Distributed Cognition

in an Airline Cockpit[0]

Edwin Hutchins
Department of Cognitive Science
University of California, San Diego
La Jolla, California
USA

Tove Klausen
Department of Communication
Aalborg University
Aalborg
DENMARK

Abstract: In earlier research on the organization of work, Hutchins developed a theory of distributed cognition that takes as its unit of analysis a culturally constituted functional group rather than an individual mind. This theory is concerned with how information is propagated through a system in the form of representational states of mediating structures. These structures include internal as well as external knowledge representations, (knowledge, skills, tools, etc.). This approach permits us to describe cognitive processes by tracing the movement of information through a system and characterize the mechanisms of the system which carry out the performance, both on the individual and the group level. In this paper we apply this approach to the structure of activity in a commercial airline cockpit. A cockpit provides an opportunity to study the interactions of internal and external representational structure and the distribution of cognitive activity among the members of the crew. Through an analysis of audio and video recordings of the behaviors of real airline flight crews performing in a high fidelity flight simulator we demonstrate that the expertise in this system resides not only in the knowledge and skills of the human actors, but in the organization of the tools in the work environment as well. The analysis reveals a pattern of cooperation and coordination of actions among the crew which on one level can be seen as a structure for propagating and processing information and on another level appears as a system of activity in which shared cognition emerges as a system level property.

Most people who travel frequently by air occasionally find themselves sitting in the passenger cabin wondering what is happening on the other side of the cockpit door. What are the pilots doing, and whatever it is they are doing, are they doing it well?

Although we cannot present you with data from an actual flight, we can give you the next best thing: data from an actual airline flight crew performing in a very high fidelity flight simulator.[1] Consider the transcript below. This is taken from a full-mission simulation of a flight from Sacramento, California to Los Angeles, California. It is the second flight of the day for this particular crew. They are about 8 minutes out of Sacramento and are climbing through nineteen thousand feet toward their cruise altitude of thirty three thousand feet. The simulated aircraft is a Boeing 727-200 which requires a crew of three: Captain (Capt), First Officer (F/O) and Second Officer (S/O).

We open the cockpit door and peek inside. The Captain has just removed a departure chart[2] from the control yoke and is replacing it in his airway manual. The first officer is flying the plane, monitoring the flight instruments and handling the controls. The second officer has completed his departure paperwork and begins a departure report by radio to the company offices on the ground.

TRANSCRIPT

0216	S/O	xxx nasa nine hundred
0224	S/O	departure report
	S/O	nasa nine hundred from eh sacramento to los angeles international we have eh /.../ fuel on board twenty seven point eight fuel boarded is not available out time is one six four five up time is one six five five
0247	Capt	oakland center nasa nine hundred request higher {F/O reaches to vicinity of altitude alert setting knob when ATC begins transmission}
0254	OAK24L	nasa nine hundred /.../ roger contact oakland center one thirty two point eight {F/O pulls his hand back from the altitude alert knob when ATC says "contact oakland center." 2.5 seconds after the end of ATC transmission, F/O looks at Capt. } {Capt looks at F/O}
0300	F/O	thirty two eight
	Capt	thirty two eight?
	F/O	yeah

	Capt	ok
0303	S/O	that's correct, nasa nine hundred
	Capt	\one three two eight ah, nasa nine hundred
		{Capt. twists knob on radio console}
		{F/O looks in direction of Captain}
0315	Capt	center nasa nine hundred twenty one point seven for two three zero requesting higher
0323		{S/O turns towards front of cockpit}
0325		{F/O looks at Captain}
0325	OAK15H	nasa nine hundred/.../ oakland center climb and maintain flight level three three zero and expedite your climb please
0327		{F/O reaches the altitude alert as ATC says "climb and maintain."}
0330		{When ATC says "expedite your climb" S/O turns to the performance tables on the S/O work surface.}
0331	F/O	ok
0333	Capt	three three zero nasa nine hundred
		{Capt. leans toward and looks at F/O}
		i didn't catch the last part
0336	F/O	expedite your climb
	Capt	ok
0339		{S/O reaches thrust levers and pushes them forward}
0341	Capt	that's firewall thrust {Captain looks at F/O}
	All	(laugh)

Unless you know quite a lot about aviation, reading this transcript probably did not help you much in deciding what the pilots are doing and whether or not they are doing it well. Of course, in a very important sense, the question of interest to you as a passenger should not be whether a particular pilot is performing well, but whether or not the system that is composed of the pilots and the technology of the cockpit environment is performing well. It is the performance of that system, not the skills of any individual pilot, that determines whether you live or die. In order to understand the performance of the cockpit as a system we need, of course, to refer to the cognitive properties of the individual pilots, but we also need a new, larger, unit of cognitive analysis. This unit of analysis must permit us to describe and explain the cognitive properties of the cockpit system that is composed of the pilots and their informational environment. We call this unit of analysis a system of *distributed cognition*.

The excerpt of cockpit activity presented above is only approximately one and a half minutes in duration, yet it is very rich. It contains within it illustrations of many of the central concepts of a theory of distributed cognition.

We will present and discuss these concepts by going through the elements of the example in chronological order and noting what the events in this example tell us about the nature of this particular system and about systems of distributed cognition in general.

This is a descriptive use of the theory. We will attempt to show that certain observed behaviors are instances of certain theoretical concepts. It is only by mapping from the data to a theory that we can generalize beyond the specifics of these observations. Establishing such a mapping from the data to the theory is itself a problematic cognitive activity. A short digression on method is in order.

THE METHOD OF ANALYSIS

In some kinds of behavioral research, the mappings from observed events to the terms of a theory are taken to be obvious. In others these mappings are justified by "operational" definitions. In our case, however, the theoretical interpretation of some events may depend on the meanings that the participants themselves attach to those events. Because the setting is not familiar to most readers, the mappings from events to theory are unlikely to seem obvious. Because of the complexity of the setting, it cannot readily be made familiar. And since the sort of thing an event is in the theory may depend on meanings that the participants attach to the event, there are no simple operational definitions of many of our terms. Instead, we must rely on an ethnography of the setting to provide the interpretive bridge from the structure of the recordings of activity to the terms of the theory of distributed cognition.

We have pursued a strategy of analysis in which we insist that the connections between the data and the theory must be established explicitly. Our analysis begins with video and audio recordings of the events in the cockpit environment. We take the video and audio records to be a first generation representation of what happened in the cockpit. Some aspects of the setting are already lost in the video and audio. The camera angle leaves some parts of the environment obscured, for example. The camera mounted in the flight simulator records a black and white image from infra-red sensors, so color is lost. Odors are not recorded by video. Although they are incomplete, the video and audio recordings are rich sources of data[3].

From the video and audio recordings we create another representation of what happened in the cockpit; this time in the medium of print. We create a *transcript* of the verbal and other behavior, in the cockpit. This representation leaves out even more than the video and audio representations, but it is still rich, and for some analytic tasks, it is far superior to the raw recordings. Both the translation from real events to video and audio recordings and the translation from video and audio to written transcript is heavily theory laden (Ochs, 1979).

The actual recorded acoustic signals are meaningless in themselves. It is only in interaction with the knowledge of a listener who understands the language that the acoustic signals become segmented into words. The role of transcriber knowledge becomes even more apparent where specialized vocabularies are employed. Most people in our culture do not speak "aviationese" and just as it is impossible to transcribe recordings in a language on does not speak, it is impossible to transcribe discourse from technical domains without knowing something about the domain of discourse. As analysts, we know well that what people hear depends on what they expect to hear, and in a noisy technical environment very little can be heard at all without some expectations. This raises an important concern. If even the transcription process involves the tacit knowledge of the researcher, might the analysis be covertly shaped by the analysts expectations?

One way to protect oneself from the possibility of unexamined assumptions driving the work is to attempt a form of "objectivity" in which all assumptions are hopefully banished. Such approaches cling to a "coding scheme", a set of "objective criteria" for the existence of instances of various classes of events. Every coding scheme, however, ultimately depends on the skills of coders to assign complex real events as instances of the coded categories. This in itself is a complex cognitive activity that is far from objective (Goodwin, 1994). We opt for another possibility, that is, making sure the assumptions do not remain unexamined (Moreman, 1969; Duranti, 1985). With this in mind, we ground the translation from video and audio record to transcription in an explicit set of propositions that are independently verifiable in the ethnography of the setting (Agar, 1986).

Consider a simple example from the excerpt above. The transcript indicates that at time 0327 the first officer reached the altitude alerter. We know this is the correct description of this event because we have access to other resources. A diagram of instrument layout shows that the altitude alerter is located just where the first officer reached. But there is more to it than that. Setting the altitude alerter is a meaningful action for the pilots at this point in time. Company procedures require that the altitude alerter be set whenever a new altitude is assigned to the aircraft.

From the transcripts we generate yet another representation of the events that were recorded. This is a description of the *actions* that took place. The stream of behavior in the transcript is segmented into culturally meaningful chunks and is related to an ethnographically grounded system of goals and expectations in which the actions achieve their meaning for the participants. Again, we attempt to be completely explicit about the grounds for the composition of every action. The development of ethnographic grounding leads us to many sources of cultural knowledge. These include operational manuals for the aircraft, the layout of the cockpit instrumentation and controls, crew training materials, published navigation procedures, commonly known "rules of thumb" in aviation, interviews with pilots, observations of pilots in actual flights, to mention only a few[4].

A fourth representation of the events gives *interpretations* to the actions that were identified in the previous stage. Again, the translation from the action representation to that of interpretations is given an explicit grounding in an independently verifiable ethnography of the setting. Furthermore, even the richest ethnography may not uniquely constrain interpretations. Any particular identified action may have many meanings.

Finally, we draw on all of these representations to create the mapping from data to the theory. As the theory of distributed cognition unfolds in this paper, the reader will recognize that this analytic device is modeled on the notion of the propagation of representational state across a series of representational media. Each representation brings a different sort of information into the foreground. This is one of the central concepts of the theory. Unfortunately, we do not have the space here to give a complete explication of the process of analysis for even this brief excerpt. What we will do instead is weave together the data, the actions, the interpretations, and the ethnographic grounding as they are needed in a narrative that seeks to present a theoretical account of the observed events.

ANALYSIS OF THE EVENT

Let's begin with a brief summary of what we saw. This is the sort of description that a pilot would give.

As the crew approached the altitude to which they were cleared, the Captain called Air Traffic Control and asked for a clearance to a higher altitude. The controller handed them off to a high altitude controller who gave them a clearance to their cruising altitude and instructed them to expedite the climb. The Second Officer increased the thrust and they continued their climb.

This is an entirely normal event. But now let us look much more closely and examine the cognitive properties of this system.

Cognitive labor is socially distributed

Flying a modern jet transport is a job that cannot (at least not in current practice) be done by an individual acting alone. This is why your safety as a passenger depends on the properties of the crew / aircraft system rather than on the skills of any individual. The excerpt we have presented begins with the crew operating in a fairly autonomous mode. They are in a relatively light workload phase of flight; the stresses of the takeoff are behind them and they have now established a climb on a constant heading. The F/O, who is actually flying the airplane is the only crew member involved in time critical performance at this point. The Captain is dividing his attention between housekeeping tasks (putting away a navigation chart) and monitoring aircraft and crew performance. In his role as "pilot not flying", he is also responsible for communications with the Air Traffic Control system (ATC), but there are no communication demands at the beginning of this example. Simultaneously, and quite independently, the S/O is involved in another kind of housekeeping task, making a report to the company of the condition of the flight. At this instant there is little explicit interaction among the members of the crew. While no member of the crew is taxed by these circumstances, the system as a whole may still be doing more cognitive work than could be done by any individual alone. The fact that such systems proceed with several individuals working autonomously in parallel is well known and from a theoretical point of view, is easy to understand. Things become much more interesting when the members of the crew are required to coordinate their activities with each other.

Planning

At time 10:02:47, the Captain calls the Oakland, California Air Route Traffic Control Center (abbreviated to "Oakland Center") low altitude controller and requests a clearance to a higher altitude[5]. This is an important piece of evidence about planning in the cockpit. The aircraft is currently climbing through an altitude of about nineteen thousand feet. It is currently cleared to an altitude of twenty three thousand feet. This means that without a clearance to a higher altitude, it cannot legally climb above twenty three thousand feet. However, the flight plan[6] filed for this flight calls for a cruise altitude of Flight Level 330 (thirty three thousand feet).

In this context we can attribute to the Captain the goal of climbing to the filed cruise altitude of FL330 and furthermore, we can attribute to him the goal of making the climb uninterrupted by leveling off at an intermediate altitude[7]. In order to realize these goals, the aircraft will need to have a clearance to climb to a higher altitude. The Captain's request is part of a plan to achieve the sub-goal of getting the required clearance. In order to have this plan now, he must have been monitoring the progress of the flight. That is his job as Captain and as the pilot not flying[8]. He used the information available, present altitude, cleared altitude, cruise altitude, plus his knowledge of the legal status of cleared altitude and the role of ATC to construct a plan. It's a tiny bit of action in the cockpit, but it is the tip of a large iceberg of information and knowledge.

Distribution of access to information

Up to now we have been primarily concerned with relatively autonomous activities of the crew. That changes when the Captain speaks. All members of the crew normally monitor the ATC frequency unless they need to be on another frequency for some reason[9]. The Captain's radio transmission can be heard by the F/O. The distribution of access to information is an important property of systems of distributed cognition. The properties of the larger system emerge from the interactions among the interpretations formed by the members of the crew and the contents of those interpretations are determined in part by the access to information.

The trajectories of information

It is important to note that we cannot predict in advance where the information will actually go. For example, we do not know that the F/O will actually attend to and hear the Captain's radio call. We do know from the structure of the setting and a knowledge of how the radios are operated that the F/O could have attended to and heard any communication with ATC. This sort of knowledge permits us to establish a set of possible pathways or trajectories for information. Occasionally, the observation of particular pilot techniques may demonstrate possible pathways that have not been anticipated on the basis of the normal operation in the setting. Once the possible pathways have been identified, it is possible to examine the data for evidence concerning where the information actually went. It is often possible, after the fact, to unambiguously determine that information has followed some particular trajectories in the system.

Formation of expectations

Given the content of the Captain's plan, we attribute to him an expectation concerning the reply from Oakland Center. His radio call is the opening turn in a conversation with a highly predictable structure. The expectation is that ATC will answer, saying something like, "Nasa nine hundred, climb and maintain flight level three three zero." If the F/O was attending to the Captain's request, he may also have formed this expectation. Note that at this point in the analysis we cannot confidently attribute this expectation to the F/O. As was the case with the potential trajectories for information structure in the system, we cannot always know what cognitive consequences follow from the arrival of a particular piece of information. Thus, even if the information reached the F/O, the development of an expectation about ATC's response is only a possibility. Additional evidence from the transcript would be required to support this interpretation.

In this case, more evidence is available in the form of the F/O's reaching toward the altitude alert setting knob as the ATC controller begins his reply to the request for a higher altitude clearance. The altitude alert system is required by federal aviation regulations. The crew must set the cleared altitude into the window. The system sounds an alarm warning of approach within seven hundred and fifty feet of the assigned altitude. Altitude busts (flying through the assigned altitude) were a frequent and serious problem prior to the introduction of these systems. We believe the F/O’s reaching behavior is evidence of a plan to change the setting of the altitude alert system in response to the expected clearance to a higher altitude. The currently cleared altitude, 23,000 feet is displayed. The F/O intends to change the setting to what ever altitude ATC specifies. He expects the filed cruise altitude of 33,000 feet. The reaching behavior gives us an additional constraint on the ascription of an expectation to the F/O.

This sequence shows how the distribution of access to information and a shared body of knowledge about the operation of the system permits the formation of shared expectations that are then the basis of coordinated actions by the crew. This is one of many events in this excerpt that highlight the cultural nature of this task performance and its reliance on shared knowledge. To the extent that coordinated actions of the crew are grounded in mental representations of possible but not yet realized states of affairs we say that shared expectations are real.

Violations of expectations

As it turns out, the expectation is violated by the response of ATC. The expected clearance to a higher altitude is not forthcoming. Instead, the crew is instructed to contact another controller at Oakland Center — this time a high altitude controller. This is a violation of the crew's expectations. Unable to carry out the planned change in the altitude alert system, the F/O withdraws his hand from the altitude alert setting knob.

The frequency change instruction gives rise to a new expectation. All information from ATC is supposed to be acknowledged[10]. Both the Captain and the F/O expect the Captain to acknowledge the instruction. But the Captain does not acknowledge the instruction immediately. Two and a half seconds after the end of the ATC transmission, the F/O looks at the Captain. The F/O's expectation of a timely acknowledgment has now been violated.

Intersubjectivity as a basis for communication

The next several actions are interesting because they establish one another's meanings. The Captain looks at the F/O and says nothing. The F/O says "thirty two eight" to the Captain. Then the Captain asks, "thirty two eight?" What is going on in this interaction?

It is useful to consider this interaction in terms of speech act theory (Austin, 1960; Searle, 1969). Speech act theory considers utterances as simultaneously being several kinds of acts at once. What a speaker actually says is called the locutionary act. The force of what is said is the illocutionary act, and the intended effect is the perlocutionary act. For example, saying "Can you pass the salt?" at the dinner table has the locutionary force of a question: is the addressee capable of passing the salt. Of course, the speaker doesn't really want an answer to that question. The illocutionary force of the utterance is an indirect request for the salt to be passed. The perlocutionary act is an enticement to lead the addressee to pass the salt.

The F/O's response to the Captain's glance is an elliptical version of the frequency that is to be acknowledged to ATC[11]. The locutionary aspect of this utterance is the specification of the frequency to be used.

That seems appropriate in context. But, what would have to be true of the world in order for that to be an appropriate thing to say? The illocutionary force is "I am answering the question you posed by looking at me without saying anything." That is, the F/O's utterance assigns a meaning to the Captain's blank stare to which it is a response. It classifies the Captain's action of looking at the F/O as a question about the frequency to be used. Once made, this assignment of meaning to the Captain's look is available for negotiation. The Captain could, for example, dispute the classification and claim that he knew the frequency. But he does not. The Captain's next utterance, repeating the frequency back with rising intonation has an illocutionary force that concurs with the F/O's classification of the looking behavior.

There is one more level of meaning in the F/O's response to the Captain's look. The perlocutionary force or intended effect of the F/O's utterance is to enable the Captain to continue with his job.

This interaction is evidence for the notion of interaction as the construction of a shared understanding of the situation in which the interactants find themselves. Certainly, the pilots entered this situation with a considerable amount of shared prior knowledge about how things are supposed to go or how they typically go. As members of a community of practice, we may expect that to be the case. In the course of their interaction, they use that shared knowledge as a resource to negotiate or construct a shared understanding of their particular situation. This constructed shared understanding of the situation is known as an intersubjective understanding (Rommetveit & Blakar, 1979; Wertsch, 1985). As D'Andrade (1980) points out, what each participant to the situation knows is itself part of the situation being jointly understood. Following this notion of intersubjectivity we would say that the F/O's original looking at the Captain is evidence that the F/O knows that the Captain is supposed to respond to the ATC call. The Captain's look at the F/O is evidence that the Captain knows that the F/O knows that the Captain is supposed to respond to the ATC call. Finally, the F/O's utterance is evidence that the F/O knows that the Captain knows that the F/O knows that the Captain is supposed to respond to the ATC call. It says, "I know that you know that I know that you should respond."

Intersubjectivity supports efficient kinds of communication. It is what permits human actors to intend and find meanings in many non-verbal behaviors and in the aspects of verbal behaviors that go beyond the literal locutionary force of the utterance. It was not just something in the Captain that made his glance at the F/O so eloquent. Rather, it was the fact that this glance occurred in a context of intersubjectively shared understandings about the nature of the current situation that permitted it to so smoothly and successfully communicate the Captain's need. Again, the shared expectations become real in the sense that they organize the behavior that determines the properties of the larger cognitive system.

It is important to note that this interaction depends on the intersubjective sharing of representations of aspects of the situation that were never made explicit by either of the interactants. There was no conversation about what each knew about what the other knew. The fact that these crew members can do this is all the more surprising when one considers that these pilots had never flow together before the day of the simulated flight. Prior to the reported excerpt they had flown one flight segment and had spent only about two hours together. Clearly, the grounds for the construction of intersubjectively shared understandings depends on a very special distribution of knowledge in the pilot community.

Intersubjectivity is important for the functioning of the system of distributed cognition because the trajectory of information in the system depended on the intersubjectivity of the crew. Norman (1990), in a paper on aviation automation, has pointed out that the communication between the current generation of automatic devices in the cockpit and the crew is primitive and leaves much room for improvement especially with regard to providing the crew feedback about the condition of automated systems. Norman compares the case of a copilot flying an airplane with the case of an autopilot flying. He points out that if a copilot encounters a situation that requires unusual control inputs in order to maintain the desired flight path, the copilot is likely to say something about it to other crew members. An autopilot of the current generation, however, will simply make whatever control inputs are required without notifying the crew. This has led to some near disasters. Some readers of Norman's paper have responded by saying that the state of the art in artificial intelligence would permit the automated system to represent the information that the pilot needs[12]. This may well be so, but the issue is not simply whether the automation could represent its own state. The issue is whether or not the system could interact with the pilots in a way that they interact with each other. With human interactants, we have seen that intersubjectively shared representations permit a silent look in a particular context to have the meaning of a request for specific information. This sort of phenomenon is a reminder of the complexity and subtlety of human interaction. It is difficult to imagine what sort of machine could engage in this kind of interaction.

Distribution of information storage

The fact that the Captain succeeds in getting the required frequency from the F/O illustrates another aspect of this system of socially distributed cognition. The distribution of access to information is such that the F/O also hears the communications with ATC, even though he is not responsible for radio communications. This permits the formation in the crew system of a redundant storage of information. Under ideal conditions, both the Captain and the F/O (and the S/O if he is not otherwise engaged) will hear all ATC clearances. This means that if for any reason, one of the members of the crew fails to attend to, store, or retrieve the information, it may be available from one of the other members of the crew. Such a redundant information storage system is robust in the face of local failures as long as there is a way to move information around inside the system. As we saw above, the communication of information inside the system can be quite efficient.

Redundant read backs for error checking

Having gotten the frequency from the F/O, the Captain reads the frequency back to the ATC controller. The expectations of the crew members are now met. Furthermore, the read back of the elements of any ATC clearance provide an opportunity for redundant error checking (Palmer, et.al. 1993). While there is no legal requirement to read back clearances, it is considered good practice in the aviation community and is the express policy of most airlines. It is normally thought that the error checking is to be provided by the ATC controller, but we can see that there is also a possibility of error checking of the read back by other members of the crew. Since both the original clearance and the read back are available not only to ATC, but to all members of the crew, including the Captain himself, every member of the crew has an opportunity to detect an error in the read back.

In the most general case, we can say that redundant error checking depends on a redundant distribution of access to information about the performance of the members of the crew. This is supported in other ways in the airplane cockpit. For example, civil transport aircraft provide duplicate flight instruments for the two pilots. There are several frequently cited functions served by these duplicate instruments. First, they permit either pilot to fly the airplane. Second, they provide a measure of redundancy in the event that the instruments on one side fail. Third, by cross checking instruments, failures that might otherwise be difficult to detect can be discovered. Seen from the perspective of distributed cognition, these duplicate instruments serve yet another important function.

They provide a redundant distribution of access to information that supports mutual monitoring between the crew members and is essential in the maintenance of intersubjectively shared understandings of and expectations about the situation of the aircraft. A similar argument can be made for the prominent position of the control "yokes." With the two yokes mechanically linked, it is easy for one pilot to monitor the flying style of the other without having to turn to watch.

There is a trend in current cockpit design to build two separate crew work stations for the two pilots. Mechanically linked control yokes are being replaced in some cockpits by side-stick controllers that are mounted outboard of the pilot's seats and are not mechanically linked to each other. From the perspective of individual pilot performance, side-stick controllers are functionally equivalent to (or perhaps superior to) control yokes. From the distributed cognition perspective, however, the side-stick equipped cockpit has a different distribution of access to information and this may affect the cognitive properties of the cockpit system. A similar situation is created by current implementations of the Flight Management Computer System (FMCS). Duplicate computer interfaces to the FMCS are provided to the two pilots. This appears on the surface to have the same desirable properties as duplicate flight instruments. This would be the case if they were in fact directly linked to each other. However, for perfectly good operational reasons, the actions taken on one interface are not necessarily reflected on the other. This results in a common complaint among pilots that unless extraordinary measures are taken to communicate intentions, one pilot may not know what the other is doing. And even if extra measures are taken, they often result in both pilots going "head down", one leaning across the center console to monitor a programming task as it is performed by the other.

The problems of restricted or non-overlapping distribution of access to information have the potential to create difficulties in normal operations and may interfere more severely with training. Although, as one pilot remarked, "the cockpit is a poor classroom," a considerable amount of training takes place there[13]. Implicit learning through shared activity is an important component of learning a complex job like flying an airplane. It is possible to design computer systems with open interfaces (Hutchins, 1990) that support learning in joint action but this can only be done when the designer goes beyond the conception of the isolated individual user.

Propagation of representational state through the system

After reading back the frequency, the Captain tunes the number one communication radio to the specified frequency. This sets the radio to transmit and receive on the specified frequency. At this time, the F/O glances at the

Captain and at the frequency window of the radio. The F/O has an expectation that the Captain will tune the radio to 132.80 MHz.

Notice the trajectory of the radio frequency information. It arrived in the cockpit as a string of spoken words. It went by way of the F/O's memory to spoken words exchanged between the F/O and the Captain. Thence by way of the Captain's memory to the read back and then on to the setting of the radio. Each appearance was slightly different from the one before it:

ATC:	"one thirty two point eight"
F/O <-> Capt	"thirty two eight"
Read back	"one three two eight"
Radio	132.80

We can see that the information moved through the system as a sequence of representational states in representational media. From speech channels to internal memories, back to speech channels, to the physical setting of a device. Its representation in each medium is a transformation of the representation in other media. Notice also that the various media in which the information is represented have different properties (Norman, 1993). Speech is ephemeral. It requires one to attend to information at the time it is delivered. Representations in the memories of individuals endure longer than those in speech. This is what permits the Captain to retrieve the information that was in the ATC instruction without having to ask the controller for it again. Although the ATC transmission had ended and was no longer available, the information in it was still represented in the memory of the F/O. Finally a portion of the information in the ATC instruction was imposed on the airplane itself, in the tuning of the radio. This is the same information that had been represented verbally, but now it is in a relatively durable representation, because the setting of the radio is continuously available and will not change until the next frequency is tuned.

This movement of information structure across various representational media and ultimately to the controls of the airplane itself is the essence of control of the aircraft and the way that coordination among aircraft is maintained. That is, if we step back and look at the entire aviation system and ask how it is that aircraft are kept separated from each other, we see that it is through the propagation of representational state of descriptions of flight paths into the state of the aircraft controls themselves.

Distribution of labor again

With the radio now set to the appropriate frequency, the Captain contacts the Oakland Center high altitude controller at 10:03:15. He is back to the point in his plan where he was with his original request for a higher altitude. That plan is still pending, and is in fact somewhat more urgent now as the plane is closing rapidly on its currently cleared altitude. In this case he gives the current altitude of the plane and the altitude to which they have been cleared, then adds the request for a higher altitude[14].

The Captain’s radio call contains the current altitude and the altitude to which the aircraft has been cleared. We may ask where these values come from. The current altitude of the aircraft must come from the airplane’s altimeter. Since the plane is climbing, this value is continually changing. Altitude is represented on the altimeter by the positions of two hands and a bar on a clock-like face of the gauge and also by a digital readout window. The Captain must transform this representation of altitude information into a spoken one. There are at least two possibilities for the source of the information about the altitude to which the plane is currently cleared. One is the Captain’s memory. The airplane was cleared to flight level 230 about four minutes before the Captain’s radio call and he may simply remember that altitude. The other is the altitude alert system. Since the altitude to which the plane is cleared should always be shown in the window of the altitude alert system, it is an alternate source of this information. In this case it does not appear that the Captain consults the altitude alert system, but we have seen many cases in which a crewman making initial contact with an ATC center will give the current altitude, pause, look at the altitude alert system, and then give the altitude to which the aircraft has been cleared.

By this time, the S/O has completed his departure report and is again attending to the actions of the other crewmen. The captain’s request is available to all members of the crew and leads them all to a shared expectation concerning the response from ATC.

Again all members of the crew have the expectation that ATC will answer back with something like "Climb and maintain flight level three three zero." This expectation is partially met and partially violated. ATC responds to the request by saying "nasa nine hundred /.../ oakland center climb and maintain flight level three three zero and expedite your climb please" As we shall see in a moment, the additional information "expedite your climb" seems to be heard by the F/O and the S/O, but not by the Captain. This bit of structure evokes in the F/O and the S/O a model of the expedited climb while the Captain seems to still be thinking standard climb.

This ATC clearance spawns more work to be conducted more or less autonomously by the members of the crew.

Memory in the state of artifacts: the altitude alert system

The F/O now has the information he needs to set the altitude alert system. As soon as ATC says, "Climb and maintain" he knows an altitude is coming next and he reaches forward to the altitude alert setting knob. The setting of the altitude in the window of the altitude alert system is similar to the setting of the radio frequency in that in both cases information that had verbal representation comes to be represented in the state of a device in the cockpit. In both cases, the representation in the medium of the device is much more durable than the representation in speech, and it is much less vulnerable to interruption or displacement by other information than the same information represented in individual internal memory.

The strategy of using physical state as a form of memory is widespread. Unfortunately, its very ubiquity may lead us to overlook its importance and miss its theoretical significance. Writing something down to remember it is a common example with which we are all familiar. This happens in the cockpit too. Each pilot has a small clipboard near at hand with slips of paper on which clearances and other information may be written. But in the cockpit there are also another set of devices that both remember the information and act on it autonomously. The altitude alert system is a simple example.

Computation by propagation and transformation of representational state: computing and using the maximum EPRs.

The portion of the clearance that said "expedite the climb" spawned some autonomous action on the part of the S/O as well. The expedited climb requires maximum thrust from the engines. The concept of the expedited climb leads, for the S/O, to the notion of setting the engines to maximum thrust. This is done by pushing the thrust levers forward until the engine pressure ratio (EPR) gauges read the maximum permissible values given the current air temperature and altitude. We attribute to the S/O the goal of setting maximum engine thrust. In order to achieve this goal, the S/O needs to know what the maximum EPR settings are.

When ATC says "expedite your climb", the S/O turns to the engine performance tables that are printed on the work surface below his instrument panel and finds the appropriate EPR values. With the EPR values in memory, the S/O turns to the thrust levers and pushes them forward while monitoring the readings on the EPR gauges for a match to the remembered values. Thus, having satisfied the sub-goal of finding the EPR values, the S/O returns to the top level goal of setting the engines for maximum thrust.

Here again, we see the propagation and transformation of representational state across a number of media. The S/O's model of the expedited climb included an implication of maximum thrust. He propagated that information (plus altitude and total air temperature) into the climb EPR table. That transformed the inputs into outputs of EPR settings for the engines which he then propagated to the EPR gauges by manipulating the thrust levers. Some of the media across which this information was propagated are internal to the S/O, others, like the EPR table, thrust levers, and the gauges, are external.

The table that the S/O uses to compute the appropriate maximum climb engine pressure ratios is a mediating artifact of a special sort. Originally, the values in the table were determined by the engineers who built the engines. This involves both empirical testing and theoretical calculations. The knowledge that was gained through that process is now crystallized as a hard artifact: the EPR table. In the EPR table, the information is represented in such a way that the task of extracting the appropriate values is very simple.

Intersubjectivity and distribution of storage again.

While the S/O was computing the maximum climb EPRs, and the F/O was setting the altitude alert system, the Captain also had a job to do. He was supposed to read the clearance back to ATC. At 10:03:33, he read back, "three three zero nasa nine hundred". This is just the part of the clearance that matched the Captain’s expectations about what sort of clearance he was to receive. Since, as we noted above, the Captain’s read back is also available to the F/O, it is possible that the Captain’s read back violated the F/O’s expectation that the read back would contain mention of the "expedite your climb" portion of the clearance.

After his incomplete read back (which was not challenged by ATC) the Captain turned to the F/O and said, "I didn’t catch the last part". The locutionary force of this statement is simply that the Captain did not hear something. The illocutionary force is an indirect request for the F/O to tell the Captain what ever the "last part" was. An interesting question at this point is: How can the F/O know what the Captain means by the phrase "the last part"? The F/O answers "expedite your climb" which is both a response to the illocutionary force of the Captain’s statement and a claim about what the Captain meant by "the last part". The Captain immediately says, "ok", which indicates that the F/O did know what the Captain meant.

One conjecture is that the F/O could establish the meaning of "the last part" on purely syntactic grounds. The instruction portion of the clearance consisted of two main clauses: "climb and maintain flight level three three zero" and "expedite your climb please". Perhaps the "last part" simply refers to the second main clause. We believe that such an interpretation is implausible because there are no pragmatic conventions for referring to grammatical structures in this way. More likely the F/O, on the basis of what he has heard from the Captain’s read back, may already suspect that the Captain did not hear the instruction to expedite the climb. Or, even without forming this expectation, when the Captain says he didn't catch the last part, the F/O may ask himself what the "last part" could mean and may remember that just one second earlier, the Captain left "expedite the climb" out of his read back. In either case, the intersubjectively shared expectations about the Captain's responsibilities in this situation form the basis for effective communication.

Firewall thrust!

Having learned that the clearance was to expedite the climb, the Captain now shares the image of the expedited climb with the other two members of the crew. As the S/O reaches the thrust levers and begins pushing them forward to the maximum climb thrust position, the Captain turns to the F/O and S/O and says, "That's firewall thrust". Notice that no command is given to the S/O to increase engine thrust. He performs his role here without explicit verbal interaction with the other members of the crew. This action is interesting in two ways. First, it is another example of a sort of seamless joint performance constructed by a team whose members met for the first time only a few hours before takeoff. It suggests a kind of interchangeability of human parts that is a striking cultural and social organizational accomplishment. Second, one has to wonder whether any crew member would do something as consequential as this without verbally interacting with other crew members if the action was not completely visible to the other members of the crew. Given the location of the thrust levers, any manipulation of them is quite accessible to both the Captain and F/O. In other portions of the flight, especially when the crew is faced with an equipment failure, the S/O takes other actions that are not visible to the pilots and notifies them of what he has done. This is only to say that the S/O makes decisions about the distribution of access to information and organizes his verbal behavior to compensate for the fact that some of his actions are not available to the other members of the crew.

The Captain's comment "That's firewall thrust!" and the reaction of other members of the crew establishes the distribution of awareness of the S/O's action. The phrase itself is a figure of speech. It is a form of trope known as a synecdoche. Its interpretation requires a bit of history. In the old days when single engine planes had an engine in the front and the pilot's cockpit directly behind the engine, there was a hopefully fireproof wall between the cockpit and the engine. In case the engine caught fire, this wall, the "firewall" was supposed to protect the crew from the fire. Throttles (the piston engine equivalent of jet thrust levers) are pushed forward for increased thrust. Maximum thrust is achieved by pushing the throttle levers right up to the firewall. Thus the expression "firewall thrust"[15]. This colorful expression brings to mind an image of pushing the thrust levers all the way forward to the stops.

The locutionary aspect of this comment is inaccurate (it is not firewall thrust) and the illocutionary force of this statement is inappropriate (one would not push the thrust levers forward to the stops in this airplane except in an emergency because doing so would most likely damage the engines). The perlocutionary aspect of the statement, however, is an assertion by the Captain that he now knows what is going on. He understands that the aircraft is cleared to climb at its maximum rate and that such a climb will require increased thrust.

DISCUSSION

In this paper, we have considered only a tiny fraction of one simulated airline flight. Yet, a close examination of even this one excerpt illustrates a number of features of the cockpit as a cognitive system. Information processing in the distributed system can be characterized as a propagation of representational state across representational media. In the cockpit, some of the relevant representational media are located within the individual pilots. Others, such as speech, are located between the pilots, and still others are in the physical structure of the cockpit. Every representational medium has physical properties that determine the availability of representations through space and time and constrain the sorts of cognitive processes required to propagate representational state into or out of that medium. Changes in the medium of representation of task relevant information or in the structure of representations within a particular medium can therefore have important consequences for the cognitive conduct of the cockpit system.

The movement of information through the system has consequences for the formation of expectations and models of the situation of the aircraft. These expectations and models organize the behavior of the crew and, when shared, permit the crew members to coordinate their actions with each other. Furthermore, the movement of information among members of the crew sometimes depends on the crew members' assessments of their own states of knowledge and those of the others. The relationship between the cognitive properties of the cockpit system, as determined by the movement of representations, and the cognitive properties of the individual pilots is therefore very complex.

The analysis identifies a set of possible pathways for information through the cockpit system during ATC clearance handling events. Some of the pathways observed are those that are anticipated by the design of the system. Others, which were perhaps not intended in the design of the system, nevertheless contribute to its performance characteristics. Although we can never know in advance which particular pathways for information will actually be used, the analysis of this event establishes a sort of existence proof for the observed pathways. As we have seen, there are many possible pathways for information in this system. In some cases the pathways are redundant so that if one is blocked, task relevant information can still proceed via another. This redundancy appears to contribute to the robustness of the system in the face of local failures.

Certainly, the cognitive properties of the cockpit system are determined in part by the cognitive properties of the individual pilots. They are also determined by the physical properties of the representational media across which task relevant representational state is propagated, by the specific organization of the representations supported in those media, by the interactions of meta-representations held by the members of the crew, and by the distributional characteristics of knowledge, and access to task-relevant information across the members of the crew. Understanding the properties of individual cognition is therefore only a first step in an effort to understand how these more complex human cognitive systems operate.

References:

Agar, M. H. (1986) *Speaking of ethnography*. London: Sage Publications.

Austin, J. L. (1960) *How to do things with words.* Oxford: Clarendon Press.

D'Andrade, R. G. (1980) The cultural part of cognition. *Cognitive Science 5,* 179-195.

Duranti, A. (1985) Sociocultural dimensions of discourse. In T. van Dijk (Ed.) *Handbook of Discourse Analysis.* Vol 1. New York: Academic Press.

Goodwin, C. (1994) Professional vision. *American Anthropologist* 96(3) 606-633.

Hutchins, E. (1990) The technology of team navigation. In J. Galegher, R. Kraut, & C. Egido (Eds.) *Intellectual teamwork: social and technical bases of collaborative work.* Hillsdale, NJ: Lawrence Erlbaum Assoc.

Moerman, M. (1969) A little knowledge. In S. Tyler (Ed.) *Cognitive Anthropology*. New York: Holt, Rinehart & Winston.

Norman, D. A. (1990) The 'problem' with automation: Inappropriate feedback and interaction, not 'over-automation'. Philosophical Transactions of the Royal Society of London, B 327.

Norman, D. A. (1993) *Things that make us smart*. Reading MA: Addison Wesley.

Ochs, E. (1979) Transcription as theory. In E. Ochs & B. Schieffelin (Eds.) *Developmental Pragmatics.* New York: Academic Press.

Palmer, E. A., E. L. Hutchins, R. A. Ritter, I. van Cleemput, (1993, October) Altitude deviations: breakdowns of an error tolerant system. NASA Technical Memorandum 108788. National Aeronautics and Space Administration, Ames Research Center, Moffett Field, CA.

Rommetveit, R., & Blakar, R.M. (Eds.) (1979) *Studies of Language, thought and verbal communication.* London: Academic Press.

Searle, J. R. (1969) *Speech acts.* London: Cambridge University Press.

Wertsch, J. V. (1985) *Vygotsky and the social formation of mind.* Cambridge, MA: Harvard University Press.

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[1] The simulator is part of the NASA-AMES research facility at Moffett Field, California. It is a very high fidelity simulation. The cockpit simulator interior is a real airline cockpit with all the appropriate instruments and controls. The "box" is mounted on hydraulic rams that give it 6-degree of freedom motion. High resolution television monitors are mounted over the windows of the cockpit to provide complete computer generated night and dusk visuals.

[2] A Standard Instrument Departure (SID) for Sacramento. This is a published procedure for departing the airport area. The aircraft has completed the departure segment and is in the

enroute climb segment of the leg, so this chart will not be needed again.

[3] Our data stream is actually richer than this indicates. Because these are flights in a computer controlled simulator, we also have data on the readings of all of the primary cockpit instruments and the settings of all of the controls for the duration of the flight. This data is very useful in reconstructing the description of the events as they occurred.

[4] The highly rationalized nature of this domain makes this sort of documentation possible. It may be that this sort of analysis would be much more difficult to conduct in a domain which lacks the long history and explicit representations of procedures and concepts that is available for aviation.

[5] This action level description of the observed verbal behavior "oakland center united nine hundred request higher." is based on ethnographic constructs involving the syntax (who is being called, who is calling, nature of request) and semantics of communications with ATC.

[6] The flight plan is actually developed by company dispatchers rather than by the pilots themselves. The planning activity here does not concern the development of the flight plan itself, but what is required in order to fly the flight as planned.

[7] The latter part of this claim depends on company policy with respect to procedures that maximize fuel econony.

[8] On every flight segment one of the pilots is designated "pilot flying" and the other "pilot not flying." This distinction marks a high level division of labor. The pilot flying is responsible for the control of the aircraft while the pilot not flying is responsible for communications. Flight crews usually alternate in these roles from one flight segment to another.

[9] In this instance, the S/O is on another channel making his departure report. Among the crew up front, it is important to know who is listening to what when. Normal procedures require a crew member to notify the other members of the crew when he is not monitoring the primary ATC frequency.

[10] The Airman's Information Manual says, " Acknowledgement of frequency changes: When advised by ATC to change frequencies, acknowledge the instruction. If you select the new frequency without acknowledgement, the controller's workload is increased because he has no way of knowing whether you received the instruction or have had a radio communications failure. (FAR-AIM, 1989; Chapter 4, Para- 193, Section d).

[11] The format of the numbers and the knowledge of the frequencies allotted to VHF radio communications for ATC (from 118.0 to 135.95 MHz) make this an abbreviated but unambiguous statement of the frequency, one hundred thirty two point eight MHz.

[12] D.A. Norman, personal communication.

[13] This is in part because training is expensive and does not generate any revenue. Operators thus have a strong economic incentive to get pilots out of the training system and into revenue operations as soon as is legally possible. Several months of actual flying experience seem to lie between legal qualification and real mastery of the cockpit.

[14] The syntax of the initial contact with a controller is spelled out in the Airman's

Information Manual Chapter 4, Section 7, Paragraph 340: ARTCC communications.

[15] Because the throttle levers are normally capped with balls, an alternate expression was "balls to the wall". In American automotive parlance, the equivalent expression is "pedal to the metal".