI2 T3.2	HMI2 T3.3	HMI0 T4.1	HMI3 T4.2	HMI3 T4.3	HMI0 T5.1	HMI1 T5.2	HMI1 T5.3
4.	HMI0 T1.2	HMI1 T1.3	HMI1 T1.1	HMI0 T2.2	HMI2 T2.3	HMI2 T2.1	HMI0 T3.2	HMI3 T3.3	HMI3 T3.1	HMI0 T4.2	HMI1 T4.3	HMI1 T4.1	HMI0 T5.2	HMI2 T5.3	HMI2 T5.1
5.	HMI0 T1.2	HMI2 T1.3	HMI2 T1.1	HMI0 T2.2	HMI3 T2.3	HMI3 T2.1	HMI0 T3.2	HMI1 T3.3	HMI1 T3.1	HMI0 T4.2	HMI2 T4.3	HMI2 T4.1	HMI0 T5.2	HMI3 T5.3	HMI3 T5.1
6.	HMI0 T1.2	HMI3 T1.3	HMI3 T1.1	HMI0 T2.2	HMI1 T2.3	HMI1 T2.1	HMI0 T3.2	HMI2 T3.3	HMI2 T3.1	HMI0 T4.2	HMI3 T4.3	HMI3 T4.1	HMI0 T5.2	HMI1 T5.3	HMI1 T5.1
7.	HMI0 T1.3	HMI1 T1.1	HMI1 T1.2	HMI0 T2.3	HMI2 T2.1	HMI2 T2.2	HMI0 T3.3	HMI3 T3.1	HMI3 T3.2	HMI0 T4.3	HMI1 T4.1	HMI1 T4.2	HMI0 T5.3	HMI2 T5.1	HMI2 T5.2
8.	HMI0 T1.3	HMI2 T1.1	HMI2 T1.2	HMI0 T2.3	HMI3 T2.1	HMI3 T2.2	HMI0 T3.3	HMI1 T3.1	HMI1 T3.2	HMI0 T4.3	HMI2 T4.1	HMI2 T4.2	HMI0 T5.3	HMI3 T5.1	HMI3 T5.2
9.	HMI0 T1.3	HMI3 T1.1	HMI3 T1.2	HMI0 T2.3	HMI1 T2.1	HMI1 T2.2	HMI0 T3.3	HMI2 T3.1	HMI2 T3.2	HMI0 T4.3	HMI3 T4.1	HMI3 T4.2	HMI0 T5.3	HMI1 T5.1	HMI1 T5.2

10.	HMI0 T1.1	HMI1 T1.2	HMI1 T1.3	HMI0 T2.1	HMI2 T2.2	HMI2 T2.3	HMI0 T3.1	HMI3 T3.2	HMI3 T3.3	HMI0 T4.1	HMI1 T4.2	HMI1 T4.3	HMI0 T5.1	HMI2 T5.2	HMI2 T5.3
11.	HMI0 T1.1	HMI2 T1.2	HMI2 T1.3	HMI0 T2.1	HMI3 T2.2	HMI3 T2.3	HMI0 T3.1	HMI1 T3.2	HMI1 T3.3	HMI0 T4.1	HMI2 T4.2	HMI2 T4.3	HMI0 T5.1	HMI3 T5.2	HMI3 T5.3
12.	HMI0 T1.1	HMI3 T1.2	HMI3 T1.3	HMI0 T2.1	HMI1 T2.2	HMI1 T2.3	HMI0 T3.1	HMI2 T3.2	HMI2 T3.3	HMI0 T4.1	HMI3 T4.2	HMI3 T4.3	HMI0 T5.1	HMI1 T5.2	HMI1 T5.3
13.	HMI0 T1.2	HMI1 T1.3	HMI1 T1.1	HMI0 T2.2	HMI2 T2.3	HMI2 T2.1	HMI0 T3.2	HMI3 T3.3	HMI3 T3.1	HMI0 T4.2	HMI1 T4.3	HMI1 T4.1	HMI0 T5.2	HMI2 T5.3	HMI2 T5.1
14.	HMI0 T1.2	HMI2 T1.3	HMI2 T1.1	HMI0 T2.2	HMI3 T2.3	HMI3 T2.1	HMI0 T3.2	HMI1 T3.3	HMI1 T3.1	HMI0 T4.2	HMI2 T4.3	HMI2 T4.1	HMI0 T5.2	HMI3 T5.3	HMI3 T5.1
15.	HMI0 T1.2	HMI3 T1.3	HMI3 T1.1	HMI0 T2.2	HMI1 T2.3	HMI1 T2.1	HMI0 T3.2	HMI2 T3.3	HMI2 T3.1	HMI0 T4.2	HMI3 T4.3	HMI3 T4.1	HMI0 T5.2	HMI1 T5.3	HMI1 T5.1
16.	HMI0 T1.3	HMI1 T1.1	HMI1 T1.2	HMI0 T2.3	HMI2 T2.1	HMI2 T2.2	HMI0 T3.3	HMI3 T3.1	HMI3 T3.2	HMI0 T4.3	HMI1 T4.1	HMI1 T4.2	HMI0 T5.3	HMI2 T5.1	HMI2 T5.2
17.	HMI0 T1.3	HMI2 T1.1	HMI2 T1.2	HMI0 T2.3	HMI3 T2.1	HMI3 T2.2	HMI0 T3.3	HMI1 T3.1	HMI1 T3.2	HMI0 T4.3	HMI2 T4.1	HMI2 T4.2	HMI0 T5.3	HMI3 T5.1	HMI3 T5.2
18.	HMI0 T1.3	HMI3 T1.1	HMI3 T1.2	HMI0 T2.3	HMI1 T2.1	HMI1 T2.2	HMI0 T3.3	HMI2 T3.1	HMI2 T3.2	HMI0 T4.3	HMI3 T4.1	HMI3 T4.2	HMI0 T5.3	HMI1 T5.1	HMI1 T5.2
19.	HMI0 T1.1	HMI1 T1.2	HMI1 T1.3	HMI0 T2.1	HMI2 T2.2	HMI2 T2.3	HMI0 T3.1	HMI3 T3.2	HMI3 T3.3	HMI0 T4.1	HMI1 T4.2	HMI1 T4.3	HMI0 T5.1	HMI2 T5.2	HMI2 T5.3
20.	HMI0 T1.1	HMI2 T1.2	HMI2 T1.3	HMI0 T2.1	HMI3 T2.2	HMI3 T2.3	HMI0 T3.1	HMI1 T3.2	HMI1 T3.3	HMI0 T4.1	HMI2 T4.2	HMI2 T4.3	HMI0 T5.1	HMI3 T5.2	HMI3 T5.3
21.	HMI0 T1.1	HMI3 T1.2	HMI3 T1.3	HMI0 T2.1	HMI1 T2.2	HMI1 T2.3	HMI0 T3.1	HMI2 T3.2	HMI2 T3.3	HMI0 T4.1	HMI3 T4.2	HMI3 T4.3	HMI0 T5.1	HMI1 T5.2	HMI1 T5.3
22.	HMI0 T1.2	HMI1 T1.3	HMI1 T1.1	HMI0 T2.2	HMI2 T2.3	HMI2 T2.1	HMI0 T3.2	HMI3 T3.3	HMI3 T3.1	HMI0 T4.2	HMI1 T4.3	HMI1 T4.1	HMI0 T5.2	HMI2 T5.3	HMI2 T5.1
23.	HMI0 T1.2	HMI2 T1.3	HMI2 T1.1	HMI0 T2.2	HMI3 T2.3	HMI3 T2.1	HMI0 T3.2	HMI1 T3.3	HMI1 T3.1	HMI0 T4.2	HMI2 T4.3	HMI2 T4.1	HMI0 T5.2	HMI3 T5.3	HMI3 T5.1
24.	HMI0 T1.2	HMI3 T1.3	HMI3 T1.1	HMI0 T2.2	HMI1 T2.3	HMI1 T2.1	HMI0 T3.2	HMI2 T3.3	HMI2 T3.1	HMI0 T4.2	HMI3 T4.3	HMI3 T4.1	HMI0 T5.2	HMI1 T5.3	HMI1 T5.1

25.	HMI0 T1.3	HMI1 T1.1	HMI1 T1.2	HMI0 T2.3	HMI2 T2.1	HMI2 T2.2	HMI0 T3.3	HMI3 T3.1	HMI3 T3.2	HMI0 T4.3	HMI1 T4.1	HMI1 T4.2	HMI0 T5.3	HMI2 T5.1	HMI2 T5.2
26.	HMI0 T1.3	HMI2 T1.1	HMI2 T1.2	HMI0 T2.3	HMI3 T2.1	HMI3 T2.2	HMI0 T3.3	HMI1 T3.1	HMI1 T3.2	HMI0 T4.3	HMI2 T4.1	HMI2 T4.2	HMI0 T5.3	HMI3 T5.1	HMI3 T5.2
27.	HMI0 T1.3	HMI3 T1.1	HMI3 T1.2	HMI0 T2.3	HMI1 T2.1	HMI1 T2.2	HMI0 T3.3	HMI2 T3.1	HMI2 T3.2	HMI0 T4.3	HMI3 T4.1	HMI3 T4.2	HMI0 T5.3	HMI1 T5.1	HMI1 T5.2
28.	HMI0 T1.1	HMI1 T1.2	HMI1 T1.3	HMI0 T2.1	HMI2 T2.2	HMI2 T2.3	HMI0 T3.1	HMI3 T3.2	HMI3 T3.3	HMI0 T4.1	HMI1 T4.2	HMI1 T4.3	HMI0 T5.1	HMI2 T5.2	HMI2 T5.3
29.	HMI0 T1.1	HMI2 T1.2	HMI2 T1.3	HMI0 T2.1	HMI3 T2.2	HMI3 T2.3	HMI0 T3.1	HMI1 T3.2	HMI1 T3.3	HMI0 T4.1	HMI2 T4.2	HMI2 T4.3	HMI0 T5.1	HMI3 T5.2	HMI3 T5.3
30.	HMI0 T1.1	HMI3 T1.2	HMI3 T1.3	HMI0 T2.1	HMI1 T2.2	HMI1 T2.3	HMI0 T3.1	HMI2 T3.2	HMI2 T3.3	HMI0 T4.1	HMI3 T4.2	HMI3 T4.3	HMI0 T5.1	HMI1 T5.2	HMI1 T5.3

Appendix F Presentation order of experimental runs

<u>Note:</u> The naming of experimental runs follows the format <traffic sample> - <HMI version> - <downlink delay>. In case of HMI0 (i.e., no RA shown, the downlink delay is not applicable. For the other HMIs, the downlink display either has the value “D” (for Datalink), indicating a delay of 0 second, or “R” (for Radar), indicating a delay of 5 seconds.

	Run number														
ATCo	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1.	2.3-2-R	1.3-1-R	5.1-0	4.3-1-R	2.2-2-D	3.2-3-D	2.1-0	1.2-1-D	4.2-1-D	4.1-0	1.1-0	5.3-2-R	3.1-0	3.3-3-R	5.2-2-D
2.	2.2-3-D	5.2-3-D	2.3-3-R	5.1-0	2.1-0	3.2-1-D	5.3-3-R	1.1-0	4.3-2-R	3.3-1-R	4.1-0	3.1-0	1.3-2-R	1.2-2-D	4.2-2-D
3.	1.1-0	4.1-0	3.3-2-R	5.3-1-R	1.2-3-D	1.3-3-R	5.2-1-D	2.2-1-D	4.2-3-D	2.3-1-R	3.1-0	2.1-0	3.2-2-D	5.1-0	4.3-3-R
4.	4.1-1-R	3.2-0	3.3-3-D	5.1-2-R	1.2-0	5.3-2-D	4.3-1-D	2.3-2-D	1.3-1-D	1.1-1-R	3.1-3-R	4.2-0	2.1-2-R	5.2-0	2.2-0
5.	2.1-3-R	1.3-2-D	2.3-3-D	4.1-2-R	4.2-0	4.3-2-D	5.3-3-D	1.2-0	3.1-1-R	3.2-0	2.2-0	5.1-3-R	5.2-0	3.3-1-D	1.1-2-R
6.	4.2-0	5.1-1-R	4.3-3-D	2.2-0	4.1-3-R	2.1-1-R	3.1-2-R	1.3-3-D	5.3-1-D	1.1-3-R	3.3-2-D	1.2-0	2.3-1-D	3.2-0	5.2-0
7.	3.2-3-R	5.1-2-D	1.2-1-R	3.1-3-D	2.2-2-R	1.1-1-D	5.3-0	2.3-0	5.2-2-R	4.1-1-D	4.3-0	4.2-1-R	3.3-0	2.1-2-D	1.3-0
8.	1.1-2-D	1.3-0	4.1-2-D	3.2-1-R	2.1-3-D	1.2-2-R	5.2-3-R	2.3-0	4.2-2-R	4.3-0	3.3-0	5.1-3-D	2.2-3-R	3.1-1-D	5.3-0
9.	5.2-1-R	2.3-0	4.1-3-D	3.3-0	1.3-0	3.2-2-R	1.2-3-R	2.1-1-D	4.2-3-R	5.3-0	5.1-1-D	2.2-1-R	1.1-3-D	3.1-2-D	4.3-0
10.	5.1-0	4.2-1-D	2.1-0	5.2-2-D	3.2-3-D	1.2-1-D	3.3-3-R	2.2-2-D	4.1-0	3.1-0	1.1-0	2.3-2-R	4.3-1-R	1.3-1-R	5.3-2-R
11	2.3-2-R	1.3-1-R	5.1-0	4.3-1-R	2.2-2-D	3.2-3-D	2.1-0	1.2-1-D	4.2-1-D	4.1-0	1.1-0	5.3-2-R	3.1-0	3.3-3-R	5.2-2-D
12.	2.2-3-D	5.2-3-D	2.3-3-R	5.1-0	2.1-0	3.2-1-D	5.3-3-R	1.1-0	4.3-2-R	3.3-1-R	4.1-0	3.1-0	1.3-2-R	1.2-2-D	4.2-2-D
13.	1.1-0	4.1-0	3.3-2-R	5.3-1-R	1.2-3-D	1.3-3-R	5.2-1-D	2.2-1-D	4.2-3-D	2.3-1-R	3.1-0	2.1-0	3.2-2-D	5.1-0	4.3-3-R
14.	4.1-1-R	3.2-0	3.3-3-D	5.1-2-R	1.2-0	5.3-2-D	4.3-1-D	2.3-2-D	1.3-1-D	1.1-1-R	3.1-3-R	4.2-0	2.1-2-R	5.2-0	2.2-0
15.	2.1-3-R	1.3-2-D	2.3-3-D	4.1-2-R	4.2-0	4.3-2-D	5.3-3-D	1.2-0	3.1-1-R	3.2-0	2.2-0	5.1-3-R	5.2-0	3.3-1-D	1.1-2-R
16.	4.2-0	5.1-1-R	4.3-D	2.2-0	4.1-3-R	2.1-1-R	3.1-2-R	1.3-3-D	5.3-1-D	1.1-3-R	3.3-2-D	1.2-0	2.3-1-D	3.2-0	5.2-0
17.	3.2-3-R	5.1-2-D	1.2-1-R	3.1-3-D	2.2-2-R	1.1-1-D	5.3-0	2.3-0	5.2-2-R	4.1-1-D	4.3-0	4.2-1-R	3.3-0	2.1-2-D	1.3-0

18.	1.1-2-D	1.3-0	4.1-2-D	3.2-1-R	2.1-3-D	1.2-2-R	5.2-3-R	2.3-0	4.2-2-R	4.3-0	3.3-0	5.1-3-D	2.2-3-R	3.1-1-D	5.3-0
19.	5.2-1-R	2.3-0	4.1-3-D	3.3-0	1.3-0	3.2-2-R	1.2-3-R	2.1-1-D	4.2-3-R	5.3-0	5.1-1-D	2.2-1-R	1.1-3-D	3.1-2-D	4.3-0
20.	5.1-0	4.2-1-D	2.1-0	5.2-2-D	3.2-3-D	1.2-1-D	3.3-3-R	2.2-2-D	4.1-0	3.1-0	1.1-0	2.3-2-R	4.3-1-R	1.3-1-R	5.3-2-R
21.	2.3-2-R	1.3-1-R	5.1-0	4.3-1-R	2.2-2-D	3.2-3-D	2.1-0	1.2-1-D	4.2-1-D	4.1-0	1.1-0	5.3-2-R	3.1-0	3.3-3-R	5.2-2-D
22.	2.2-3-D	5.2-3-D	2.3-3-R	5.1-0	2.1-0	3.2-1-D	5.3-3-R	1.1-0	4.3-2-R	3.3-1-R	4.1-0	3.1-0	1.3-2-R	1.2-2-D	4.2-2-D
23.	1.1-0	4.1-0	3.3-2-R	5.3-1-R	1.2-3-D	1.3-3-R	5.2-1-D	2.2-1-D	4.2-3-D	2.3-1-R	3.1-0	2.1-0	3.2-2-D	5.1-0	4.3-3-R
24.	4.1-1-R	3.2-0	3.3-3-D	5.1-2-R	1.2-0	5.3-2-D	4.3-1-D	2.3-2-D	1.3-1-D	1.1-1-R	3.1-3-R	4.2-0	2.1-2-R	5.2-0	2.2-0
25.	2.1-3-R	1.3-2-D	2.3-3-D	4.1-2-R	4.2-0	4.3-2-D	5.3-3-D	1.2-0	3.1-1-R	3.2-0	2.2-0	5.1-3-R	5.2-0	3.3-1-D	1.1-2-R
26.	4.2-0	5.1-1-R	4.3-D	2.2-0	4.1-3-R	2.1-1-R	3.1-2-R	1.3-3-D	5.3-1-D	1.1-3-R	3.3-2-D	1.2-0	2.3-1-D	3.2-0	5.2-0
27.	3.2-3-R	5.1-2-D	1.2-1-R	3.1-3-D	2.2-2-R	1.1-1-D	5.3-0	2.3-0	5.2-2-R	4.1-1-D	4.3-0	4.2-1-R	3.3-0	2.1-2-D	1.3-0
28.	1.1-2-D	1.3-0	4.1-2-D	3.2-1-R	2.1-3-D	1.2-2-R	5.2-3-R	2.3-0	4.2-2-R	4.3-0	3.3-0	5.1-3-D	2.2-3-R	3.1-1-D	5.3-0
29.	5.2-1-R	2.3-0	4.1-3-D	3.3-0	1.3-0	3.2-2-R	1.2-3-R	2.1-1-D	4.2-3-R	5.3-0	5.1-1-D	2.2-1-R	1.1-3-D	3.1-2-D	4.3-0
30.	5.1-0	4.2-1-D	2.1-0	5.2-2-D	3.2-3-D	1.2-1-D	3.3-3-R	2.2-2-D	4.1-0	3.1-0	1.1-0	2.3-2-R	4.3-1-R	1.3-1-R	5.3-2-R