How a cockpit remembers its speeds

Edwin Hutchins

Distributed Cognition Laboratory
Department of Cognitive Science
University of California, San Diego

Introduction

Thirty years of research in cognitive psychology and other areas of cognitive science have given us powerful models of the information processing properties of individual human agents. The cognitive science approach provides a very useful frame for thinking about thinking. When this frame is applied to the individual human agent, one asks a set of questions about the mental processes that organize the behavior of the individual.[1] In particular one asks how information is represented in the cognitive system and how representations are transformed, combined, and propagated through the system (Simon, 1981). Cognitive science thus concerns itself with the nature of knowledge structures and the processes that operate on them. The properties of these representations inside the system and the processes that operate on representations are assumed to cause or explain the observed performance of the cognitive system as a whole.

In this paper I will attempt to show that the classical cognitive science approach can be applied with little modification to a unit of analysis that is larger than an individual person. One can still ask the same questions of a larger socio-technical system that one would ask of the individual. That is, we wish to characterize the behavioral properties of the unit of analysis in terms of the structure and processing of representations that are internal to the system. With the new unit of analysis, many of the representations can be observed directly, so in some respects, this may be a much easier task than trying to determine the processes internal to the individual that account for the individual's behavior. Posing these questions in this way reveals how systems that are larger than an individual may have cognitive properties in their own right that cannot be reduced to the cognitive properties of individual persons (Hutchins, 1995). Many of the outcomes that concern us on a daily basis are produced by cognitive systems of this sort.

Thinking of organizations as cognitive systems is not new, of course.[2] What is new is the examination of the role of the material media in which representations are embodied, and in the physical processes that propagate representations across media. Applying the cognitive science approach to a larger unit of analysis requires attention to the details of these processes as they are enacted in the concrete activities of real persons in interaction with real material media. The analysis presented here shows that structure in the environment can provide much more than external memory (Norman, 1993).

I will take the cockpit of a commercial airliner as my unit of analysis and will show how the cockpit system performs the cognitive tasks of computing and remembering a set of correspondences between airspeed and wing configurations. I will not present extended examples from actual observations because I don't know how to render such observations meaningful for a non-flying audience without swamping the reader in technical detail. Instead I will present a somewhat stylized account of the use of the small set of tools in the performance of this simple task that is accomplished every time an airliner makes an approach to landing.

The procedures described below come straight from the pages of a major airline's operations manual for a mid-sized jet, the McDonnell Douglas MD-80. Similar procedures exist for every make and model of airliner. The explanations of the

procedures are informed by my experiences as a pilot and as an ethnographer of cockpits. In conducting research on aviation safety during the past 6 years,[3] I have made over 100 flights as an observer member of crew in the cockpits of commercial airliners. These observations span the range of old and new technology cockpits, domestic and international (trans-oceanic) operations, and both foreign and US-flag carriers.

Applying the Cognitive Frame to the Cockpit System

If we want to explain the information processing properties of individuals, we have no choice but to attempt to infer what is inside the individual. Cognitive scientists do this by constructing careful contexts for eliciting behavior in which they can attribute internal states to actors. However, if we take the cockpit system as the unit of analysis, we can look inside it and directly observe many of the phenomena of interest. In particular, we can directly observe the many representations that are inside the cockpit system, yet outside the heads of the pilots. We can do a good deal of research on the cognitive properties of such a system (that is, we can give accounts of the system's behavioral properties in terms of its internal representations), without saying anything about the processes that operate inside individual actors (Hutchins, 1990, 1991, 1995). This suggests that rather than trying to map the findings of cognitive psychological studies of individuals directly onto the individual pilots in the cockpit, we should map the conceptualization of the cognitive system onto a new unit of analysis: the cockpit as a whole.

Remembering Speeds

Why Speeds Must be Remembered

As an illustration of the application of the cognitive science frame to the cockpit system, consider the events having to do with the remembrance of speeds in the cockpit of a midsize civil transport jet (a McDonnell Douglas MD-80) on a typical descent from a cruise altitude above 30,000 feet, followed by an instrument landing system (ILS) approach and landing. Virtually all of the practices described in this paper are mandated by federal regulations and/or airline policy. A reader may wonder "how many crews do these things" The answer is that very nearly all of them do these things on every flight. Exceptions are extremely rare. In all of my observations, I have never seen a crew fail to compute and set the approach speeds. This is what is known in the aviation world as a "killer" item. It is something that can cause a fatal accident if missed. Of course, sometimes crews do miss these items, and sometimes they make headlines as a result. To understand what the task is and how it is accomplished one needs to know something about the flight characteristics of commercial jet transports and something about the mandated division of labor among members of the crew.

Flaps and Slats

The wings of airliners are designed to enable fast flight, yet performance and safety considerations require airliners to fly relatively slowly just after takeoff and before

landing. The wings generate ample lift at high speeds, but the shapes designed for high speed cannot generate enough lift to keep the airplane flying at low speeds. In order to solve this problem, airplanes are equipped with devices, called slats and flaps,[4] that change the shape and area of the wing. Slats and flaps are normally retracted in flight, giving the wing a very clean aerodynamic shape. For slow flight, slats and flaps are extended, enlarging the wing and increasing its coefficient of lift. The positions of the slats and flaps define *configurations* of the wing. In a "clean" wing configuration, the slats and flaps are entirely retracted. There is a lower limit on the speed at which the airplane can be flown in this configuration. Below this limit, the wing can no longer produce lift. This condition is called a wing stall.[5] The stall has an abrupt onset and invariably leads to loss of altitude. Stalls at low altitude are very dangerous. The *minimum maneuvering speed* for a given configuration and aircraft weight is a speed that guarantees a reasonable margin of safety above the stall speed. Flying slower than this speed is dangerous because the airplane is nearer to a stall.   Changing the configuration of the wing by extending the slats and flaps lowers the stall speed of the wing, thus permitting the airplane to fly safely at slower speeds. As the airplane nears the airport, it must slow down to maneuver for landing. In order to maintain safe flight at slower speeds, the crew must extend the slats and flaps to produce the appropriate wing configurations at the right speeds. The coordination of changing wing configuration with changing speed as the airplane slows down is the first part of the speed memory task. The second part involves remembering the speed at which the landing is to be made.

V_{ref}

Within the range of speeds at which the airplane can be flown in its final flap and slat configuration, which speed is the right speed for landing? There are tradeoffs in the determination of landing speed. High speeds are safe in the air because they provide good control response and large stall margins, but they are dangerous on the ground. Limitations on length of runway, energy to be dissipated by braking, and the energy to be dissipated if there is an accident on landing, all suggest that landing speed should be as slow as is feasible. The airplane should be traveling slowly enough that it is ready to quit flying when the wheels touch down, but fast enough that control can be maintained in the approach and fast enough that if a landing cannot be made, there is enough kinetic energy in the airplane to climb away from the ground. This speed is called the reference speed, or V_{ref}. Precise control of speed at the correct value is essential to a safe landing.

The minimum maneuvering speeds for the various wing configurations and the speed for landing (called the reference speed) are tabulated in the FLAP/SLAT CONFIGURATION MIN MAN AND REFERENCE SPEED table (Table 1.) If weight were not a factor, there would be only one set of speeds to remember and the task would be much simpler.

<insert Table 1 about here>

Crew Division of Labor

All modern jet transports have two pilot stations, each equipped with a complete set of flight instrumentation. While the airplane is in the air, one pilot is designated the

pilot flying (PF) and other is the pilot not flying (PNF). These roles carry with them particular responsibilities with respect to the conduct of the flight. The pilot flying is concerned primarily with the control of the airplane. The PNF communicates with air traffic control (ATC), operates the aircraft systems, accomplishes the checklists required in each phase of flight, and attends to other duties in the cockpit.

Three Descriptions of Memory for Speeds

With an understanding of the problem and the basics of crew organization we can now examine the activities in the cockpit that are involved with the generation and maintenance of representations of the maneuvering and reference speeds. Here I will provide three descriptions of the same activities. The first description is procedural. It is the sort of description that a pilot might provide. The second and third descriptions are cognitive in the sense that they concern representations and processes that transform those representations. The second description treats the representations and processes that are external to the pilots. This description provides the constraints for the final description of the representations and processes that are presummed to be internal to the pilots.

A Procedural Description of Memory for Speeds

Prepare the landing data. After initiation of the descent from cruise altitude and before reaching 18,000 feet, the PNF should prepare the landing data. This means to compute the correspondences between wing configurations and speeds for the projected landing weight. The actual procedure followed depends on the materials available, company policy, and crew preferences.[6] For example, many older cockpits use the table in the operations manual (Table 1) and a hard plastic landing data card on which the arrival weather conditions, the go-around thrust settings, the landing gross weight, and the landing speeds are indicated with a grease pencil. Still others use the table in the operations manual and write the speeds on a piece of paper (flight paperwork, printout of destination weather, etc.). Crews of airplanes equipped with flight management computer systems can look up the approach speeds on a page display of the computer. The MD-80 uses a booklet of *speed cards*. The booklet contains a page for each weight interval (usually in 2,000 pound increments) with the appropriate speeds permanently printed on the card (Figure 1).

MANEUVERING

FLAPS/SLATS SPEED

FLAPS/SLATS		SPEED
0/RET	**-**	**227**
0/EXT	**-**	**177**
11	-	155
15	-	152
28	-	142
40	-	137

VREF

28/EXT	**-**	**132**
40/EXT	**-**	**128**

122,000 LBS

Figure 1. A speed card from an MD-80 speed card booklet.

The preparation of landing data consists of the following steps:

1) Determine the gross weight of the airplane and select the appropriate card in the speed card booklet. Airplane gross weight on the MD-80 is continuously computed and displayed on the fuel quantity indicator on the center flight instrument panel (Figure 2).

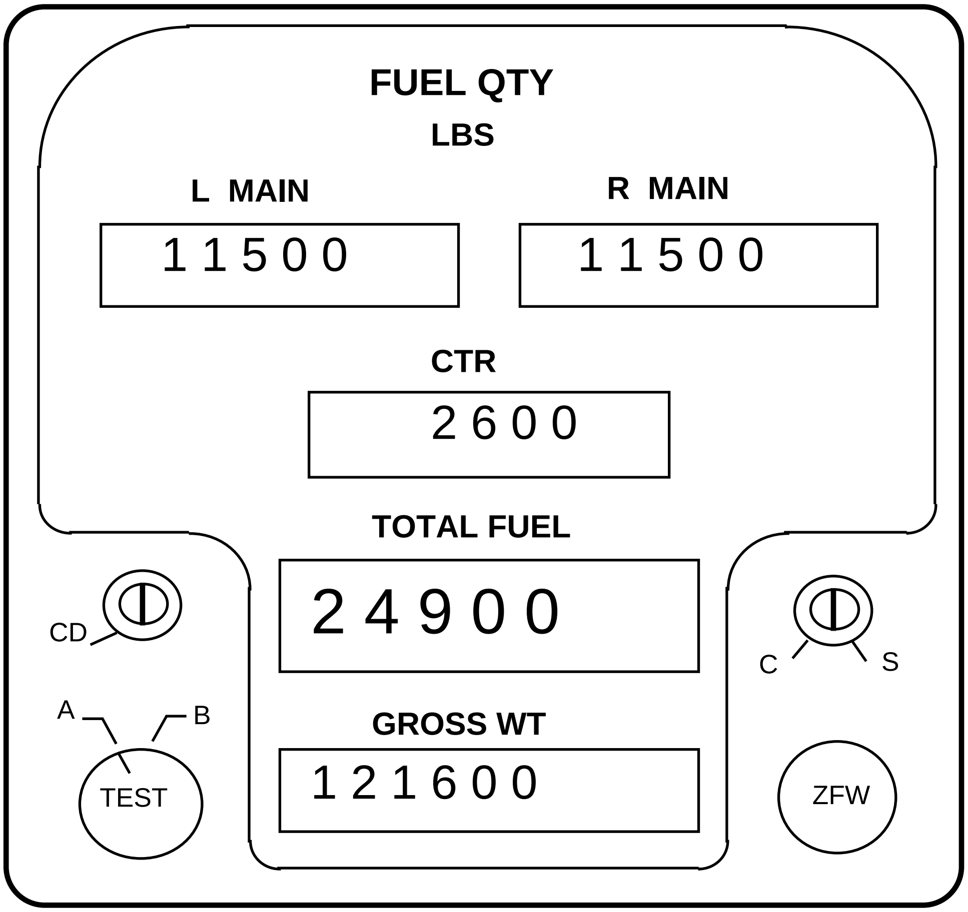

Figure 2. The fuel quantity indicator.

2) Post the selected speed card in a prominent position in the cockpit.

3) Set the speed bugs on both airspeed indicator (ASI) instruments (Figure 3) to match the speeds shown on the speed card.

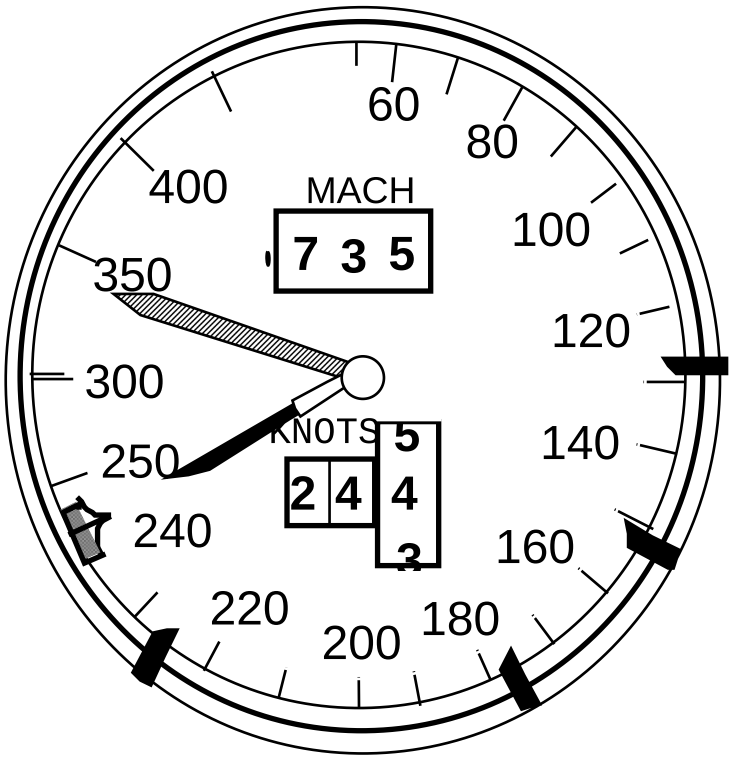

Figure 3. Speed bugs. This illustration is modeled on the airspeed indicator instrument in the McDonnell Douglas MD-80, as described by Teeney, 1988.

On the instrument depicted in figure 3, the airspeed is shown both in knots (the black-tipped dial pointer indicating 245) and Mach (the digital indicator showing 0.735). The striped indicator at 348 knots indicates the maximum permissible indicated air speed (IAS). The four black speed bug pointers on the edge of the dial are external to the instrument and are manually set by sliding them to the desired positions.   The other speed bug (called the "salmon bug" for its orange color) is internal to the instrument and indicates the speed commanded to the flight director and/or the autothrottle system (which is shown differing from the indicated airspeed by about 2 knots).

Starting with the bug at 227 knots and moving counterclockwise, the bugs indicate: 227—the minimum maneuvering speed with no flaps or slats extended; 177— minimum maneuvering speed with slats, but no flaps, extended; 152— minimum maneuvering speed with flaps at 15° and slats extended; 128—landing speed with flaps at 40° and slats extended (also called V_{ref}).

The preparation of the landing data is usually performed about 25 to 30 minutes prior to landing. The speed bugs are set at this time because at this point crew workload

is relatively light and the aircraft is near enough to the destination to make accurate projections of landing gross weight. Later in the approach, the crew workload increases dramatically.

The descent. During the descent and approach, the airplane will be slowed in stages from cruise speed to final approach speed.

Before descending through 10,000 feet MSL (mean sea level), the airplane must slow to a speed at or below 250 KIAS (knots indicated air speed). This speed restriction exists primarily to give pilots more time to see and avoid other traffic as the big jets descend into the congested airspace of the terminal area and into the realm of small, slow, light aircraft which mostly stay below 10,000 feet.

At about 7,000 feet AFL (above field level) the crew must begin slowing the airplane to speeds that require slat and flap extension. At this point they use the previously set external speed bugs on the ASI as indicators of where flap extension configuration changes should be made. Some companies specify crew coordination cross-checking procedures for the initial slat selection. For example, "After initial slat selection (0°/EXT), both pilots will visually verify that the slats have extended to the correct position (slat TAKEOFF light on) before reducing speed below 0/RET Min Maneuver speed..."

Since it is dangerous to fly below the minimum maneuvering speed for any configuration, extending the flaps and slats well before slowing to the minimum maneuvering speed might seem to be a good idea. Doing so would both increase the safety margin on the speeds and give the pilots a wider window of speed (and therefore of time) for selecting the next flap/slat configuration. Unfortunately, other operational considerations rule this out. As one operations manual puts it, "To minimize the air loads on the flaps/slats, avoid extension and operation near the maximum airspeeds. Extend Flaps/Slats near the Min Maneuver Speed for the Flap/Slat configuration." The extension of the flaps and slats must be coordinated fairly precisely with the changes in airspeed. This makes the accurate memory of the speeds even more important than it would otherwise be.

The crew must continue configuration changes as the airplane is slowed further.

The final approach. After intercepting the glide slope and beginning the final approach segment, the crew will perform the final approach checklist. One of the elements of this checklist is the challenge/response pair, "Flight instruments and bugs/ Set and cross-checked."

The PNF reads the challenge and both pilots check the approach and landing bug positions on their own ASI against the bug position on the other pilot's ASI and against the speeds shown on the speed card. Both crew members will verbally confirm that the bug speeds have been set and cross checked. For example, the captain (who sits in the left seat) might say, "Set on the left and cross-checked" while the first officer would say, "Set on the right and cross-checked." A more complete cross-check would include a specification of the actual value. (e.g., "One thirty two and one twenty seven set on the left and cross-checked")

At about 1,000 feet AFL, the crew will select the final flap setting of 28° or 40°, and maintain the approach speed.

At 500 feet AFL, the PNF calls out the altitude, the airspeed relative to the approach airspeed, and the descent rate. For example, "Five hundred feet, plus four, seven down," meaning, 500 feet above the field elevation, 4 knots faster than desired approach speed, descending at 700 feet per minute. The pilot not-flying may also specify relation to the glide slope, indicating whether the airplane is below, on, or above the glide slope.

Once final flaps are set on the final approach segment, the PNF calls out airspeed whenever it varies more than plus or minus 5 knots from approach speed.

A Cognitive Description of Memory for Speeds — Representations and Processes Outside the Pilots

Let us now apply the cognitive science frame to the cockpit as a cognitive system. How are the speeds represented in the cockpit? How are these representations transformed, processed and coordinated with other representations in the descent, approach, and landing? How does the cockpit system remember the speeds at which it is necessary to change the configuration of the wing in order to maintain safe flight?

The observable representations directly involved in the cockpit processes that coordinate airspeed with flap and slat settings are: the gross weight display (Figure 2), the speed card booklet (Figure 1), the two airspeed indicator instruments with internal and external bugs (Figure 3), the speed select window of the flight guidance control panel, and the speed-related verbal exchanges among the members of the crew. The speed-related verbalizations may appear in the communication of the values from PNF to PF while setting the speed bugs, in the initial slat extension cross-check, in the subsequent configuration changes, in the cross-check phase of the before-landing checklist performance, in the PNF's approach progress report at 500 feet AFL, and in any required speed deviation call outs on the final approach segment after the selection of the landing flap setting.

In addition to the directly observable media listed above, we may also assume that some sort of representation of the speeds has been created in two media that are not directly observable: the memories of the two pilots themselves. Later we will consider in detail the task environment in which these memories may form. For now let us simply note that these mental memories are additional media in the cockpit system which may support and retain internal representations of any of the available external representations of the speeds.

Accessing the speeds and setting the bugs. The speed card booklet is a long-term memory in the cockpit system. It stores a set of correspondences between weights and speeds that are functionally durable in the sense that they are applicable over the entire operating life of the airplane. The weight/speed correspondences represented in the printed booklet are also physically durable in the sense that short of destroying the physical medium of the cards, the memory is nonvolatile and cannot be corrupted. This memory is not changed by any crew actions. (It could be misplaced, but there is a

backup in the form of the performance tables in the operating manual.) The appropriate speeds for the airplane are determined by bringing the representation of the airplane gross weight into coordination with the structure of the speed card booklet. The gross weight is used as a filter on this written memory, making one set of speeds much more accessible than any other. The outcome of the filtering operation is imposed on the physical configuration of the speed card booklet by arranging the booklet such that the currently appropriate speed card is the only one visible. Once performed, the filtering need not be done again during the flight.

The physical configuration of the booklet produced by opening it to the correct page becomes a representation of the cockpit system's memory for both the projected gross weight and the appropriate speeds. That is, the questions, "Which gross weight did we select?" and "What are the speeds for the selected weight?" can both be answered by reading the visible speed card. The correspondence of a particular gross weight to a particular set of speeds is built into the physical structure of each card by printing the corresponding weight and speed values on the same card. This is a simple but effective way to produce the computation of the speeds, since selecting the correct weight can't help but select the correct speeds.

Posting the appropriate speed card where it can easily be seen by both pilots creates a distribution (across social space) of access to information in the system that may have important consequences for several kinds of subsequent processing. Combined with a distribution of knowledge that results from standardized training and experience, this distribution of access to information supports the development of redundant storage of the information and redundant processing. It also creates a new trajectory by which speed-relevant information may reach the PF. Furthermore, posting the speed card provides a temporally enduring resource for checking and cross checking speeds so that these tasks can be done (or redone) at any time. And since the card shows both a set of speeds and the weight for which the speeds are appropriate, it also provides a grounds for checking the posted gross weight against the displayed gross weight on the fuel quantity panel (Figure 2), which is just a few inches above the normal posting position of the speed card. This is very useful in deciding whether the wrong weight, and therefore the wrong speeds, may have been selected.

In addition to creating a representation of the appropriate speeds in the configuration of the speed card booklet, the PNF creates two other representations of the same information: the values are represented as spoken words when the PNF tells the PF what the speeds are, and the speeds are represented on the airspeed indicator in the positions of the speed bugs.

By announcing aloud the values to be marked, the PNF both creates yet another representation of the speeds, and notifies the PF that the activity of setting the speed bugs should commence at this time. Unlike the printed speed card, the verbal representation is ephemeral. It has no endurance in time. If it is to be processed, it must be attended to at the time it is created. The required attending can be handled by auditory rather than visual resources, and the latter are often over-taxed while the former are often under-utilized in the cockpit.[7] By reading back the values heard, the PF creates yet another representation that allows the PNF to check on the values being used by the PF to set the PF's bugs.

The PF may make use of any of the representations the PNF has created in order to create a representation of the bug speeds on the PF's airspeed indicator. The spoken representation and the speed card provide the PF's easiest access to the values although it is also possible for the PF to read the PNF's airspeed indicator. Since all of these representations are available simultaneously, there are multiple opportunities for consistency checks in the system of distributed representation.

When the pilots set the speed bugs, the values that were listed in written form on the speed card and were represented in spoken form by the PNF are re-represented as marked positions adjacent to values on the scale of the airspeed indicator (ASI). Since there are two ASI's, this is again a redundant representation in the cockpit system. And it provides a distribution of access to information that will be taken advantage of in later processes.

The external speed bug settings capture a regularity in the environment that is of a shorter time scale than the weight/speed correspondences that are represented in the speed card booklet. The speed bug settings are a memory that is malleable, and that fits a particular period of time (this approach). Because of the location of the ASI and the nature of the bugs, this representation is quite resistant to disruption by other activities.

Using the configuration change bugs. The problem to be solved is the coordination of the wing configuration changes with the changes in airspeed as the airplane slows to maneuver for the approach. The location of the airplane in the approach and or the instructions received from ATC determine the speed to be flown at any point in the approach. The cockpit system must somehow construct and maintain an appropriate relationship between airspeed and slat/flap configuration. The information path that leads from indicated airspeed to flap/slat configuration includes several observable representations in addition to the speed bugs.

The airspeed is displayed on the ASI by the position of the airspeed indicator needle. Thus, as the ASI needle nears the speed bug that represents the clean-configuration minimum maneuvering speed, the pilot flying can call for "Flaps 0." The spoken flap/slat setting name is coordinated with the labels on the flap handle quadrant. That is, the PNF positions the flap handle adjacent to the label that matches (or is equivalent to) the flap/slat setting name called by the PF. Movement of the flap handle then actuates the flaps and slats themselves which produce the appropriate wing configurations for the present speed. The contribution of the speed bugs to this process is to provide the bridge between the indicated airspeed and the name of the appropriate flap/slat configuration for the aircraft at its present gross weight.

The cockpit procedures of some airlines require that the configuration that is produced by the initial extension of slats be verified by both crew members (by reference to an indicator on the flight instrument panel) before slowing below the clean MinMan speed. This verification activity provides a context in which disagreements between the settings of the first speed bug on the two ASIs can be discovered. It also may involve a consultation with the speed card by either pilot to check the MinMan speed, or even a comparison of the weight indicated by the selected speed card and the airplane gross weight as displayed on the fuel quantity panel. The fact that these other checks are so easy to perform with the available resources highlights the fact that the physical

configuration of the speed card is both a memory for speed, and a memory for a decision that was made earlier in the flight about the appropriate approach speed. Any of these activities may also refresh either pilot's internal memory for the speeds or the gross weight. The depth of the processing engaged in here, that is, how many of these other checks are performed, may depend on the time available and the sense the pilots have of things going well or not. It is probably not possible to predict how many other checks may be precipitated by this mandated cross check, but it is important to note that several are possible and may be occasioned here.

When the pilot flying calls for a configuration change, the PNF can (and should) verify that the speed is appropriate for the commanded configuration change. The mandated division of labor in which the PF calls for the flap setting, and the PNF actually selects it by moving the flap handle, permits the PF to keep hands on the yoke and throttles during the flap extension. This facilitates airplane control because changes in pitch attitude normally occur during flap extension. It is likely that this facilitation of control was the original justification for this procedure. However, this division of labor also has a very attractive system-level cognitive side effect in that it provides for additional redundancies in checking the bug settings and the correspondences between speeds and configuration changes.

Using the salmon bug. On the final approach the salmon bug provides the speed reference for both pilots, as both have speed related tasks to perform. The spatial relation between the ASI needle and the salmon bug provides the pilots with an indication of how well the airplane is tracking the speed target, and may give indications of the effects on airspeed of pitch changes input by the crew (or other autoflight systems in tracking the glide slope during a coupled approach) or of local weather conditions such as windshear.

The salmon bug is also the reference which the PNF computes the deviation from target speed. The PNF must make the mandatory call out at 500 feet AFL, as well as any other call outs required if the airspeed deviates more than five knots from the target approach speed. In these call outs, the trajectory of task-relevant representational state is from the relationship between the ASI needle and the salmon bug to a verbalization by the PNF directed to the PF. Since the final approach segment is visually intensive for the PF, the conversion of the airspeed information from the visual into the auditory modality by the PNF permits the PF access to this important information without requiring the allocation of precious visual resources to the ASI.

Summary of representations and processes outside the pilot.. Setting the speed bugs is a matter of producing a representation in the cockpit environment that will serve as a resource that organizes performances that are to come later. This structure is produced by bringing representations into coordination with one another (the gross weight readout, the speed card, the verbalizations, etc.) and will provide representational state (relations between speed bug locations and ASI needle positions) that will be coordinated with other representations (names for flap positions, flap handle quadrant labels, flap handle positions, etc.) ten to fifteen minutes later when the airplane begins slowing down. I call this entire process a cockpit system's "memory" because it consists of the creation, inside the system, of representational state that is then saved and used to organize subsequent activities

A Cognitive Description of Memory for Speeds — Representations and Processes Inside the Pilots

Having described the directly observable representational states involved in the memory for speeds in the cockpit system during the approach, let us return and ask of that same cycle of activity, "What are the cognitive tasks facing the pilots?"

The description of transformations of representational state provided in the previous section is both a description of how the system processes information and a specification of cognitive tasks facing the individual pilots. It is, in fact, a better cognitive task specification than can be had by simply thinking in terms of procedural descriptions. The task specification is detailed enough in some cases to put constraints on the kinds of representations and processes that the individuals must be using.

In much of the cockpit's remembering, significant functions are achieved by a person interpreting material symbols, rather than by a person recalling those symbols from his or her memory. So we must go beyond looking for things that resemble our expectations about human memory in order to understand the phenomena of memory in the cockpit as a cognitive system.

Computing the speeds and setting the bugs. The speeds are actually computed by pattern matching on the airplane gross weight and the weights provided on the cards. The pilots don't have to remember what the weights are that appear on the cards. It is only necessary to find the place of the indicated gross weight value in the cards that are provided. However, repeated exposures to the cards may lead to implicit learning of the weight intervals, and whatever knowledge of this sort that does form may be used as a resource in selecting the appropriate speed card for any given gross weight. With experience pilots may develop internal structures to coordinate with predictable structure in the task environment.

Once the appropriate card has been selected, the values must be read from the card. Several design measures have been taken to facilitate this process. Frequently used speeds appear in larger font size than do infrequently used speeds and there is a box around the Vref speeds to help pilots find these values. (Wickens & Flach, 1988). Reading is probably an over-learned skill for most pilots. Still, there is a need for working memory — transposition errors are probably the most frequent sort of error committed in this process (Norman, 1991; Wickens & Flach, 1988).

Setting any single speed bug to a particular value requires the pilot to hold the target speed in memory, read speed scale, locate the target speed on the speed scale (a search similar to the search for weight in the speed card booklet), and then manually move the speed bug to the scale position. Since not all tick marks on the speed scale have printed values adjacent to them, some interpolation or counting of ticks is also required.

Coordinating reading the speeds with setting the bugs is a more complicated activity. The actions of reading and setting may be interleaved in many possible orders. One could read each speed before setting it or read several speeds, hold them in memory, and then set them one by one. Other sequences are also possible. The demands on

working memory will depend on the strategy chosen. If several speeds are to be remembered and then set, they may be rehearsed to maintain the memory. Such a memory is quite vulnerable to interference from other tasks in the same modality (Wickens & Flach, 1988), and the breakdown of such a memory may lead to a shift to a strategy that has less severe memory requirements.

The activities involved in computing the bug speeds and re-representing them in several other media may permit them to come to be represented in a more enduring way in the memory of the PNF. Similarly, hearing the spoken values, possibly reading them from the landing data card, and setting them on the airspeed indicator may permit a more enduring representation of the values to form in the memory of the PF. Lacking additional evidence, we cannot know the duration or quality of these memories. But we know from observation that there are ample opportunities for rehearsals and associations of the rehearsed values with representations in the environment.

Using the configuration change bugs. The airspeed indicator needle moves counter-clockwise as the airplane slows. Since the airspeed scale represents speed as spatial position and numerical relations as spatial relations, the airspeed bugs segment the face of the ASI into regions that can be occupied by the ASI needle. The relation of the ASI needle to the bug positions is thus constructed as the location of the airplane's present airspeed in a *space of speeds*. The bugs are also associated with particular flap/slat setting names (e.g. 0°/RET, 15°/EXT, etc.) so the regions on the face of the ASI have meaning both as speed regimes and as locations for flap/slat setting names. Once the bugs have been set, the pilots do not simply take in sensory data from the ASI, rather the pilots impose additional meaningful structure on the image of the ASI. They use the bugs to define regions of the face of the ASI, and they associate particular meanings with those regions (Figure 4). The coordination of speed with wing configuration is achieved by superimposing representations wing configuration and representation of speed on the same instrument.

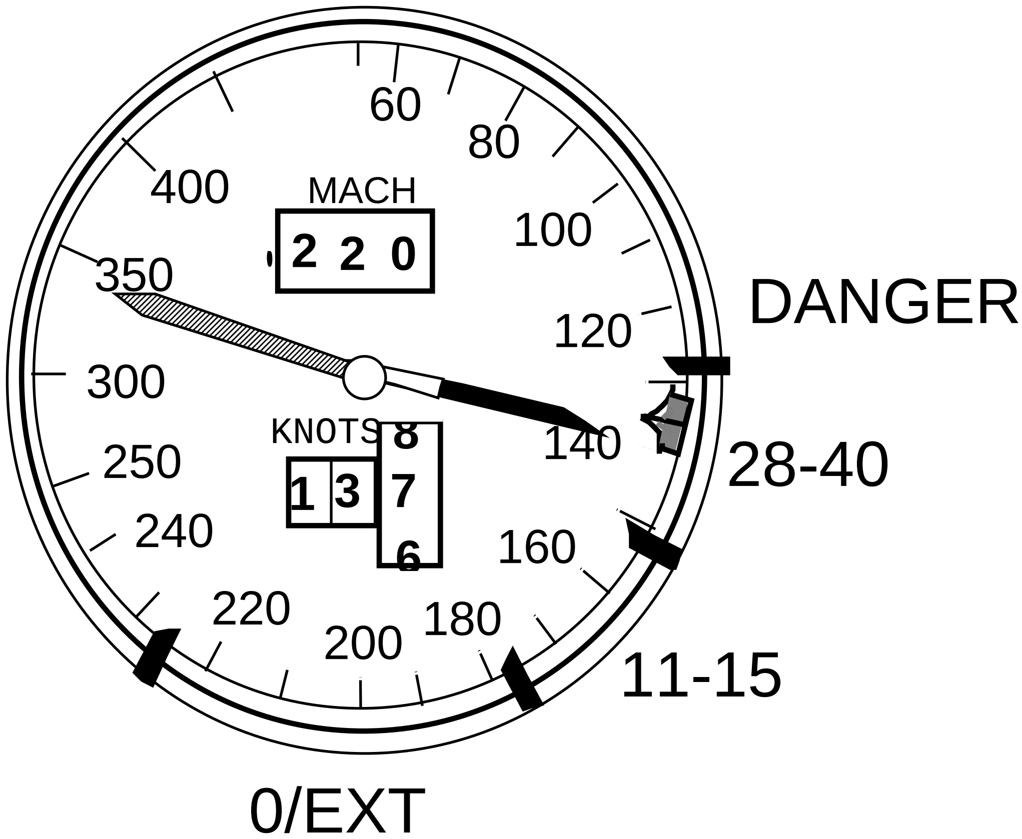

Figure 4. Meaningful regions of the airspeed indicator face. The pilots “see” regions of the airspeed indicator scale as having meanings in terms of the configurations required to fly the airplane at the speeds in each region.

Once the bugs are set, it is not necessary to actually read the scale values at which they are placed, but it is necessary to remember the meanings of each of the bugs with respect to names for flap/slat configurations. Since the regions of speed scale that are associated with each configuration are not permanently marked on the jet ASI, the pilot must construct the meanings of the regions in the act of "seeing" the ASI with bugs as a set of meaningful regions.

Speed bugs are part of what Luria called a functional system (Luria, 1979). It is a constellation of structures, some of them internal to the human actors, some external, involved in the performance of some invariant task. It is commonplace to refer to the speed bug as a memory aid (Norman, 1991; Tenney, 1988). They are said to help the pilot remember the critical speeds. But now that we have looked at how speed bugs are setup and how they are used, it is not so clear that they contribute to the pilot's memory at all. The functional system of interest here is one that controls the coordination of airspeeds with wing configurations. It is possible to imagine a functional system without speed bugs in which pilots are required to read the speeds, remember the speeds, remember which configuration change goes with each speed, read the scale, etc. Adding speed bugs to the system does nothing to alter the memory of the pilots, but it does permit

a different set of processes to be assembled into a functional system that achieves the same results as the system without speed bugs. In the functional system with speed bugs, some of the memory requirements for the pilot are reduced. What was accomplished without speed bugs by remembering speed values, reading the ASI needle values and comparing the two values is accomplished with the use of speed bugs by judgments of spatial proximity. Individual pilot memory has not been enhanced; rather, the memory function is now a property of a larger system in which the individual engages in a different sort of cognitive behavior. The beauty of devices like speed bugs is that they permit these reconfigurations of functional systems in ways that reduce the requirements for scarce cognitive resources. To call speed bugs a "memory aide" for the pilots is to mistake the cognitive properties of the reorganized functional system for the cognitive properties of one of its human components. Speed bugs do not help *pilots* remember speeds, rather they are part of the process by which the *cockpit system* remembers speeds.

Using the salmon bug. Without a speed bug, on final approach the PF must remember the approach speed, read the airspeed indicator scale to find the remembered value of the approach speed on the airspeed indicator scale, and compare the position of the ASI needle on the scale with the position of the approach speed on the scale. With the salmon bug set, the pilot no longer needs to read the airspeed indicator scale. One simply looks to see whether or not the indicator needle is lined up with the salmon bug. Thus a memory and scale reading task is transformed into a judgment of spatial adjacency. It is important to make these tasks as simple as possible because there are many other things to be done on the final approach. The pilot must continue monitoring the airspeed while also monitoring the glide path and runway alignment of the aircraft. Deviations in any of these may require corrective actions.

In making the required speed call outs, the PNF uses the salmon bug in a way similar to the PF. In order to determine the numerical relation between the indicated speed and the setting of the salmon bug, the PNF could use mental arithmetic and subtract the current speed from the value of *Vref*. This is the sort of cognitive task we might imagine to be facing the crew if we simply examined the procedural description. A less obvious, but equally effective method is to use the scale of the ASI as a computational medium. The base of the salmon bug is about ten knots wide in the portion of the speed scale relevant to maneuvering for approach and landing. To determine if the current speed is within 5 knots of the target, one need only see if the airspeed pointer is pointing at any part of the body of the salmon bug. This strategy permits a conceptual task to be implemented by perceptual processes.

Having determined the deviation from target speed, the PNF calls it out to the PF. Notice the role of the representation of information. Twice in this example, a change in the nature of the representation of information results in a change in the nature of the cognitive task facing the pilot. In the first case, the speed bug itself permits a simple judgment of spatial proximity to be substituted for a scale reading task operation. In the second case, the PNF further transforms the task facing the PF from a judgment of spatial proximity (requiring scarce visual resources) into a task of monitoring a particular aural cue (a phrase like "five knots fast"). Notice also that the change in the task for the pilot flying changes the kinds of internal knowledge structures that must be brought into play in order to decide on an appropriate action.

The pilot's memory for speeds. Memory is normally thought of as a psychological function internal to the individual. However, memory tasks in the cockpit may be accomplished by functional systems which transcend the boundaries of the individual actor. Memory processes may be distributed among human agents, or between human agents and external representational devices.

In some sense the speeds **are** being remembered by the crew. Partly, I suspect, in the usual sense of individual internal memory. But the speeds are also being read, written, and compared to other speeds in many representations. They are being compared to long-term memories for the typical or expected speeds for a plane of this specific weight. The comparison might be in terms of numbers, i.e. "Is 225 KIAS a fast or a slow speed for initial flap extension?" The comparison could also take place in terms of the number in the pilot's head, or on the landing data card, or on the position of the first bug on the airspeed indicator, or all of these together.

In this setting, the pilot's memory of these speeds may be a richly interwoven fabric of interaction with many representations that seem superficial or incomplete, compared to the compact localized internal memory that cognitive scientists usually look for. The memory observed in the cockpit is a continual interaction with a world of meaningful structure. The pilots are continually reading and writing, reconstituting and reconstructing the meaning and the organization of both the internal and the external representations of the speeds. It is not just the retrieval of something from an internal storehouse, and not just a recognition or a match of an external form to an internally stored template. It is, rather, a combination of recognition, recall, pattern matching, cross modality consistency checking, construction and reconstruction that is conducted in interaction with a rich set of representational structures, many of which permit but do not demand the reconstruction of some internal representation that we would normally call the "memory" for the speed.

In the cockpit's memory for speeds we see many examples of opportunistic use of structure in the environment. Some of these were never anticipated by designers. Using the width of the salmon bug as a yardstick in local speed space is a wonderful example. The engineer who wrote the specifications for the airspeed indicator in the Boeing 757/767 reported to me that the width of the base of the command airspeed pointer (salmon bug) is not actually spelled out in the specifications. The width of the tip of the pointer is explicitly specified, but the width of the base is not. On engineering drawings, the base is shown just fitting between the large ticks at ten-knot intervals on the scale. The engineers say it has this width so that it will be easy to find, but will never obscure more than one large tick mark at a time. If it covered more than one large tick mark, it might make it difficult to interpolate and read speeds. That constraint solves a design problem for the engineers that the pilots never notice (because the difficulty in reading the scale that would be caused by a wider bug never arises) and provides a bit of structure in the world for the pilots that can be opportunistically exploited to solve an operational problem that the designers never anticipated.

Cognitive Properties of the Cockpit System

The task is to control the configuration of the airplane to match the changes in speed required for maneuvering in the approach and landing. The flaps are controlled by positioning the flap handle. The flap handle is controlled by aligning it with written labels for flap positions that correspond to spoken labels produced by the PF. The spoken labels are produced at the appropriate times by speaking the name of the region on the ASI face that the needle is approaching. The regions of the ASI are delimited by the settings of the speed bugs. The names of the regions are produced by the PF through the application of a schema for seeing the dial face. The speed bugs are positioned by placing them in accordance with the speeds listed on the selected speed card. And the speed card is selected by matching the weight printed on the bottom with the weight displayed on the fuel quantity panel.

This system makes use of representations in many different media. The media themselves have very different properties. The speed card booklet is a relatively permanent representation. The spoken representation is ephemeral and endures only in its production. The memory is ultimately stored for use in the physical state of the speed bugs. It is temporarily represented in the spoken interchanges, and represented with unknown persistence in the memories of the individual pilots. The pilot's memories are clearly involved, but they operate in an environment where there is a great deal of support for recreating the memory.

Speed bugs are involved in a distribution of cognitive labor across social space. The speed bug helps the solo pilot by simplifying the task of determining the relation of present airspeed to V_{ref}, thereby reducing the amount of time required for eyes on the airspeed indicator during the approach. With multi-pilot crews, the cognitive work of reading the airspeed indicator, and monitoring the other instruments on the final approach can be divided among the pilots. The PF can dedicate visual resources to monitoring the progress of the aircraft, while the pilot not flying can use visual resources to monitor airspeed and transform the representation of the relation between current airspeed and V_{ref} from a visual into an auditory form.

Speed bugs permit a shift in the distribution of cognitive effort across time. They enable the crew to calculate correspondences between speeds and configurations during a low workload phase of flight, and save the results of that computation for later use. Internal memory also supports this redistribution of effort across time, but notice the different properties of the two kinds of representation; a properly set speed bug is much less likely than a pilot's memory to "forget" its value. The robustness of the physical device as a representation permits the computation of speeds to be moved arbitrarily far in time from the moment of their use and is relatively insensitive to interruptions, distractions, and delays that may disrupt internal memories.

This is a surprisingly redundant system. Not only is there redundant representation in memory, there is also redundant processing and redundant checking. The interaction of the representations in the different media gives the overall system the properties it has. This is not to say that knowing about the people is not important, but

instead to say that much of what we care about is in the *interaction* of the people with each other and with physical structure in the environment.

The analog ASI display maps an abstract conceptual quantity, speed, onto an expanse of physical space. This mapping of conceptual structure onto physical space allows important conceptual operations to be defined in terms of simple perceptual procedures. Simple internal structures (the meanings of the regions on the dial face defined by the positions of the speed bugs) in interaction with simple and specialized external representations perform powerful computations.

Discussion

The cockpit system remembers its speeds, and the memory process emerges from the activity of the pilots, but the memory of the cockpit is not made primarily of pilot memory. A complete theory of individual human memory would not be sufficient to understand that which we wish to understand because so much of the memory function takes place outside of the individual. In some sense, what the theory of individual human memory explains is not how this system works, but why this system must contain so many components that are functionally implicated in cockpit memory yet are external to the pilots themselves.

The speed bug is one of many devices in the cockpit that participate in functional systems which accomplish memory tasks. The altitude alerting system and the many pieces of paper that appear in even the most modern glass cockpit are other examples. The properties of functional systems that are mediated by external representations differ from those that rely exclusively on internal representations and may depend on the physical properties of the external representational media. Such factors as the endurance of a representation, the sensory modality via which it is accessed, its vulnerability to disruption, and the competition for modality specific resources may all influence the cognitive properties of such a system.

This paper presents a theoretical framework that takes a socio-technical system rather than an individual mind as its primary unit of analysis. This theory is explicitly cognitive in the sense that it is concerned with how information is represented and how representations are transformed and propagated through the system. Such a theory can provide a bridge between the information processing properties of individuals and the information processing properties of a larger system such as an airplane cockpit.

One of the primary jobs of a theory is to help us look in the right places for answers to questions. This system-level cognitive view directs our attention beyond the cognitive properties of individuals to the properties of external representations and to the interactions between internal and external representations. Technological devices introduced into the cockpit invariably affect the flow of information in the cockpit. They may determine the possible trajectories of information or the kinds of transformations of information structure that are required for propagation. Given the current rapid pace of

introduction of computational equipment, these issues are becoming increasingly important.

References:

de Montmollin, M. (1986). L'intelligence de la tâche: Eléments d'ergonomie cognitive (Deuxième ed.). Berne: Peter Lang.

Engestrom, Y. (1990). Learning, working and imagining: Twelve studies in activity theory. Helsinki: Orineta-Konsultit Oy.

Goodwin, C., & Goodwin, M. (in press). Formulating planes: seeing as situated activity. In D. Middleton & Y. Engestrom (Eds.), Cognition and communication at work. Cambridge University Press.

Gras, A., Moricot, C., Poirot-Delpech, S., & Scardigli, V. (1991). Le Pilote, le contrôleur, et l'automate (Réédition du rapport prédéfinition PIRTTEM - CNRS et du rapport final SERT - Ministère des transports. ed.). Paris: Editions de L'Iris.

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 Assc.

Hutchins, E. (1991). Organizing work by adaptation. Organization Science, 2(2).

Hutchins, E. (1995). Cognition in the wild. Cambridge, MA: MIT Press.

Luria, A. R. (1979). The making of mind: A personal account of Soviet psychology. (M. Cole & S. Cole, Trans.). Cambridge, MA: Harvard University Press.

March, J. & Simon, H. (1958) Organizations. New York: Wiley.

Morgan, G. (1986). Images of organization. Beverly Hills: Sage Publications.

Newell, A., & Simon, H. A. (1972). Human problem solving. Englewood Cliffs, NJ: Prentice Hall.

Norman, D. A. (1991). Cognitive science in the cockpit. CESERIAC Gateway, 2 (2), 1-6.

Norman, D. A. (1993). Things that make us smart. Addison Wesley.

Orr, J. (1990). Sharing knowledge, celebrating identity: Community memory in a service culture. In D. Middleton & D. Edwards (Eds.), Collective Remembering. London: Sage Publications.

Scribner, S. (1984). Studying working intelligence. In B. Rogoff & J. Lave (Eds.), Everyday cognition: Its development in social context Cambridge, MA: Harvard University Press.

Simon, H. A. (1981). The sciences of the artificial (2nd ed.). Cambridge, MA: MIT Press.

Simon, H. A., & Kaplan, C. A. (1989). Foundations of Cognitive Science. In M. Posner (Eds.), Foundations of cognitive science Cambridge, MA: MIT Press.

Suchman, L. (1987). Plans and situated actions: The problem of human-machine communication. New York: Cambridge University Press.

Tenney, D. C. (1988, December). Bug speeds pinpointed by autothrottles mean less jockeying but more thinking. Professional pilot, pp. 96-99.

Theureau, J. (1990). Introduction a l'etude du cours d'action: Un programme de recherche en ergonomie et anthropology cognitive. University Paris-Nord, Laboratoire Communication et Travail.

Webb, J. (1971). Fly the wing. Ames, Iowa: Iowa State University Press.

Wickens, C., & Flach, J. (1988). Information processing. In E. Wiener & D. Nagel (Eds.), Human factors in aviation. New York: Academic Press.

Acknowledgments

An initial analysis of speed bugs as cognitive artifacts was completed in November of 1988. Since then my knowledge of the actual uses of speed bugs and my understanding of their role in cockpit cognition has changed dramatically. Some of the ideas in this paper were presented in a paper titled "Information Flow in the Cockpit" at the American Institute for Aeronautics and Astronautics symposium, "Challenges in Aviation Human Factors: The National Plan," in Vienna, Virginia. The current draft also benefited from the comments of members of the Flight Deck Research Group of the Boeing Commercial Airplane Company and from the participants of the second NASA Aviation Safety/Automation program researchers meeting. Thanks to Hank Strub, Christine Halverson, and Everett Palmer for discussions and written comments on earlier versions of this paper.

This research was supported by grant NCC 2-591 from the Ames Research center of the National Aeronautics and Space Administration in the Aviation Safety/ Automation Program. Everett Palmer served as Technical Monitor.

Correspondence and requests for reprints should be sent to Edwin Hutchins, Department of Cognitive Science, University of California, San Diego, La Jolla, CA 92093-0515; or email to: hutchins@cogsci.ucsd.edu.

---

[1] This notion is widespread in cognitive science. See Simon & Kaplan, 1989. The canonical statement of what is currently accepted as the standard position appears in Newell & Simon, 1972. See also Wickens & Flach, 1988 for a direct application of this perspective to aviation.

[2] March and Simon staked out this territory with their seminal book, Organizations, in 1958. For a review of conceptions of organizations see Morgan, 1986.

[3] This research was performed under a contract from the flight human factors branch of the NASA Ames research center. In addition to my activities as an observer, I hold a commercial pilot certificate with multiengine and instrument airplane ratings. I have completed the transition training course (both ground school and full-flight) for the Boeing 747-400 and the ground schools for the McDonnell Douglas MD-88, and the Airbus A320. I am grateful to the Boeing Commercial Airplane group, McDonnell Douglas, and America West Airlines for these training opportunities.

[4] Slats are normally on the leading edge of the wing. Flaps normally on the trailing edge.

[5] This "stall" has nothing to do with the functioning of the engines. Under the right conditions, any airplane can stall with all engines generating maximum thrust.

[6] The procedural account given here has been constructed from in-flight observations, and from

analyses of video and audio recordings of crews operating in high fidelity simulators of this and other aircraft. The activities described here are further documented in airline operations manuals and training manuals, and in the manufacturer's operational descriptions. Since these manuals, and the documentation provided by the Douglas Aircraft company, are considered proprietary, the actual sources will not be identified. Additional information came from other published sources, e.g. , Webb, 1971; Tenney, 1988 and from interviews with pilots. There are minor variations among the operating procedures of various airline companies, but the procedure described here can be taken as representative of this activity.

[7] See Gras et al., 1991:49 ff for a discussion of the balance among the senses in the modern cockpit. Of course, aural attending may produce an internal representation that endures longer than the spoken words.