Reinventing the Familiar:
Exploring an Augmented Reality Design Space for Air Traffic Control

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ABSTRACT

This paper describes our exploration of a design space for an augmented reality prototype. We began by observing air traffic controllers and their interactions with paper flight strips. We then worked with a multi-disciplinary team of researchers and controllers over a period of a year to brainstorm and prototype ideas for enhancing paper flight strips. We argue that augmented reality is more promising (and simpler to implement) than the current strategies that seek to replace flight strips with keyboard/monitor interfaces. We also argue that an exploration of the design space, with active participation from the controllers, is essential not only for designing particular artifacts, but also for understanding the strengths and limitations of augmented reality in general.

Keywords: Augmented Reality, Design Space, Interactive Paper, Participatory Design, Video Prototyping

INTRODUCTION

Air traffic control is a complex, collaborative activity, with well-established and successful work practices. The work is highly situated, requiring rapid responses to constantly-changing conditions. The work is also risky: a controller holds the fates of thousands people in the course of an hour. Mistakes that result in crashes are simply not acceptable.

The tools and procedures used by controllers were initially developed over forty years ago. Although the details have evolved continuously as traffic and other conditions have changed, the basic tools have not. Controllers use radio and telephone for communication, RADAR to see a two-dimensional representation of the planes, and paper flight strips to track and modify information about planes and flight plans (see Hopkin, 1995, for an excellent summary).

Despite the success of the current system, mounting levels of traffic and aging equipment make it imperative that the system be improved. This is an interesting design challenge: The existing system is already extremely safe: No fatalities have ever been attributed to French civilian controllers. Any new tool must enable controllers to effectively manage the compromise between the safety of the planes and the smooth flow of traffic, enhancing the controllers' judgment without decreasing their vigilance and effectiveness. Unfortunately, the history of automation is filled with examples of expensive new computer systems that reduced user productivity or were completely discarded as unusable (Zuboff, 1988, Dertouzous, 1990). Air traffic control is no exception: numerous research projects have been ultimately rejected as unusable by the controllers.

Many air traffic controllers are investigating new tools that either replace flight strips with electronic versions (Leroux, 1993, Bressolle et al., 1995) or get rid of them entirely (Vortac et al., 1990, Bentley et al., 1992). Although these projects acknowledge the importance of flight strips, they generally concentrate on the information they contain, rather than the controllers' interactions with them. The problem with these approaches is that they force an abrupt change in the controllers' familiar styles of interaction. Controllers must learn to use new input and output devices that work perfectly from the first day, are immune to equipment failures, and can be easily adopted even by controllers with many years of experience with flight strips.

We propose an alternative solution, based on a radical change of assumption: Automation need *not* require getting rid of paper strips. We suggest keeping the existing paper flight strips as physical objects, with all their subtlety and flexibility, and augmenting them directly by capturing and displaying information to the controllers. Enhancing the flight strip separates issues of input and output from the content of the flight tools themselves, emphasizing the controllers' interactions with the strips as much as the information they contain. Augmented strips may also provide a more modern input/output solution than the old mouse and keyboard designed for office automation.

Augmented flight strips have several advantages: We can take advantage of the highly successful work practices that already exist. We can introduce changes incrementally and give controllers a more active role in the design. We can develop new kinds of interaction with the system and among controllers that were never before possible. Note that this approach does not preclude eventually replacing strips. Rather, it provides an evolutionary path to any of a number of new methods of flight control. Our work has

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two main components: investigation of the existing work practices of air traffic controllers and exploration of a range of possibilities for augmenting flight strips. Our goal is to ground our design explorations in the real-world activities of air traffic controllers and to understand the advantages and disadvantages of different technical solutions.

This article describes the participatory design project that accompanied our ethnographic study of a team of air traffic controllers (Mackay & Fayard, 1997a). We first describe paper flight strips and our design approach. We then explain why augmenting existing flight strips may prove a better path to automating air traffic control than replacing them with electronic strips. We describe our exploration of the design space of augmented flight strips, using a series of prototypes developed in collaboration with the air traffic controllers. We conclude by arguing that exploring a design space is essential, not only for the particular problem of air traffic control, but for the more general problem of understanding augmented reality and its relation to new forms of human-computer interaction.

Flight strips and air traffic control

We observed controllers from team 9W in the Paris en route control center (Fig. 1), arguably the most complex in Europe. They handle air traffic traveling in all directions over approximately one-fifth of France, including traffic going to and from the two main Paris airports, Roissy Charles de Gaulle and Orly. The air space is divided into "sectors", complex three-dimensional airspaces crossed with various routes. Controllers work in teams and are qualified to handle either "east" or "west" traffic. West consists of 11 sectors, which may be merged in different configurations and managed from as little as one position (late at night). Controllers rely on flight plans, requests by pilots, requests from other sectors, current weather and traffic conditions to manage the air traffic, judging the safest and most efficient ways for planes to proceed through the air space.

Figure 1 : Controllers working with flight strips at the Paris en route control center in Athis Mons, France.

Unlike airport control centers that handle take-off and landing, Athis Mons has no control tower. Controllers "see" the airplanes via the RADAR screen. Each plane is represented by a point of light, accompanied by the flight identifier, current speed, flight level and a tail showing recent positions. Some but not all routes and beacons are indicated in background. The two-dimensional RADAR image represents a dynamic, three-dimensional space.

The other key tool for tracking planes is the flight strip, shown in Figure 2. Flight strips are similar from control room to control room: They consist of a band of paper printed with flight information, including airline, flight number and type of aircraft, as well as the requested and authorized flight plan (speed, level and route, with expected times for particular cross-points). Preux (1994) provides a detailed description of flight strips used in Athis Mons.

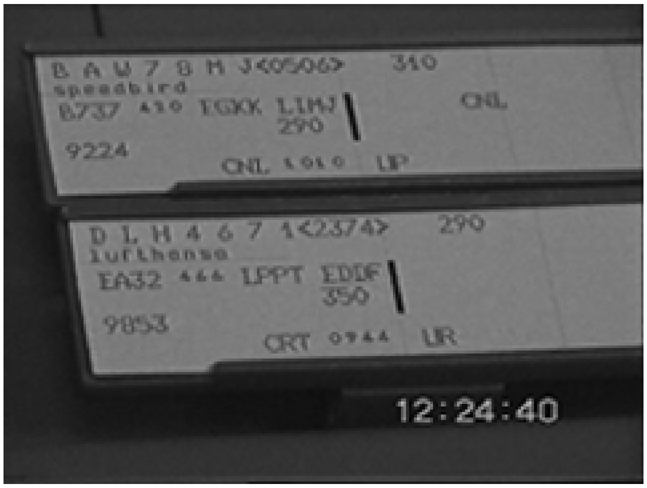

Figure 2: Two flight strips in strip holders.

Unlike airport control towers that pass (or throw!) strips from sector to sector, en route control centers print a new strip for each sector. Figure 3 shows a set of annotated strips, indicating changes in flight level, routing, and speed.

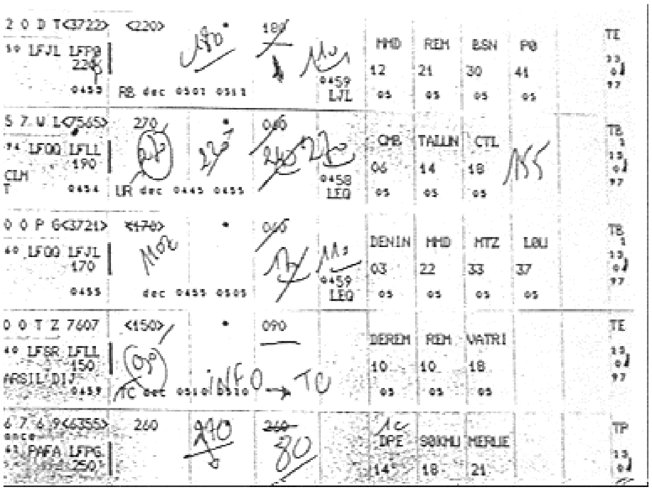

Figure 3 : Annotations on a set of flight strips

Like most en route centers, Paris controllers place paper strips into plastic stripholders. Figure 4 shows how the strip holders fit into metal rails (the stripboard), making it easy to slide and rearrange the strips. Some control centers, as in Bordeaux, do not use strip holders but instead lay the strips on a "stepped" table located between controllers.

Figure 4 : Fight strips in a strip board at Athis Mons

The importance of flight strips

Many researchers have emphasized the importance of flight strips (Harper et al., 1991, Preux, 1994, Hopkin, 1993). Our own observations confirm that they are extremely flexible, taking advantage of both visual and tactile memory. Controllers often take strips in their hands as a reminder to do something. They slide them left or right to highlight different conditions, such as two planes in conflict. Even the act of writing is important: controllers find it easier to remember something they wrote than an item from a menu. Controllers have a dynamic, physical relationship to the strips and with each other (Figure 5).

Figure 5: Controllers communicate physically, via strips

Two controllers may work simultaneously on different strips on the same stripboard, using body language to indicate the importance of different annotations or actions (e.g., by sliding or rearranging). Stressful situations can be identified not only by the number of strips; but by how the controllers collectively interact with them and each other.

Our studies have led us to challenge two widely-held assumptions. The first is that controllers resist new systems because they are "conservative" and dislike new technology. In fact, we found many computer enthusiasts in team 9W; they enjoy discussing the latest software and debating the merits of Macs vs. pc's. They do not fear computers; on the contrary, they look forward to using more 'modern' tools. They do, however, resist systems that slow them down with a mouse or keyboard to enter data.

It is also a mistake to assume that air traffic control systems are static simply because they rely on non-computer tools. Over the past year and a half, we have seen numerous changes, from adding a new sector to changing the controllers' schedules. Even senior controllers being requalified struggle to relearn details. Air traffic control is understandably conservative, since no one wants to reduce safety. On the other hand, it is organized to constantly evolve, flexibly handling ever-increasing levels of traffic.

Thus the "conservatism" we see with respect to new computer interfaces is not due to a general resistance to computers, nor to a general resistance to change. It appears to be , in fact, a rational response. Software designers tend to focus on the added functionality a new system will provide. Controllers must also consider the functionality they will lose with a new system. French controllers have a powerful voice; they can afford to wait until something arrives that adds new functionality without interfering with their existing, highly-functional work practices.

PARTICIPATORY DESIGN APPROACH

Our research approach involves "triangulating" (Mackay & Fayard, 1997b) across scientific and design disciplines (Figure 6). As in the English air traffic control studies (Hughes et al., 1992, Bentley et al., 1992), we use a combination of ethnography and design. However, we emphasize keeping rather than replacing flight strips. These design activities let controllers innovate, not just evaluate. The goal is to create an environment that controllers can co-

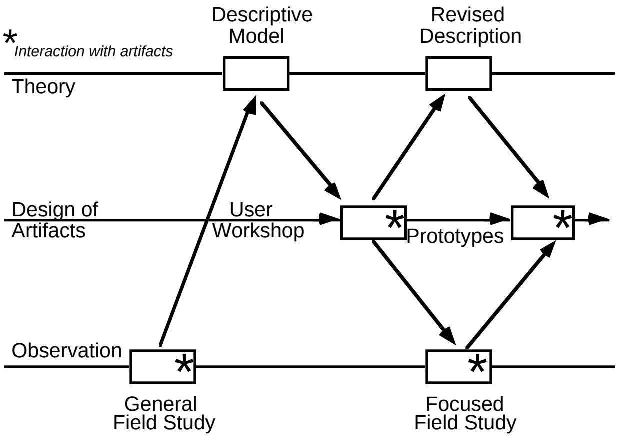

Figure 6: The project involves traditional inductive and deductive methods, observing behavior in real world settings and generating theoretical frameworks, in conjunctive with participatory design to create and evaluate prototypes.

adapt, simultaneously evolving the technology and their work practices to meet their continuously-changing needs.

Ethnographic Study

We studied team 9-West from the Paris en route control center, following their schedule for four months, including nights and weekends, in order to experience a full range of traffic conditions. They welcomed us and spent many hours explaining their work and patiently answering questions.

The Paris center is organized around self-managed teams of 12-15 people. Team 9W had five students, six qualified controllers and four senior controllers, plus various guests, such as controllers being requalified. Students are generally given as many hours as possible, making it difficult to find situations in which the traffic was being controlled exclusively by senior controllers. The Paris center has a reputation for being particularly informal, perhaps because they deal with the most complex traffic conditions. Controllers who are not currently needed generally congregate near team members who are working, chatting with each other until some subtle cue tells them they are needed. They then can stop, mid-sentence, and turn to help the controllers. They never ask what needs to be done: all the information they need is available via strips, RADAR and the peripheral cues that tell them what is going on.

We made detailed, timed notes of over 100 hours of observation, including 50 hours of video over a full range of air traffic situations. We paid particular attention to their communication patterns and their use of tools, especially paper flight strips, RADAR, Digitatron, radio and telephone. We selected ten sessions for more in-depth coding and quantitative and qualitative and analysis. A complete report on the results is beyond the scope of this article. However, the following observations from this analysis directly affected our design explorations:

1. *Air traffic control is mostly routine*: Controllers engage in a constantly-repeated cycle of systematically looking at each plane on the RADAR and the corresponding paper flight strip. This routine is important, not only when things are hectic, but also when things are slow. During emergencies, this routine enables controllers to handle all the other simultaneous jobs that do not go away. In slow periods, the routine enables controllers to stay vigilant. Computer tools that successfully reduce the controllers' work in high-stress situations by eliminating routine activities risk creating dangerous situations under low-traffic conditions, since controllers can become bored and stop paying attention.
2. *Strips form part of a controller's mental representation of the traffic*. Controllers maintain an active picture of the traffic in their heads, letting them look away and handle interruptions. Strips also provide a focal point for updating mental images of the traffic and allow controllers to instantly communicate the current state of the traffic to each other. The physical nature of strips, the ability to hold them and write on them, contributes to this shared mental representation.
3. *Controllers often communicate physically rather than verbally*, taking advantage of each other's peripheral awareness. For example, a controller who points to or writes on a strip is making an implicit statement about the urgency of dealing with that particular situation.
4. *In busy situations, controllers hold new strips in their hands* prior to integrating them into the strip board. This tactile memory is very difficult to replace.
5. *The very act of writing serves as a reminder and helps clarify thoughts*. We observed that even controllers in centers without flight strips (e.g. Maastsricht and Amsterdam approach) write notes to themselves. One controller admitted that she did not always re-read what she wrote; it was just important to be able to write it.
6. *Controllers operate in a highly interrupt-driven environment*. Most controllers dislike the noise and the urgency of the telephone, particularly when it is used for non-urgent situations. New tools should give controllers the communication flexibility they use when next to each other, even at a distance, letting them easily distinguish between urgent and less urgent problems.
7. *Controllers sometimes create hand-written strips to deal with unusual situations*. For example, planes carrying parachute jumpers stay in a particular sector for several hours without a flight plan. Controllers must track the plane in conjunction with all the other planes, giving permission when it is safe for parachutists to jump.

Design activities

We invited members of team 9-West to participate in a 9-month participatory design project, using results from the ethnographic study. We ran a series of workshops with controllers and researchers, using a combination of brainstorming, prototyping and scenario-building exercises to explore ways of augmenting flight strips. We began by showing controllers video of our other augmented reality work and a summary of their interactions with strips (drawn from our video data). Subsequent workshops were more interactive, letting controllers and researchers brainstorm new ideas and experience different prototypes. Rather than simply writing brainstormed ideas, we encouraged people to "act out" their ideas with cardboard mockups and Wizard of OZ techniques. Videotapig these ideas help us visualize the interactions and served as useful reminders as the prototypes changed over time. Video was a useful Wizard of Oz technique: the "wizard' would observe the user's interactions with real paper strips and "project" feedback using a projector above or a monitor below. This style of prototyping allowed us and the controllers to experience a variety of different augmented strips, long before any physical prototypes were operational.

We also developed scenarios, drawing from both routine and unusual activities that occurred during the ethnographic studies. Once validated by the controllers, they served as a design tool to ground our explorations of user functionality and later helped us test our prototypes with controllers.

DESIGN SPACE EXPLORATION

Rather than developing a single solution, we were interested in exploring the design space of ways to augment paper flight strips. Our exploration involved developing and comparing various prototypes and identifying a range of user functions and styles of interaction. These activities are orthogonal and complementary: we implemented each user function with at least two technical solutions and applied each technology to multiple user functions.

For example, controllers wanted a link between the paper strips and the RADAR. We implemented the idea with a graphics tablet prototype, in which the user taps the pen or writes on the paper strip to see the relevant plane change color on the RADAR. For the touch screen prototype, the user points to the desired strip with a finger in order to see the plane on the RADAR. One controller who tried it suggested that we highlight the plane's route as well. The implemented version turned out to be controversial: while several controllers liked it, others argued that it would encourage students to avoid memorizing the routes. In the subsequent implementation, one tap or point highlighted the plane and two such interactions highlighted the route.

Prototype development was accompanied by on-going observations in the control room, guided by questions raised during the workshops. One of the most important issues was the role of writing on the strips. A key insight was that annotations not only serve different functions, but also are intended for different *audiences*:

1. *For themselves: memorization and anticipation*

• reminders	(talk to pilot about change in flight level)
• highlight	(circle all the planes landing at Orly)
• reinforce	(arrow to show plane is descending)
• warning	(potential conflict)
• not in the system	(hand-written for parachute planes)

2. *For each other: communication*
    - between the radar and planning controller
    - between the current and the incoming relief controller
    - between one sector and another (or the chef de salle)
    - between groups during a regroupment or degroupment

3. *For posterity*
    - to provide a legal record
    - to provide an economic record

A forth audience appears for automated systems:

4. *For the computer*
    - to update automated tools like Erato (Leroux, 1993)

This insight helped us greatly, both to identify useful functions for the controllers and to reduce technical problems: Instead of trying to interpret everything the controllers write, we need only interpret what is necessary.

When controllers write for themselves, the system need not capture or interpret the information at all. Often the very act of writing is sufficient. When controllers use annotations to communicate with each other, the writing must be interpretable by another person, but not necessarily the computer. We need only capture the image, preferably in context, but not decipher the meaning. The 9-West controllers made it very clear they would not write solely for the "system", even if it generated useful information. On the other hand, writing to communicate with other controllers was considered both acceptable and important.

The few remaining situations in which the computer must both capture and interpret the writing can often be dealt with by taking advantage of the context. For example, a number located in a particular box on a flight strip must be one of only five or six possible flight levels.

Our prototypes emphasize communication among controllers, since writing for themselves is already handled admirably with ordinary paper and others have studied how to interpret hand-written marks by computer (Chatty and Lecoanet, 1996). Also, the 9-West controllers were most interested in support for communication, especially if it did not involve adding new, more complex interactions. The prototypes were designed to be evolvable by the controllersm with minor changes in writing conventions facilitating interpretation of certain annotations, providing interesting new features and access to new tools, and generally encouraging the use of the system.

Technology prototypes

The technology prototypes addressed three basic design problems: how to *capture* information from strips, how to *track* the location of the strips and how to *present* information onto strips. Future technologies, such as electronic paper by N. Sheridon at Xerox PARC and electronic ink by J.Jacobson at MIT (Negroponte, 1996), especially combined with small pen-based computers, will make augmented flight strips both light-weight and practical. Since these are not yet available, we used existing, somewhat less-convenient technology in order to experience different styles of interaction and experiment with ways of integrating augmented flight strips into current work practices. Our exploration of the design space helped us to evaluate the trade-offs generated by the technology in the context of the real work environment of air traffic control.

Capturing information

The choice of technology to capture information is tied to the intended use of the information: passing it on to another human being is quite different from evaluating it as numeric computer data. We limited our choices to information that could be captured directly from flight strips, eliminating devices such as the mouse or keyboard, to avoid forcing controllers to enter the same information twice. We experimented with three basic input devices:

1. Graphics tablet with pen input (several sizes)
2. Touch-sensitive screen
3. Video camera (still or moving images)

The graphics tablet allowed us to use ordinary flight strips in ordinary stripholders, allowing us to capture whatever controllers write with a pen. The touch-screen also permitted controllers to write with a pen, but restricted their movements, since they could not rest their hands on the screen. The video camera could capture anything written, as long as it was not obscured by the controller's hand or body, but had problems with resolution and being trained on the appropriate image. We experimented with software developed by Elissaoui (1997) that offers a solution: it zooms automatically when it detects a particular color (say the cap of a red pen) and grabs an image from the correct position on the strip. The graphics tablet is best at capturing precise data, whereas the video is the best at capturing information in context. The touch-screen is less precise than the graphics tablet, but permits information to be presented directly onto the strips.

Presenting information

We experimented with three projection approaches:

1. Video projector (for computer images or video)
2. Computer monitor or LCD screen
3. Touch-sensitive screen

We had already experimented with projection onto paper in Video Mosaic (Mackay & Pagani, 1994) and Ariel (Mackay, 1996). Projecting information onto flight strips is less feasible, since controllers must be able to immediately see the information and not worry about blocking the light source. Computer monitors provide high-quality images, but can only present information next to, not directly onto, the strips. The touch-screen, when used with transparent strips, can project high-quality information (from below) onto any part of the strip.

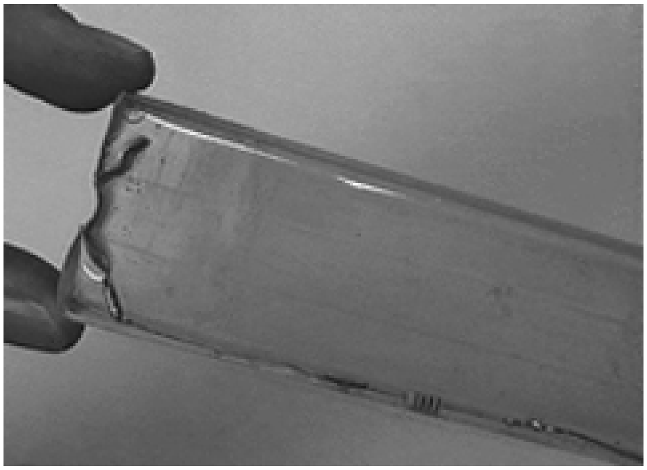

Figure 7: Transparent strip holder with diodes and contacts.

Tracking information

We experimented with two tracking approaches:

1. Video camera
2. Stripboard that detects resistance in strip holders

We tried placing information on the strips that could be detected by the video camera. However we concentrated on a second approach, Médini (1997) to track the position of stripholders in a stripboard. We embedded resistors into stripholders with metal contacts at either end (Figure 7). A special stripboard (Figure 8) measures the resistance in the strip holders and can determine precisely which stripholder is located in which position. Solid-color strip holders were created to hold ordinary paper strips and were placed over the graphics tablet. Transparent strip holders held transparent strips and were placed over the touch screen. This prototype solved the problem of linking the relevant strips to the writing detected via the graphics tablet or touch screen.

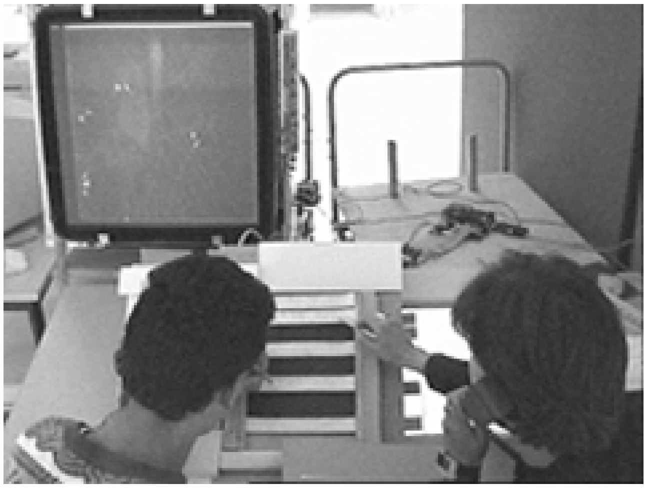

Figure 8: Stripboard that tracks position of strip holders, linked to RADAR with simulated air traffic

User functionality: The media space

The best user functions are often the most invisible: controllers value simplicity over functionality. Ideas popular with visitors and management, such as correcting flight plan information from the strip, were generally rejected as too complex by the controllers. They pointed out that the current Digitatron (a touch-screen) lets the planning controller make updates when it is convenient, rather than forcing the RADAR controller to do it. The most successful user functions were the linking of the strips to the RADAR (described earlier) and using the strips to communicate with controllers at other sectors via a modified media space (Bly et al., 1994).

We were struck by how controllers working next to each other communicate. In stressful situations, especially when the RADAR controller talks continuously to the pilots, they avoid speaking and communicate with body language and placement of strips. If the planning controller places a strip in the normal spot next to the RADAR controller, she knows that the RADAR controller is peripherally aware of it and will deal with it when he is ready. If she places it on top of the stripboard, she is placing it within his focus. If she stands up, slides several strips down, inserts the strip and writes on it, she is demanding that he look at it NOW. Similarly, the RADAR controller can wait for the planning controller's actions or actively shift his focus and integrate the strip into his working set. Others have described peripheral awareness (Heath and Luff, 1991) and situational awareness (Endsley, 1988) in various settings. We noted that controllers decide to actively or passively slide between peripheral and focused awareness, pushing information at each other or pulling information in. This subtle, but effective behavior works extremely well for controllers who are sitting next to each other, but breaks down completely for controllers at a distance. This rich interplay is reduced to a telephone call; a noisy interruption of a potentially busy person. The caller has no way of knowing if the other controller is dealing with three critical conflicts or relaxing. Similarly, the callee cannot tell if the call is urgent or could be handled at any time. Controllers complain about telephone interruptions, particularly from student controllers reassuring themselves.

We experimented with a common type of cross-sector communication, the negotiation of transfer flight levels. Before handing off a plane, two controllers must agree on a particular flight level. Each flight strip has a section with the next sector and the requested and authorized flight levels. When a controller writes a flight level in this box, other controllers immediately know that that's the proposed transfer level. When the flight level is underlined, they know the pilot has agreed and the next sector will accept the flight at that level.

If we capture what the controller writes on this section of the flight strip and make it available to the controller at the next sector, we can begin to simulate the light-weight interaction that exists when controllers are next to each other. Since this information is captured for another human being, not the computer, we need only send it, not interpret it. We experimented with several interfaces. For example, one controller writes the new flight level. The writing is captured and displayed on the appropriate section of the other controller's strip. If she underlines the flight level, everyone knows that the negotiation is done. If she writes a new level, the original controller may accept it or call to discuss it. We experimented with different ways of "sending" the information, such as having a tiny image appear and get successively bigger over time, to simulate the controller pushing the information deeper and deeper into the other controller's awareness. We are still exploring the range of possibilities suggested by this approach.

Evaluation

Throughout the project, we invited controllers to come to our laboratory and see or try out various technologies and experiment with different user functions. Our last workshop presented the most developed prototype, linked to a working simulation of real air traffic. The resulting system can now take advantage of any of the on-line tools developed by CENA (or externally). We also introduced an "Interaction Browser" that lets controllers try different ways of interacting with the strips and associating those interactions with any of the functionality available on-line. For example, a controller might specify that making an underline mark in the identification section of the strip causes information about the flight plan to appear next to the relevant plane on the RADAR. The same underline mark located in the flight transfer section of the strip is interpreted as an agreement that a particular flight level has been accepted. Controllers can save their profiles and try out the interactions on a scenario based on real traffic. The goal is to provide controllers with a system that is explicitly designed to be evolved, to take advantage of new on-line tools as they appear and to let controllers decide together on their preferred styles of interaction. (Note that the goal is not to have an individual profile for every controller, but to let controllers experiment with a range of possibilites and then collectively agree on a limited set of annotations that can be interpreted in a consistent way, just as they do now with writing conventions on paper.)

Technology: We were somewhat surprised that controllers liked the transparent strips: they could easily see why having external information displayed on the strips would be useful. (However, they were even more intrigued by future technologies such as electronic paper/ink, which promise the same advantages without the drawbacks.) Presenting information next to the strips was acceptable, particularly for functions like linking the strips and the RADAR. They did not like projection very much, since they are most likely to block the light source when they most need the information. The system for tracking the position of the strip holders made it possible to experience the flexibility of future augmented strips.

User functions: Some of the user functions were controversial, with some controllers liking a particular function and others rejecting it. Sometimes it was possible to reach a compromise, as in the two-step linking of strips and RADAR. Controllers were most likely to reject functionality that was too complex (particularly software displays or interaction techniques that required multiple steps). They were also wary of functionality that replaced part of their mental representation of the traffic: they wanted to be sure they could handle the traffic even without the RADAR and strips in case of a massive failure. Finally, they were most positive about functions that reduced annoyances, such as too many telephone interruptions.

CONCLUSIONS AND FUTURE DIRECTIONS

After conducting a four-month ethnographic study, we embarked on a nine-month participatory design effort to explore the idea of augmenting paper flight strips. We ran a series of workshops with researchers and controllers, using brainstorming, prototyping and scenario-building techniques to explore the design space. We returned often to the control room for further observations and discussions and incorporated the controllers' reactions and ideas at each stage of the prototyping process. The final workshop involved a working prototype connected to a training simulator, with access to RADAR with simulated traffic and a range of on-line tools. Our 'interaction browser' let controllers experiment with different types of annotations and link them to different on-line tools. We presented at least two different ways of handling each type of interaction, enabling us to compare both technology ideas and user interactions. A full report of the design space exploration and our data will be presented as a CENA technical report.

We began this work with a particular bias: Physical objects play an important role in cooperative work and automation efforts that get rid of them risk losing important aspects of the interface. Our observations in the Paris control center convinced us that paper flight strips play a complex role in air traffic control, beyond their information content. We argue that designers of new air traffic control systems should consider separating the problem of input/output from the content of the tools and experiment with augmenting paper flight strips. Perhaps then we can take full advantage of their rich, existing role in air traffic control, without losing the other benefits of automation.

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