Supporting Air Traffic Control Collaboration with a TableTop System

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ABSTRACT

Collaboration is key to safety and efficiency in Air Traffic Control. Legacy paper-based systems enable seamless and non-verbal collaboration, but trends in new software and hardware for ATC tend to separate controllers more and more, which hinders collaboration. This paper presents a new interactive system designed to support collaboration in ATC. We ran a series of interviews and workshops to identify collaborative situations in ATC. From this analysis, we derived a set of requirements to support collaboration: support mutual awareness, communication and coordination, dynamic task allocation and simultaneous use with more than two people. We designed a set of new interactive tools to fulfill the requirements, by using a multi-user tabletop surface, appropriate feedthrough, and reified and partially accomplishable actions. Preliminary evaluation shows that feedthrough is important, users benefit from a number of tools to communicate and coordinate their actions, and the tabletop is actually usable by three people both in tightly coupled tasks and parallel, individual activities. At a higher level, we also found that co-location is not enough to generate mutual awareness if users are not engaged in meaningful collaboration.

Author Keywords

CSCW, tabletop, collaboration, air traffic control.

ACM Classification Keywords

H.5.3 Information Interfaces and Presentation: Group and Organization Interfaces.

General Terms

Design, Human Factors.

INTRODUCTION

The goal of Air Traffic Control (ATC) is to maximize both safety and capacity, so as to accept all flights without compromising their safety or creating delays. Because air traffic is expected to double by 2030, authorities in Europe and the USA have decided to design new ATC systems. The SESAR [10] and NextGen [6] consortia, both involving billions of euros or dollars, are aimed at changing hardware, software, air space organization and procedures followed by human controllers.

ATC is a highly collaborative activity [1,11]. Collaboration makes controllers more efficient and is essential for safety. The trustworthiness of the global system comes not only from its individual parts (hardware, software or people), but emerges from the process of checking and crosschecking each other's activity. Over the years, various computer systems have been introduced to support ATC activities and controllers were able to use them as a basis for collaboration. However, most recent systems have been largely based on single-person interaction paradigms, and computerization has been obtained at the expense of collaboration. How can designers mitigate this in the systems that are currently being defined?

Recent hardware advances in multi-touch multi-user tabletop systems enable us to imagine potential solutions for collaboration support. Designing such systems requires a deep analysis and understanding of the actual activity to be supported. Even with a sound activity analysis, designers need to find what set of interactions are useful to actually support collaboration: how can tabletop systems improve collaboration compared to other digital systems? How do we maximize users' awareness of what teammates do? How can we enable seamless dynamic task allocation? What set of guidelines should we follow to design effective collaborative tools on tabletop? This paper provides preliminary answers to these questions.

We first summarize the ATC activity and its evolution, so as to clarify the context in which designers work. We then report on an activity analysis focused on collaboration and performed by combining available literature on ATC activities and additional interviews with controllers. From this analysis, we extract a set of requirements and design guidelines. We then present the system and an evaluation.

AIR TRAFFIC CONTROL AND ITS EVOLUTION

In this section, we briefly outline the tasks of en-route controllers on a typical workstation, and focus on the role of collaboration in traditional ATC workstation designs. We

then explain why these designs are progressively abandoned and what problems this might pose.

Traditional en-route ATC tools and procedures
The activity of en-route air traffic controllers consists mainly of maintaining a safe distance between aircraft. To do this the airspace is divided into sectors, each sector being under the responsibility of a team of controllers. When a flight crosses a sector, the controllers guide the pilot by giving clearances (heading, speed, or altitude orders) until the flight reaches an adjacent sector, where other controllers take responsibility for the flight.

In a typical setting, two controllers sit at a Control Position, which is especially designed to support their activities. A traditional Control Position (in France and other countries in Europe) includes a set of vertical screens (the main one being a radar-type visualization), and a horizontal board on which paper flight strips lie [11]. There are two radar screens, one for each controller, often with different configurations (e.g. pan and zoom), and a single horizontal strip board, shared by both controllers. One controller is the *tactical* controller, who gives orders to pilot by radio, and write down his orders on the paper strips. The other controller is the *planning* controller, who is in charge of preparing the newly arriving flights for the tactical controller (possibly by writing notes on the corresponding strips), and of "shooting" exiting flights to other sectors.

Importance of collaboration in traditional ATC
Past studies have shown that paper flight strips are more than mere information holders and serve as a communication medium [1,5,7,11]: the acts of physically moving, orienting, sticking, holding, and writing on a strip deliver non-verbal messages from one controller to the other. Moreover, as the strips are simply papers on which one can write notes, anyone can interact with them; both controllers can move them and update the information with a regular pen. Other people can also interact with them; for example, in storm situations up to five people might gather at a control position and manipulate the strips. In addition, the flexible co-manipulation of strips enables users to answer very quickly to unexpected events and errors, and enables resilience [14].

Non-verbal communication has been shown to represent up to 50% of all communication acts [2]. Usually, non-verbal communication is done while seeing the teammate and/or the shared environment: physical co-presence enables teammates to use multiple sorts of gestures that improve common understanding of the situation, including deictic gestures, object passing, utterance-like gestures and touching the shoulder to generate awareness [2]. Physical distance between co-workers need not weaken performance in collaborative activities, but it leads them to engage in more demanding communication acts [5,21]. The supplemental work is done at the expense of the main activity, which may be problematic in a situation where work is complex and cognitive load is high. Furthermore, knowledge that one's collaborators know as much as oneself makes the interpretation of collaborators' intentions easier, which in turn makes collaboration better [2,23]. Multimodal communication involving speech and co-located gestures is better at building this mutual knowledge than speech alone [2].

Automation and its consequences
In order to increase airspace capacity significantly, US and European programs promote *automation* of separation (between aircraft) monitoring and control [6,10]. By delegating the separation assurance function to systems on the ground and in the cockpit, they assume that controllers would shift their attention to such tasks as optimization of traffic flow, or accommodating pilots' requests for route changes. However, the accuracy and efficiency of automated separation depend on the system's up-to-date knowledge of planned and modified trajectories. The current paper and voice-based interaction do not update the system with modifications and orders from controllers, thus preventing the use of automation. This has led to projects that aim at replacing paper and voice with digital tools.

Many software-based systems have been introduced in support of control procedures, including problem management [2], flight lists to partly replace strip boards, etc. However, most introduced systems have used the WIMP paradigm and rely on mouse-based interaction (an exception is [3]), likely because such systems are easy to design and develop. Keyboards and mice are personal devices that are not normally shared: this hinders the ability of a user to interact with her/his teammate's view while the latter is engaged in a conversation on the radio for example. As teamwork is a major asset of previous systems for both safety and efficiency, such individualized tools lower at least efficiency (and some of them have been rejected by users for this reason), and possibly also safety.

RELATED WORK
A number of research projects have tackled the problem of designing a digital system that can be updated, while preserving collaboration. DigiStrips is a prototype that makes use of two touch screens (one per controller) and finely designed graphics and feedback to support group collaboration [13]. DigiStrips' designers argue that touch screens are appropriate tools to support collaboration:

• They increase mutual awareness. Since touch screens involve gesture, seeing what a colleague is doing with his hand (directly or in peripheral vision) on a touch screen provides many clues on his activity.

• Unlike mice, touch screens are shareable in a fluid manner: a user can interact on his touch screen as well as on his teammate's.

DigiStrips mimics the ability of actual strip boards to lay out the electronic strips so as to convey information. For example, a planning controller may slightly shift or rotate a

strip to the left to make it salient for the tactical controller. Though users could interact with the teammate's screen in DigiStrips, the gap between touch screens prevented fluid passing of objects or the emergence of shared territory [17].

Direct Collaboration interfaces aims at reducing the role of explicit coordination. One strategy of Direct Collaboration is to design interactive objects that serve as a coordination medium [20]. Author proposed three prototypes of interfaces for order preparation and communication. However, they only serve as a demonstration purpose, and were at a too early stage to be tested.

As an alternative to replacing paper flight strips with digital systems, paper strips can be augmented with computing functions. Mackay et al describe how augmented paper strips can provide information to the system, while maintaining paper strips' properties and users' habits [12].

As shown in [8], subtleties in settings can greatly improve collaboration. In an experiment for a new control tool [2], experimenters noticed that a pair of controllers collaborated more when the two radar screens were made closer to one another, and oriented slightly towards the other as opposed to strictly facing the two controllers.

In other domains, numerous systems have been proposed to support close collaboration with tabletops or similar devices (see [18] for a survey on this topic). However, those systems were either a support for a usage or CSCW study, or did not require as precise collaboration as ATC's. Nevertheless, we relied on tabletop design guidelines available in the literature ("System Design" section).

COLLABORATIVE ACTIVITIES IN ATC

In order to assess the possible benefits of new interaction technologies on ATC collaboration, we need an activity analysis focused on collaboration and how it is supported by traditional tools. A number of studies have been published on the activity of controllers [1,2,5,7,11]. However, practices evolve and subtle differences from past systems may have significant impact on the effectiveness of providing support for an activity. In addition, the available data was not obtained with the exact same purpose of feeding research on interaction design. Therefore, in order to understand current practices we organized four workshops in which we interviewed six different controllers and five ATC experts. During these workshops we aimed at identifying and analyzing situations that involve collaboration in the current French ATC system. We then combined our results with the available analyses to identify the following collaborative activities and situations.

Organization and management of flights' lifecycle
A paper flight strip is the principal embodiment of a flight. Both controllers can manipulate the layout of strips on the board. Layout and orientation changes, hand-written updates to information, and strip disposal are all visible, accountable actions that permit situational awareness to arise non-verbally.

Analysis and resolution of problems
The problem space is always under construction: both controllers are required to perform a "tour of the radar image" or a "tour of the strip board" from time to time in order to discover forgotten actions or unnoticed problems. Working as a pair helps controllers to remember and double-check things to do, and is a cornerstone of safety.

Anticipation, preparation, sequencing and sharing of tasks
When a flight arrives in a sector, the planning controller checks whether it might enter into conflict with another flight in the near future (anticipation). If so, she traces a W on the strip (for "Warning"), and ensures the tactical controller notices the warning when placing the strip on the board (by tapping it with a pen, or by tapping the tactical controller's shoulder). She can also propose changes to flight parameters such as altitude (preparation). Layout on the board can have a variety of significance. For example, flights can be ranked in column by the time of crossing over a beacon: in this case, the planning controller can stack a flight, or insert it in the stack (sequencing). Usually, the tactical controller is in charge of devising a strategy to avoid the potential conflict. However, devising the strategy may be a shared task.

Activity allocation
Activity allocation depends on workload, habits from local culture, and habits arising between the particular pair of controllers. Allocation is always dynamic; no workflow exists that would allow controllers to act in a step-by-step manner, since situations evolve rapidly and allocation requires real-time decision making that is strongly dependant on the current state. Hence, controllers use their tools (radar image, strip boards) more as a whiteboard, on which lie problems to be discovered, problems to be solved, and actions to be done. Actually, part of the activity of a planning controller is to evaluate the status of the other controller in order to devise the best help he can provide. The planning controller constantly adjusts his interpretation of the actions and the state of the other controller. Sometimes, a tactical controller will indicate that the planning controller is wrong in his evaluation, either subtly, or more explicitly (even by shouting at him). The two controllers share responsibilities, but the current paper-based interface does not enforce awareness of responsibility: in fact, responsibility is in users' head and actions, not in the system.

Execution and monitoring of actions
When a flight must turn to follow the planned route, or when the controller has devised an avoidance strategy, the controller needs to give orders to the pilot at the right moment. Hence, part of the activity is devoted to remembering which actions to do at present, or in the near future. Furthermore, resolution of problems depends on the actual execution of orders by the pilots. Hence, controllers must monitor that pilots actually follow orders as given. The planning controller also checks and monitors the

actions of the tactical controller and possibly corrects them in high workload situations.

Training and high load situations
Approximately 50% of the time there are more than two controllers on a control position. Often, controllers are apprentices: becoming an expert on a particular sector takes time. During training, the team of controllers includes the apprentice, an expert controller, and a second expert controller to back up the apprentice. In addition, in high workload situation such as storms or emergencies, up to five controllers can gather around the control position to help until the problem is resolved.

SYSTEM REQUIREMENTS

Based on this analysis of collaborative situations in ATC, we devised a set of requirements for our system. Our primary design goal was to foster seamless collaboration by requiring less explicit communication and fewer coordination acts. Our main assumption is that better collaboration will yield benefits in terms of capacity and safety. More precisely, the system should:

- be updated with controllers' orders. As seen above, this is a prerequisite, and it disqualifies the paper-based system.

- allow more than two users to interact simultaneously with it. This should allow capacity increases since multiple users will be able to handle tasks concurrently. It is also required for *monitoring* and *training & high-load situations*.

- foster mutual awareness. Safety should increase because users will have more means to be aware of teammates' activity and more means to detect problems (*analysis* and *monitoring*).

- foster communication and coordination. This should improve both safety (knowledge of teammate actions) and capacity (less latency). This is required for *organization* and *preparation*.

- foster dynamic task allocation. Capacity should increase because users will be able to pick up new tasks to be done as soon as they have completed existing tasks (*activity preparation* and *allocation*).

SYSTEM DESIGN

In this section, we describe the various features of our systems. Because of limited space, we focus on features that are explicitly designed to fulfill the requirements, and not the entire system.

In particular, the requirements can be fulfilled if users are aware of tasks to be done, or are able to evaluate workload of their colleague. In addition, it can only be done if any user is allowed to interact with any representation or tools while the other user is engaged in another task. We used a shared, multi-touch, multi-users surface as the basis of our system. Shared surfaces are supposed to exhibit these

Figure 1: hardware and visualization settings

properties: users are close to each other, and they enable interacting simultaneously if designed appropriately.

Hardware design
The hardware design is as follows (see Figure 1):

- Two radar displays are presented vertically on the position. These serve as a reference view of the traffic situation and are dedicated to information visualization rather than data input. The radar display is not the focus of the work presented here: it is not touchable and provides for minimal configuration (pan and zoom only).

- A horizontal DiamondTouch (64x48cm) is placed below the radar displays. A projector displays a 1400x1000 image on it. The surface centralizes the input mechanisms, and provides all control tools. More than two controllers can use this shared surface if necessary. We relied on the DiamondTouch ability to identify users, in order to differentiate synchronous interactions [4].

Representation and Interaction
The horizontal multi-touch screen displays an environment that includes a number of interactive graphical objects. All tools can be seen in Figure 2. We devised the following guidelines to design interactive tools so that they support collaboration:

- Reify actions into objects. Since objects lie on the table, their manipulation may enable accountability [20]; furthermore, they can be passed around and allow for task reallocation.

- Enable partial accomplishment of actions. An action can be separately prepared, checked and accomplished, possibly by different users, thus offering seamless workload allocation.

- Provide as much feedthrough as possible. Since activities must be accountable, it is important that appropriate feedback provide an opportunity for teammates to observe one another's actions.

We also used several guidelines from tabletop and CSCW literature (orientation [9], territoriality [17], tabletop [16], direct collaboration [20] and coupling [22]). In the following, we mention the guidelines that we applied. We
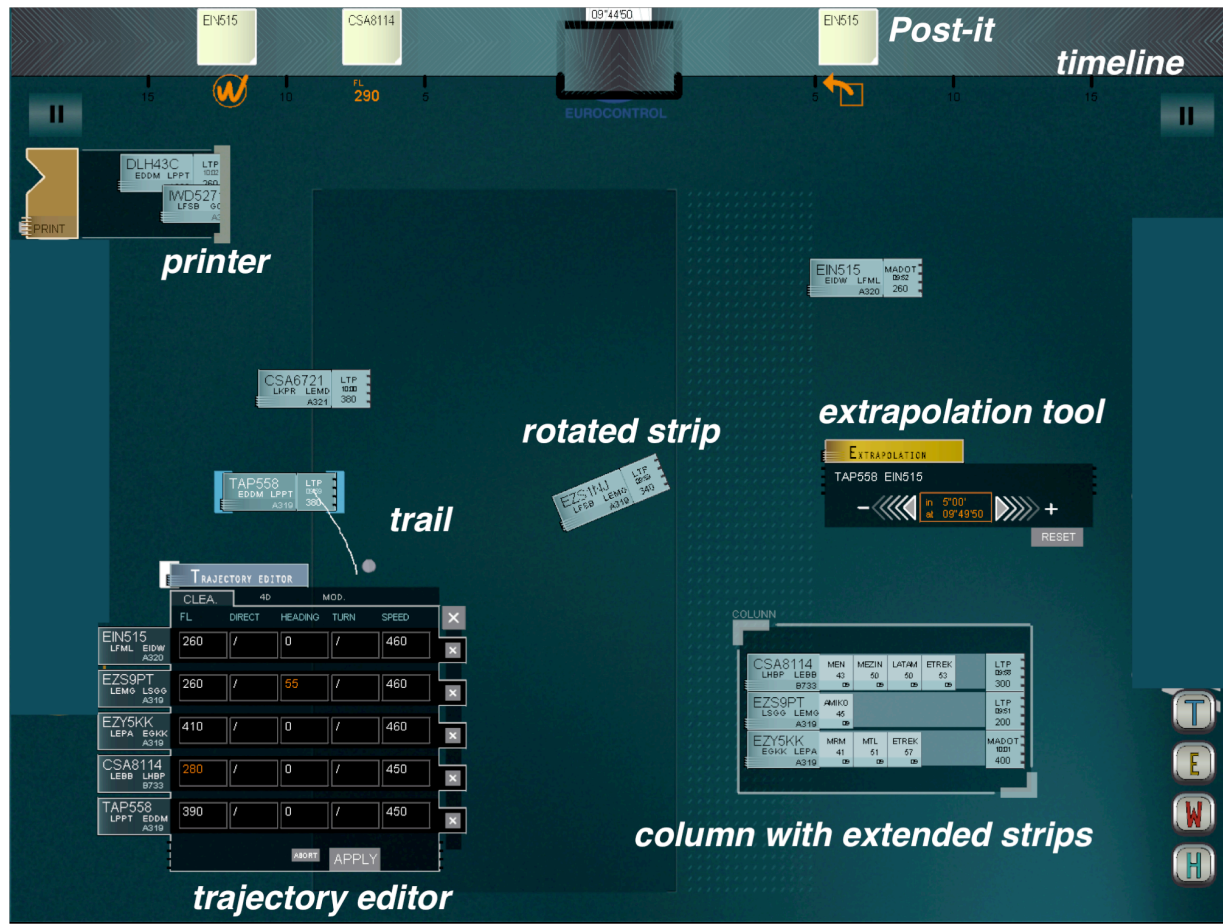
Figure 2: tabletop view, with interactive objects (named in white/italic)

chose not to prevent inter-controller conflicts using technical features; instead, we relied on social norms.

Desktop
Similarly to the well-known desktop metaphor, the background display is used as a placeholder for other objects. Unlike the radar image, the X and Y dimension of the background has no predetermined semantics; users are free to lay out the objects anywhere on the background. However, users can decide to bring semantics to a specific territory (as discussed in [17], e.g., every entering flight might be placed to the right by controllers) or layout (the top-most flight is the next to enter the sector).

Strips
A strip embodies each flight, and displays textual information about it such as call sign, altitude, speed and heading. Strips initially appear in a "printer" box, a metaphor to current hardware. Strips can be dragged and dropped anywhere on the desktop. Users can orient strips non-verbally communicated and provide coordination, as explained in [9]. A column can help organize and manipulate a set of strips as a group; strips inside a column automatically stack onto one another and a strip can be inserted in a column by drag and drop.

Trajectory editor
The primary interaction with a strip consists of moving it around. We also chose a spatial model for strip editing rather than a temporal one: in order to edit information on a strip, a controller drops it in a *trajectory editor*. When the drop occurs, a new horizontal tab appears in the editor. Each editable field appears in an edit box: when a field is tapped, a specialized interactor allows for data entry (a radial slider for heading, a vertical slider for altitude, etc.). The trajectory editor fulfills the first requirement (*update the system with orders*).

The trajectory editor lies on the desktop and can be moved around freely for convenience and to allow sharing between multiple users. Edited values are not applied instantaneously: instead, the user must press the "apply" button to confirm changes. Though this seems contradictory to the immediate feedback rule, it allows orders to be prepared and applied later, possibly by another user: this enables users to more finely allocate tasks.

Extrapolation tool
The extrapolation tool allows a controller, usually the planning controller, to predict future conflict between two flights (see Figure 3). The tool allows flight paths to be

projected forwards in time, displaying computed future trajectories for selected flights on the two radar images. This provides the tactical controller with an opportunity to be aware of the problems the planning controller is solving.

Figure 3: trajectory extrapolation on radar (top), each colored segment represents the future position in 1 (orange), 2 (green) and 3 (blue) minutes. The extrapolation tool on the table (bottom) controls the amount of future time.

Post-it
Controllers can create Post-its that display a number of call signs and optionally an icon depicting a specific action related to the flights written on the Post-it. To create a special-purpose Post-it, a user triggers the corresponding gesture (S for shoot to next sector, W for warning etc.). Post-its act both as a reminder of actions to do in the future and as a preparation tool similar to the trajectory editor. One controller can prepare an action with a Post-it for another controller to execute later.

Timeline
In order to help remember future actions, controllers can place Post-its on a timeline. The timeline is a horizontal strip that lies at the top of the screen. The X dimension of the timeline depicts the time: current time is at the center, and the future extends outwards in both directions, from the center to the edges of the timeline. A ruler that depicts the time according to the X position helps users to position Post-its. Once attached to the timeline, Post-its move automatically towards the center at a pace that follows real time (see Figure 4). As Post-its reach the center, controllers are encouraged to accomplish the associated action, before the Post-its disappear. The double-sided aspect of the timeline enables users to allocate responsibility: each user is responsible for the Post-its that lie on his or her side. Controllers can rearrange the strips, either to specify a different action time or to implicitly redistribute responsibility by moving a Post-it from one side to the other. As Post-its move to the center, they become easier to take from the other controller.
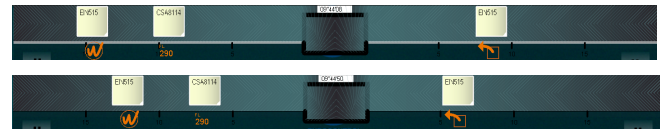

Figure 4: timeline at two consecutive times: Post-its get closer to the center.

The timeline and post-it may raise the question of responsibility awareness. We decide not to foster awareness of responsibility, relying instead of the same mechanisms that users employ with the current system. In fact, placing a post-it in the part of the timeline of a controller is of the same nature than placing a paper strip in front of him: nothing will remind a controller to deal with this particular strip, except the other controller.

Figure 5: Post-its with audio annotation

Audio annotation
As seen above, users can create general purpose Post-its if no specific Post-it applies. In order to remember why they created the Post-it, they can associate an audio message to the Post-it by talking into a microphone while pressing on the "Rec" icon (see Figure 5). Teammates can listen to the message later to be reminded of the action or other contextual information. Controllers can also prepare a vocal order, to be dropped later onto a "radio" object: the audio message is then played on the radio as if the controller were speaking to the pilot. This enables seamless integration of vocal order preparation with current tools and procedures.

Feedback and feedthrough
In order to improve situational awareness, the system supports various strategies for making controllers aware of what other controllers do. The system uses direct manipulation, which helps users to understand the actions of others since each action requires gestures and time to accomplish [19]. Controllers' attention is divided between

the vertical radar screen and the horizontal screen. Feedback displayed onto each screen is translated appropriately onto the other: for example, touching a strip highlights the corresponding representation on the radar image. This allows controllers to be aware of each others' actions even while looking at the radar. Additionally, any touch interaction on the surface leaves a trail on the surface that gradually disappears (see Figure 6). This allows a controller who looks elsewhere to get an idea of what has been done when his attention returns to the table. Finally, all actions use smooth animation to depict state transition, which helps users notice changes made by their colleagues [15]. For example, inserting a strip in a column makes the other strips separate smoothly to make room.
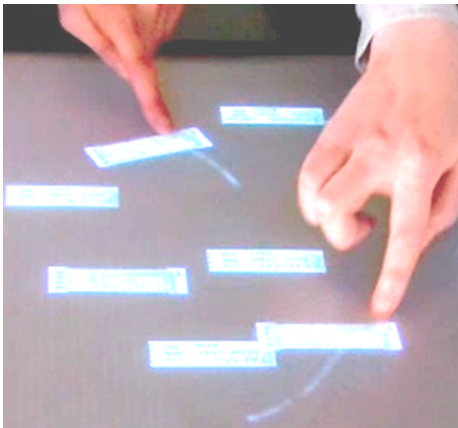

Figure 6: touch gestures leave transient trails

PRELIMINARY EVALUATION

We have conducted four pilot studies to evaluate our design choices. The studies were qualitative and involved a limited number of subjects and trials. As such, they yielded preliminary results only; however, we did make several useful observations. The studies were not meant to test whether our system is better than current systems in terms of capacity or safety. Rather, they test to what extent the requirements we listed above (orders notification, more than two users, mutual awareness, communication and coordination, dynamic task allocation) are fulfilled.

Participants, settings and procedure

The study participants were three air traffic controllers and five ATC experts. Study 1 involved four groups of two, Studies 2 and 3 two groups of two, while Study 4 involved the three current ATC controllers only. We used specialized software that replays recorded air traffic in real-time. The radar display and the tabletop view display the traffic by "listening" to the replay software. The replay software is able to modify the simulated traffic according to orders given by users. The setting is shown in Figure 7.

In addition to direct observation, we videotaped the sessions with two cameras: one with a large field of view, to film the whole setting (people, horizontal surface, and vertical radar screen) and to catch any interaction between

people, and one close to the multi-touch surface to catch gestures and the interactive environment.

After we provided a general introduction to the system, the participants were allowed to interact with it. They performed the main possible interactions in order to discover and learn how to interact with the system. Once they appeared familiar with the system (~10min) they ran through each study, which consisted of reading instructions and fulfilling a set of tasks. We also ran a discussion with subjects after each study.

Study 1: mutual awareness

The main objective of the first study was to evaluate how the interactive surface affects the awareness of each other's action. The two controllers each had a list of six actions to perform. After completing the scenario, each controller was asked to describe the actions performed by the other. Four groups of two controllers performed this test.

The results were identical for all four groups: no controller was able to describe any action performed by the other. This can be explained by two observations. First, as we noticed in the video, subjects were still performing as beginners and spent a lot of time and cognitive resources discovering how to interact with the table, at the expense of mutual awareness. Later studies benefited from this learning process; however, this study was negatively impacted. Second, the actions required were not embedded in a real activity and were not strongly related to one other, making them less "guessable" by a colleague.

Hence, study 1 did not show that our system supports mutual awareness. However, it does illustrate that proximity is not necessarily sufficient for awareness of other participants' actions: context and engagement in a meaningful collaboration is also important.

Study 2: communication

The main objective of our second study was to evaluate how the interactive surface might facilitate collaboration between the two controllers, through the different artifacts provided. Three scenarios were exercised during the test.

Scenario 1: non-verbal communication

In the first scenario, the tactical controller was asked to give clearances to aircraft via orders over the radio, and to update the system using the trajectory editor. In parallel, the planning controller was asked to integrate new flights by dragging the flight strips from the printer box to the appropriate column. Then, the planning controller was asked to focus the attention of the tactical controller on a conflict. We instructed the subjects that they could use any features afforded by the system (Post-it, orientation, timeline) to accomplish their tasks but that they were not to speak to one another. In practice, the ability for the planning controller to communicate with the tactical controller silently is important since the tactical controller may be speaking to pilots by radio.

Figure 7: Multiple users engaged in the task and interacting simultaneously

Planning controllers from both groups used Post-its associated with the two flights in conflict as communication artifacts. They dragged the Post-it into the timeline on the tactical controllers' side. The planning controller of the second group additionally placed the associated flight strips beside the tactical controller's column, in order to make later processing easier. While the first group succeeded in communicating, the second group failed, despite the additional step. Two observations may explain this result. The first group was composed of two current controllers. Before alerting the tactical controller, the planning controller actually checked whether there was a potential conflict. To do so, he used the extrapolation tool, and verified on the radar screen where and when trajectories cross. Feedthrough on radar allowed the tactical controller to notice planning controller's actions. This helped the tactical controller build mutual awareness, and made her more eager to pay attention to potential problems. Both controllers confirmed this during debriefing interviews.

The planning controller of the second group, who was not a current controller, selected the two flights randomly. This provided insufficient feedthrough to support the tactical controller (a current controller), who in turn was not engaged enough to really pay attention to a fake problem. It is probable that two current controllers are more used to paying attention to each other's actions. However, the efficiency of tools in supporting collaboration is highly dependent on whether or not the controllers share the same skills, knowledge and training [2].

Scenario 2: verbal communication
Scenario 2 was similar to scenario 1, except that verbal communication was allowed. The planning controller was asked to integrate new flights and to realize an extrapolation on two flights. In parallel, the tactical controller was asked to call the planner's attention on a flight in order to initiate a route negotiation with an adjacent sector.

The two groups chose the same strategy to achieve this goal successfully: the tactical controller took the flight strip, placed it under the planning controller's eyes, and talked to him while pointing at the label. In both groups, the planning controller understood immediately what to do.

It is interesting to underline that this is the current means of collaboration between French air traffic controllers: they use the paper flight strips to enhance the efficiency of verbal communication and to eliminate ambiguity about involved flights. This property of a single physical flight representation has disappeared in some new systems where each controller has his own screen to display flight plan information. The shared surface restored the flight representation as a coordination object.

Study 3: coordination
The aim of Study 3 was to evaluate the efficiency of the Post-it as a mean for coordination. The tactical controller was asked to give clearances and to update the system, using the trajectory editor. In parallel, the planning controller was asked to edit a Post-it on a flight, in order to notify the tactical controller of a "frequency change."

Despite the Post-it motion executed by the planner on the tactical controller's side of the timeline, neither of the two tactical controllers noticed the Post-it. It appears that the topological configuration makes it difficult to share information between seated users: as the timeline lies at the top of the interactive surface, it is out of the visual field and difficult to reach when one is seated.

Study 4: more than two users and dynamic task allocation
The aim of our fourth study was to assess the effectiveness of the system in supporting collaboration in situations involving more than two users, such as training or storms. The study involved real controllers only: two of them were asked to do a regular air traffic control using the tabletop system. After five minutes, a third controller (the "supporting" controller) was asked to help the others to control traffic (see Figure 7).

First period: two controllers
We made the following observations of the first period:

- Controllers moved the printer box, initially placed on the left top of the interactive surface, to a location between them. In this position, both controllers can access the printer box and integrate new flights. This illustrates the ability to configure the environment so as to foster collaboration.

- Flight strips on the surface were actively used to highlight and locate flights on the radar image. Hence flight information served as an individual aid (which may improve mutual awareness), as well as communication support (highlighting a flight for each other).

Second period: Three controllers
We asked the third controller to come and help due to a peak of traffic. She stood behind the two principal controllers and began to manage new flights that had piled up in the printer box. The three controllers then succeeded in working together on the surface (Figure 7). Several situations were observed:

- A situation consisting of close collaboration between the tactical and supporting controller, using the flight strip combined with the radar image;

- A situation consisting of parallel activities, where the tactical and supporting controller worked on one problem while the planning controller worked on another.

Controllers succeeded in allocating tasks to the newly arrived controller. They did it in a fluid manner thanks to the capability of organizing the flight strips on the horizontal surface. It enabled a natural division of the surface into private spaces for each controller and common spaces used for exchanges (findings similar to [17]). However, during the debriefing session, the main negative feedback from the controllers was related to the surface size: it appeared too small when used by three people.

DISCUSSION
Our evaluation was partial: we did not test every feature of our system. For example, in our trials no subject used the audio annotation. We do not know whether the fading visual trails helped controllers with mutual awareness. Testing this feature would be hard in practice since it would require a scenario in which a peripheral system would distract one controller such that she has to understand what she missed during the disturbance. Even if she did not appear to benefit, this would not allow us to infer that such a feature is useless. Longitudinal studies would be better to really assess it. However, we learned a number of lessons through these studies.

Subjects did not make a heavy use of orientation. This may be due to the complexity of our rotation interaction: one has to press, wait half a second to enter the rotate mode, then rotate the strip. This finding is consistent with guidelines for rotation [9]: we failed to provide a fluid interaction for rotation, which prevents actual use (the device we used makes it difficult to implement a multi-touch multi-user system without a temporal mode). Similarly, the position of the timeline was not adequate, which is consistent with previous work on territoriality [17].

Another finding of this work is that activity knowledge and engagement are very important for the assessment of the effectiveness of the tools. In fact, we "forced" collaboration for the sake of study 1. This led the two subjects to execute unneeded collaborative tasks and prevents the formation and assessment of mutual awareness. In study 2, actual controllers succeeded in building mutual awareness because they were engaged in a meaningful collaboration and they shared a common understanding of the situation.

We found that tabletop effectively supports communication and coordination: users were able to communicate verbally and non-verbally by using gestures and territories. Feedthrough plays a role in building mutual awareness. For example, the extrapolation tool helped the tactical controller understand what the planning control was doing. Highlights on radar screen also helped users gaining an idea of their teammate's actions. The fact that mutual awareness is key to safety in critical systems highlights the importance of good feedthrough.

Study 4 (with 3 controllers) gave very interesting results. The controllers had manipulated the system during the previous studies, and they were at ease in using it in real-time conditions. Moreover, we observed that users were really engaged in their task: the flow of action was very smooth, since the interface allowed multiple controllers to manipulate it at the same time. Users were able to dynamically allocate tasks, and engage in tightly coupled or parallel tasks. This truly illustrates what we expect from such a system: that appropriate, seamless technologies and tools make collaborative activities such as air traffic control smooth and efficient.

During the debriefing and discussions we had with the participants, they made remarks about possible benefits of the system. For example, in storm situation the combination of multiple people and multiple concerns often leads to contradictory actions. Even if the reified actions are not a complete description of the strategies involved, a trained controller can infer the appropriate action from the available information. The training process might also benefit from our system. At the beginning of ATC training, apprentices practice in simulation under observation by instructors. As in the storm situation, the reified actions and the timeline might help the instructor better understand the apprentice's strategy. The instructor can then revise apprentices' priorities (the major difficulty faced by apprentices) by rescheduling planned actions on the timeline while explaining the corrective actions to the apprentices by showing or tapping on other reified actions (i.e. speechless explanation). After the simulation ends, another tool could replay the actions performed by the apprentice. According to the instructors, "such a tool would be invaluable". During actual traffic control, an apprentice could prepare and apply actions that an instructor would in turn validate in order to execute them effectively.

CONCLUSION
We have described a complete example of a digital tabletop system designed for ATC, a real-world, complex task environment. We designed the system to circumvent flaws associated with traditional technology in the context of a highly cooperative activity. We based our design on an analysis of ATC controllers' activity, with a focus on collaboration, and provided a set of requirements (support more than 2 users, mutual awareness, communication and coordination, task allocation). We devised a set of

guidelines to design our system (reification, partial accomplishment of actions, feedback), and presented a set of new interfaces and interactions. Finally, the paper provides initial data of an exploratory evaluation with ATC experts on the effectiveness of the specific interface design features included into the system. Researchers and practitioners can use the design guidelines as is, and get inspiration from the artifacts. They can also gain some insights into the utility of the specific interface design concepts in this, and potentially other complex, collaborative task domains.

We obtained mixed results with the evaluation, a typical outcome of non-tightly controlled experiments: fluidity and dynamic repartition are largely unpredictable (it depends heavily on the particular pair of users for example), and thus difficult to control. Nevertheless, pilot studies show that our tools partially fulfill our expectations, and give insight on future evaluation or ideas. Assessing the effectiveness of our tools requires more than a few studies (new digital systems for ATC have been in the design phase for 20+ years because assessing them is so difficult). As tabletop technology matures, more accurate and reliable systems can benefit from the work presented in this paper. Together with longitudinal studies with reliable systems, it can provide convincing arguments to the introduction of tabletop based systems in real-world, critical activities.

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