CHAPTER 14

Aviation

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Flying an aircraft is one of the greatest challenges to the cognitive capabilities of humans, involving as it does the knowledge of how to control a vehicle that defies the natural forces of gravity. From the standpoint of cognitive psychology, the task of flying will be considered from three different, but intersecting perspectives: the cognitive analysis of the different tasks a pilot must carry out (Seamster *et al.* 1997); a description of the physical characteristics of the aircraft system that is the focus of those tasks; and a representation of the pilot's information-processing structures that are most critical, in different combinations, to achieving those tasks. In this chapter, we first describe the physical characteristics of airplane flight that impose so heavily upon the pilot's cognitive capabilities. Then, after representing the pilot as an information-processing system, we proceed to describe the cognitive demands imposed by the following aviation task categories: aviating, navigating, communicating, and systems management. Within each category, we discuss ways in which the design of aircraft and of the airspace is evolving to remediate (but sometimes exacerbate) those demands. Then we address two general issues, falling within the purview of cognitive psychology, that transcend the different task categories: actions and tasks and the cognitive issues of automation.

THE AIRCRAFT AS A DYNAMIC SYSTEM

Effective control of any complex dynamic system depends upon the operator possessing an accurate *mental model* of the system from which to establish expectancies of system response to environmental and control inputs (Bellenkes *et al.* 1997; Moray 1997). The foundations of the mental model of the aircraft are based in its dynamics, represented schematically in Figure 14.1a, which presents a graphic presentation of the aircraft. Figure 14.1b presents a more schematic and abstract version of its dynamic elements. As shown in both figures, the aircraft can be characterized first by control of its *attitude* (orientation or rotation) in three-dimensional space, a vector defined by *pitch*, *bank* (or roll), and *yaw*. As shown in the middle row of Figure 14.1b, as the aircraft moves forward, its attitude parameters then produce rates of change, vertical velocity generally being influenced by

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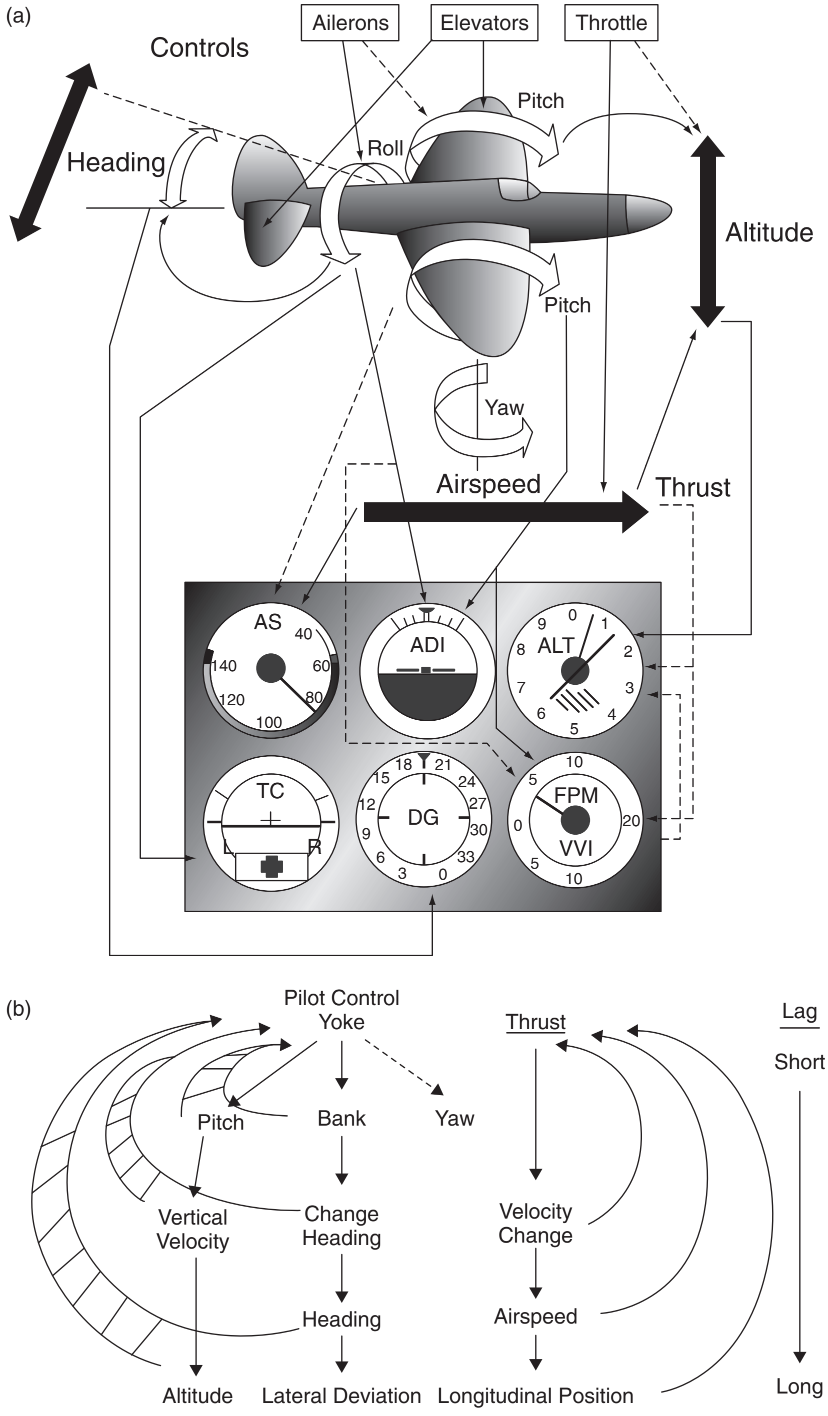
(a)
Ailerons
Elevators
Throttle
Controls
Heading
Roll
Pitch
Pitch
Altitude
Yaw
Airspeed
Thrust
AS
140
120
100
80
60
40
ADI
ALT
0
1
2
3
4
5
6
7
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TC
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18
21
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FPM
VVI
10
5
0
5
10
20
(b)
Pilot Control
Yoke
Pitch
Bank
Yaw
Vertical Velocity
Change Heading
Heading
Altitude
Lateral Deviation
Thrust
Velocity Change
Airspeed
Longitudinal Position
Lag
Short
Long

Figure 14.1 A representation of flight dynamics: (a) shows the relation between three flight control inputs (top boxes), the movement (heavy black arrows) and rotation (heavy white arrows) of the aircraft, and how these movements are displayed to the pilot in six critical flight instruments (bottom). Within the instrument panel, across the top row are displays of airspeed, attitude (pitch and bank) and altitude. Across the bottom row are displays of turning style, heading (compass) and vertical velocity. The thin dashed lines represent sources of "cross-coupling" between axes of flight. (b) Represents the flight axes in more schematic form. The pilot directly controls inner loop variables at the top, to affect control of middle and outer loop variables toward the bottom

pitch, and heading change being influenced primarily by roll. Changes in forward movement (acceleration) are primarily influenced by the thrust from the aircraft engines. As shown in the next row of Figure 14.1b, the changes along the vertical, heading, and forward motion (longitudinal) dimensions, produce new *positions* in altitude, heading, and airspeed. Finally, as shown in the bottom row, heading and airspeed produce lateral deviations (from a desired flight path), and longitudinal position along the flight path, respectively. This causal sequence of aircraft dynamic behavior is represented by the three embedded control loops in Figure 14.1b. These may be referred to as inner loop, middle loop and outer loop control.

As shown in Figure 14.1a, in most aircraft the pilot has, or can assume, direct control over pitch, bank, and thrust. Using these parameters the pilot must perform two fundamental tasks which we shall discuss in more detail below: maintaining stable flight control and lift or *aviating* (avoid stalling the aircraft such that it falls out of the air), and *navigating* to reach certain desired points in three-dimensional space and avoid other hazardous regions (bad weather, terrain, other aircraft). Because the aviate task is accomplished by maintaining an adequate velocity of airflow relative to the wings' orientation, it depends critically upon control of attitude (pitch and bank) and airspeed. The navigate task is based upon control of the variables, altitude (above ground or above sea level), lateral deviation, and longitudinal position, at the bottom level of Figure 14.1b, since these are the variables that define positions in three-dimensional airspace.

Three characteristics of the aviate and navigate tasks impose very complex cognitive demands on the pilot: first, as noted, control of the attitude parameters of pitch and roll must serve two, not always compatible tasks: preventing stall (aviate), and using these to influence rate of change, which will in turn influence position, in order to satisfy navigational goals. Second, control of the outer loop navigational variables is *sluggish*. This is shown by the causal sequence of arrows in Figure 14.1b. The pilot must control inner loop parameters to influence middle loop parameters, and use these in turn to influence outer loop parameters. As a result, the latter variables of lateral and vertical position change slowly; they have a greater *lag*, as shown to the right of the figure**.** This lag will be amplified on larger aircraft. The control of sluggish systems is a cognitive challenge, because it requires a great degree of *mental prediction and extrapolation* (Wickens 1986; Wickens & Hollands 2000). Third, as reflected in the line arrows in Figure 14.1a, the causal effects of control variables is not as simple as the representation in Figure 14.1b suggests. This is because the three axes of flight show considerable *crosstalk*, such that, for example, changes in bank affect pitch (the aircraft will pitch down if its wings are not level), and changes in pitch affect airspeed (pitch down increases airspeed), while changes in speed can affect altitude.

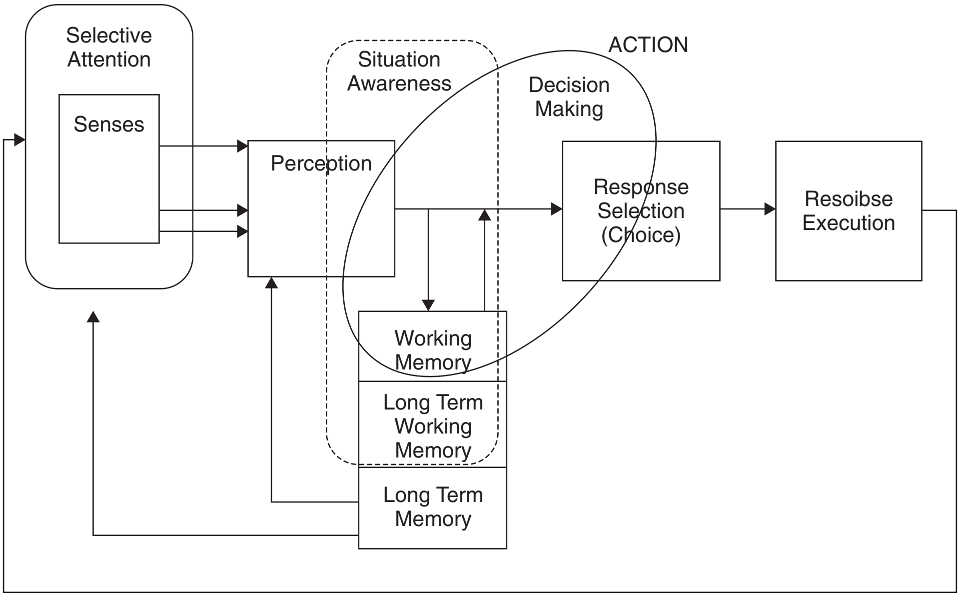

Figure 14.2 Representation of the pilot as an information-processing system

A representation of the pilot as an information-processing system is shown in Figure 14.2, which integrates the collective findings of years of studies from basic and applied cognitive psychology (see Wickens & Hollands 2000; Wickens & Carswell in press). 1 Within the figure, the pilot is represented monitoring the airspace world, both inside and outside the cockpit, by selectively deploying his/her senses, in order to notice and process relevant events. This is the role of *selective attention*. What is passed on from this selective process is then *perceived*, whether these events are discrete, like the appearance of a cockpit alert, or continuous, like the flow of the ground beneath a landing airplane. This perceptual interpretation of the world is said to be guided by both *bottom-up* processes, analyzing the flow of information from the senses, and *top-down processes*, characterizing the heavy role of expectancy stored in long-term memory. These expectancies lead us to perceive what we expect to perceive, even if the sensory message is unclear, or, in fact, different from what is expected.

Sometimes the pilot's perception may immediately trigger a selected and then executed action, as when a perceived deviation from the desired altitude leads to a corrective movement of the yoke control. Such an action often has consequences to the environment, and so leads to feedback to the senses (Jagacinski & Flach 2003). But often, the contents of perception lead to an evolving updating of *situation awareness* of the dynamic situation both within and outside the cockpit, as represented in the dashed box, and discussed fully in Chapter 7 above (see also Endsley 1995; Wickens 2002). Two properties of situation awareness are particularly critical. First, good situation awareness really involves the blending of the cognitive processes of perception and *working memory*. Working memory is that rehearsable but very vulnerable temporary store of information the pilot might use to retain, for example, an air traffic control command until it is executed. Those very limited properties of working memory are well documented in extensive research (Baddeley 1986). Situation awareness also includes what is called "long-term working memory" (Kintch & Ericsson 1995), information that, while not actively rehearsed, can be rapidly retrieved if necessary. Second, situation awareness, understanding the temporary state of affairs and its future implications, provides the basis of effective *aeronautical decision-making*: the appropriate choice of action, such as whether to continue a flight, or divert in the face of deteriorating weather. The process of decision-making, shown in the oval in Figure 14.2, will not be discussed in this chapter, and the interested reader should consult O'Hare (2003). Finally, we note that many of these processes are *resource-limited* (Norman & Bobrow 1975), which means that carrying out concurrent operation is sometimes difficult (e.g., studying a map while talking), and sometimes nearly impossible (e.g., listening to the copilot while speaking to air traffic control).

The pilot must, at a minimum, bring these processes to bear on the tasks of aviating and navigating. But these core tasks often spawn others. Because the airspace must usually be shared with other users, it is necessary to *communicate* with other aircraft or with air traffic control, to avoid collision. Because the aircraft itself depends on the functioning of many other mechanical, hydraulic, digital, and electrical *systems*, it is often necessary for the pilot to understand what those systems are doing (systems management). In addition, any aircraft has a *mission requirement* (e.g., transport passengers or cargo, engage in rescue, surveillance or combat). Finally, carrying out the aviation, navigation, communications, and systems subtasks generally requires judgment and knowledge of very specific *procedures and actions.* The pilot must accomplish tasks within these various categories, as well as *prioritize* among them (Schutte & Trujillo 1996), a prioritization scheme that generally dictates a hierarchy of aviate, navigate, communicate, systems management (sometimes known as ANCS), but often may need to temporarily deviate from it. We discuss each of these major task categories in the following sections, before discussing cognitive issues brought about by their automation.

AVIATE: MAINTAINING STABILITY

As shown in Figure 14.1a, the requirement to maintain adequate airflow over the wings, to avoid stalling and to direct the aircraft in a way that satisfies the outer loop navigational goals, is a complex process. A pilot may rely on one of two generic sources of visual information to accomplish this. When flying in good weather, *visual contact* information is provided by the view of the earth outside the aircraft, using the flow of information across the visual field (Gibson 1979; Warren & Wertheim 1990) to update the pilot's attitude awareness. For example, the angle and vertical location on the windscreen of the horizon line provide an accurate representation of bank and pitch, respectively. When flying toward or along a textured surface as an approach to landing, the pilot may use the texture gradient to judge altitude changes, and may use texture flow to judge ground speed, and the orientation of the flight path related to the ground plane (Haber 2003; Palmisano & Gillam 2005).

While such holistic or ecological visual cues are intuitive and can be rapidly perceived, many of them are imprecise, subject to visual illusion (Previc & Ercoline 2004), and, of course, may be unavailable at night or in poor weather. Furthermore, since they are all based on ground features, none of them offers reliable information regarding velocity through the air (airspeed vector) which, as pointed out above, is a critical variable for preventing stall. As a consequence of these shortcomings, all conventional aircraft have been equipped with a minimum standard set of (generally six) instruments, shown at the bottom of Figure 14.1a.

Visual Scanning

Examination of cockpit visual scanning (Fitts *et al.* 1950; Carbonnell *et al.* 1968; Harris & Christhilf 1980; Bellenkes *et al.* 1997) has revealed important differences between the six flight instruments, in terms of the frequency and dwell duration with which they are scanned (selective attention), and how these differences in turn are affected by pilot skill levels. These skill-related differences implicate changes in the pilot's mental model of the flight dynamics. For example, a repeated finding from cockpit scanning research is that the attitude directional indicator, or "artificial horizon," shown in the upper center of the instrument panel, is the most important instrument. It is visited most frequently, and the gaze dwells there longest when it is visited (Harris & Christhilf 1980; Bellenkes *et al.* 1997). Two reasons can be offered for its importance. First, it is the only instrument which offers two channels of information integrated into one – the horizon line both pitches and banks, hence conveying the two most critical aspect of attitude; second, as noted in Figure 14.1b, pitch and bank represent the most rapidly changing inner loop information source (highest bandwidth) which simultaneously serves two task goals: maintaining stability (aviate), and influencing (and thereby *predicting*) the middle and outer loop parameters to affect navigational goals (bank → heading → lateral position; pitch → altitude = vertical position). Collectively, these features establish the ADI as both the most important and the most informative instrument, hence, explaining its scanning parameters.

Visual scanning analysis has revealed important differences between experts and novices and good and poor performing pilots (Bellenkes *et al.* 1997; Wickens *et al.* 2006). For example, experts more than novices tend to look more at predictive instruments (and therefore better compensate for lags), as well as show a scan pattern more sensitive to cross-coupling, both facets reflecting a more accurate mental model. Many other aspects of expert/novice differences in aviation are discussed in Seamster *et al.* (1997), and more general discussion of expert/novice differences in cognition can be found in Chapter 4.

Solutions to Visual Demand Problems

The scanning costs here are substantial enough that aircraft designers have pursued three avenues to alleviate these attention demands. First, capitalizing on electronic display technology, efforts are being made to improve the symbology by providing more integrated and cognitively compatible information. Figure 14.3 provides an example, in which predictive information is explicitly and intuitively displayed (rather than needing to be cognitively derived), via the three-dimensional "pathway in the sky" extending into the future (Theunissen 1997; Prinzel *et al.* 2004; Alexander *et al.* 2005). The naturalistic ego-referenced viewpoint, and three-dimensional pathway are compatible with the way we naturally move through the environment, and so such displays provide easy-to-fly, intuitive, and precise control. Also, vertically-oriented instruments representing airspeed

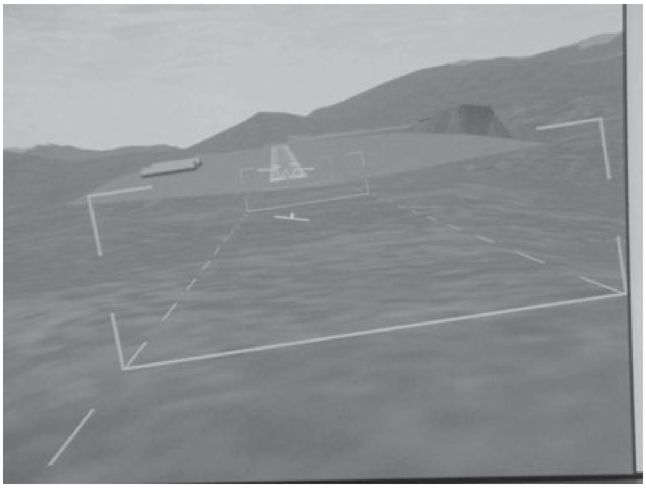

Figure 14.3 Example of a three-dimensional "highway in the sky" flight instrument, superimposed on a three-dimensional synthetic display of terrain. The small white inverted "T" is a prediction symbol that shows where the plane will be in five seconds

and altitude have often replaced "round dial" instruments, hence presenting a more cognitively compatible representation of these linear "higher-lower" quantities (Roscoe 1968; Wickens & Hollands 2000).

Second, many aircraft can present this critical flight information in a "head-up" location, superimposed on the outside world, hence in theory reducing the visual attention demands away from the visual view outside the cockpit (Figure 14.4; Weintraub & Ensing 1992; Wickens *et al.* 2004).

While HUDs do improve the ability of the pilot to divide attention between the instruments and the outside world, relative to a head-down configuration (Fadden *et al.* 1998, 2001; Wickens *et al.* 2004), because of the reduction in scanning that results from the overlay, they do not guarantee parallel processing. Such parallel processing or divided attention between inside and outside may be hindered because of the clutter caused by overlapping imagery (Wickens & Long 1995; Fadden *et al.* 2001). In particular, the perception of unexpected and non-salient events that are viewed in or through a HUD image appears to suffer (Wickens & Long 1995; Fadden *et al.* 1998, 2001). However, when HUDs can be designed such that their instruments overlay or "conform" to features of the world beyond, like the horizon line or runway outline shown in Figure 14.4, then pilots may effectively "fuse" HUD information with the environmental information, creating a single visual "object." Research in visual attention has shown the success with which attention can be more readily divided across the features of one object (Kramer & Jacobson 1991; Jarmasz *et al.* 2005) than of several. Hence, not surprisingly, HUDs with conformal imagery appear to do a better job of supporting the division of attention between instruments and the far domain (Wickens & Long 1995; Fadden *et al.* 1998, 2001).

Third, designers have pursued the option of using *autopilots* to control the short lag, high bandwidth inner loop variables of pitch and bank, as well as the mid-loop variables of heading change (turn) and altitude change, an issue we discuss in the context of the

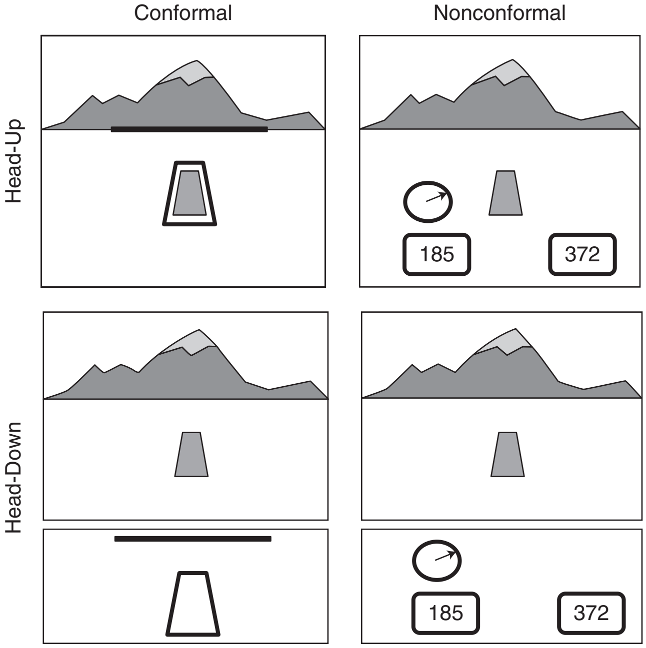

Figure 14.4 Example of a head-up display (top two panels). The instrument panel containing both conformal (the horizon line and runway outline) and nonconformal information (the round dial gauges) is superimposed on the view of the "far" domain. The bottom two panels show this lane info head down

flight management system. Such automation does not relieve the pilot from needing to be aware of these inner-loop variables, but does unburden the need for the continuous monitoring of these high BW instruments necessary for continuous active manual control.

NAVIGATION

The pilot's navigational task is critical. Several examples of *controlled flight into terrain* or CFIT (Wiener 1977) have exemplified the dangers when pilots flying a perfectly stable airplane, lose awareness of their three-dimensional position with respect to the terrain, and crash. Less severe in their consequences, but still of major concern, are instances in which pilots, initially flying in good visibility, find themselves flying into bad weather or clouds, for which they do not have qualifications (Wiegmann *et al.* 2002). In the previous section we explained how pilots could control their orientation and trajectory in three-dimensional space via the control of inner- and middle-loop variables. In this section we consider the cognitive factors involved in *understanding* or *maintaining spatial awareness* of their actual position and of the locational goals – paths, trajectories, and destinations – to pursue, and of hazards to avoid (weather, air traffic, and terrain) (Wickens 1999, 2003; Wickens *et al.* 2005). Such aviation navigational issues can be addressed in two contexts: in *visual contact flight*, the pilot has the terrain in sight, and navigates by virtue of a map, while searching the airspace for possible traffic and bad weather. In *instrument flight* (which must be assumed in poor visibility, but may also be characteristic of much flight in good visibility), the pilot navigates by reference to navigational instruments and air traffic control, assuming the latter has kept the path ahead clear of other traffic.

Visual Flight: The Role of Navigational Checking

In visual flight, the pilot's navigational task is supported by a map, often a two-dimensional paper display, or increasingly, the GPS electronic map. As a flight proceeds, the pilot continuously updates awareness of location, by confirming a correspondence between the image of the terrain perceived in the forward field of view, and an inferred position represented on the map (Aretz 1991; Williams *et al.* 1996; Schreiber *et al.* 1998; Hickox & Wickens 1999; Figure 14.5). If correspondence is confirmed, positional awareness is maintained. If it is not confirmed, the pilot may be considered lost.

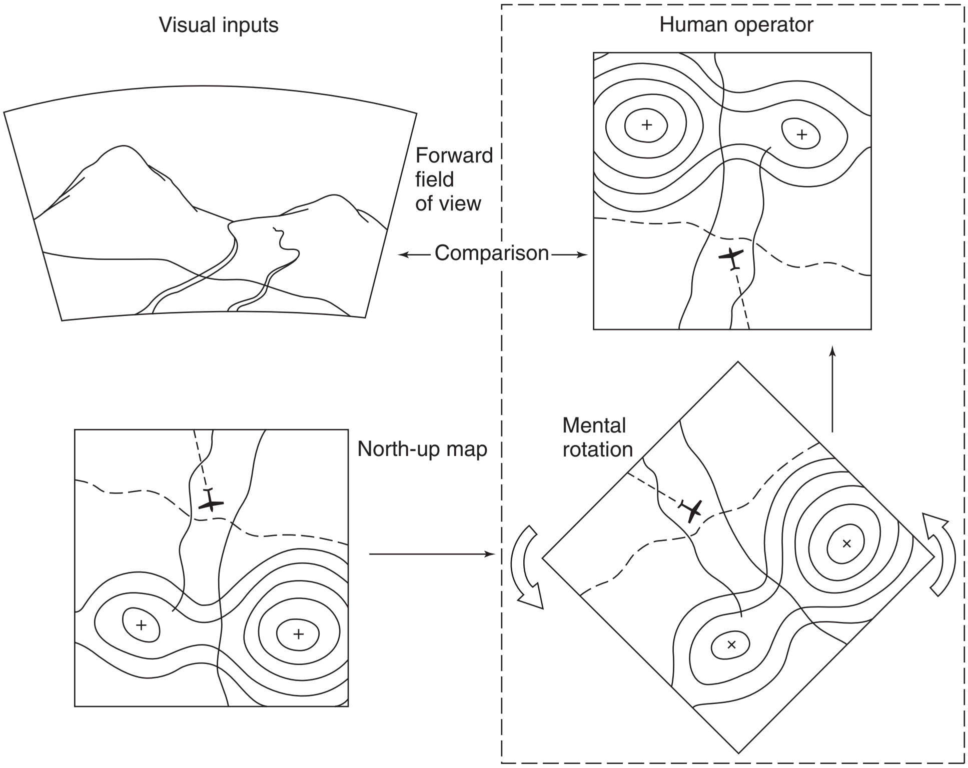

Figure 14.5 Representation of the navigational checking task and its transformations. A forward field of view (upper left) must be compared with a north-up map view (lower left) to assure their congruence or correspondence. To make this comparison pilots will mentally rotate this map to a track-up position (right column), and then envision the two-dimensional rotated image (upper right) as it would appear in three dimensions. The mental rotation component can be eliminated by directly displaying the map in track-up mode (upper right), and the envisioning component can be eliminated by displaying the map in three dimensions

As with image comparison in basic cognitive psychology (Shepard & Cooper 1982), so in map comparison the pilot must perform various types of cognitive image transformations to assure that the map (where I should be) corresponds with the view in the real world (where I am).

In particular, as shown in Figure 14.5, these include: (1) *lateral mental rotation*, if the map is held in a north-up orientation in order to read its text, while the pilot is heading in a direction other than north; and (2) three-dimensional *envisioning,* in order to imagine the three-dimensional appearance of the terrain, represented on the two-dimensional map. The latter two operations are represented in Figure 14.5.

The findings of transformation costs in navigational checking have a direct bearing on the development of electronic maps to support visual navigation (Hickox & Wickens 1999); to minimize these costs, currently most electronic maps rotate laterally so that up is in the direction of travel, and the aviation community is beginning to design three-diemsnional maps that present the world in a three-dimensional perspective (Olmos *et al.* 1997; Prinzel *et al.* 2004). We discuss more features of electronic map design below.

Instrument Flight

Traditional navigational displays to assist the pilot when the terrain cannot be viewed have not served the pilot's cognitive processes very well for several reasons (Wickens 2003). A digital display of distance along a track to or from a fixed navigational beacon presents information, sometimes indicating the distance *to* a beacon being approached, and sometimes indicating the distance *from* a beacon that has been passed, thus leading to an *inconsistent* representation. The pilot's awareness of lateral deviation from the ground track must be perceived from an analog indicator that violates principles of motion compatibility (Roscoe 1968; Wickens & Hollands 2000), by depicting a moving flight path symbol and a stationary aircraft symbol, when in actuality it is the airplane that moves. Finally, the indication of altitude, obtained from the traditional analog round dial altimeter, is obtained from a third separated location in the cockpit, and registers altitude above sea level, rather than above the ground, the hazard that is the cause of controlled flight into terrain accidents. Thus, to obtain a true three-dimensional sense of position the pilot must integrate three sources of separately located, differently, and inconsistently represented information. Such a task imposes heavily on working memory and cognitive information integration capabilities, a violation of the *proximity compatibility principle* which states that items needing to be integrated for a task should be integrated or displayed close together in a display (Wickens & Carswell 1995; Wickens 2003).

Fortunately, good human factors assistance, coupled with advanced display technology, has been applied to improve navigational awareness in the design of dynamic electronic maps. For example, the cockpits of most advanced and transport category aircraft are equipped with integrated representations of position in the lateral and longitudinal axes, the so-called *horizontal situation display* (Fadden *et al.* 1991; Wickens 2003). Furthermore, such maps are designed to rotate to a track-up orientation in order to maintain congruence between the visual representation of position, and the manual control of that position (e.g., a leftward position on the map is pursued by a leftward movement of the control); and this map rotation is as beneficial in instrument flight as it is in visual flight

(Wickens *et al.* 1996). Current technology allows the aircraft position to be established on the basis of satellite-based communications (the Global Positioning System) rather than ground-based navigational beacons.

We now discuss two particular challenges imposed by this advanced display technology: designing three-dimensional displays; and addressing clutter.

Three-Dimensional Displays

Three-dimensional displays, such as that shown in Figure 14.3, are beginning to be considered for navigation. Not only does the prediction and preview of such displays support smooth, stable, and easy flying (aviate), but the pathway or highway provides an accurate, spatially compatible (and flexible) command trajectory to support navigation (Prinzel
4 *et al.* 2004; Alexander *et al.* 2005). Furthermore, the three-dimensional display can also "host" the display of hazards to be avoided in the forward path, particularly terrain, as shown in Figure 14.3. This supports visual, contact-like flight in low visibility. However the three-dimensional hazard display in the relatively egocentric frame shown in Figure 14.3 has the important limitation that it cannot render hazards located above, below, and to the side of the aircraft (e.g., traffic on a 90 degree collision course), nor the representation of hazards at greater distances. In the absence of such representation on the very compelling primary flight display shown in Figure 14.3, there is a danger that the pilot might "cognitively tunnel" attention to the forward path and lose global spatial awareness of other hazards not located there (Wickens & Prevett 1995; Wickens 2005).

Under these circumstances, the electronic map can be made to host these wider-ranging hazard representations, in directions beyond the forward path. But should this also be a three-dimensional display? Research suggests that it is very important that such displays do contain an analog representation of vertical information, which the two-dimensional
5 map does not support (Hughes 2004; Alexander *et al.* 2005), but when the vertical information is presented on a three-dimensional perspective display of hazards, this invites problems of the *ambiguity* of precisely locating hazards in three-dimensional space on the two-dimensional surface of a three-dimensional display (McGreevy & Ellis 1986; Wickens & Prevett 1995; Wickens 2003). At present the perceptual and cognitive issues of presenting hazard and navigational information on a three-dimensional display involve tradeoffs of sufficient complexity that they cannot be addressed here (see Wickens 1999, 2000, 2003; Wickens *et al.* 2005 for a further discussion).

Clutter

A second cognitive challenge in developing navigational/hazard displays is that of clutter. Two forces create clutter in electronic maps. First, the large scope necessary for long-range navigational planning often forces a vast amount of material to be depicted in a restricted spatial region on the cockpit panel. Second there is a legitimate desire for integrating information about traffic, terrain, and weather all on a single panel, a design decision that makes good sense when it is realized that a pilot may need to mentally integrate such information when choosing a safe path of travel (Kroft & Wickens 2003). However from
a cognitive perspective, clutter has two serious drawbacks. First, it slows visual search for E1

target information, as the number of "things" that have to be examined increases (Remington *et al.* 2000; Yeh & Wickens 2001), replicating the classic serial self-terminating search model (Neisser 1963). On a cluttered cockpit map, this slowing of search may be as long as 4–5 seconds. Second, clutter hinders the reading of information once it is located, replicating the failures of focused attention from closely arranged items in space (Eriksen & Eriksen 1974; Broadbent 1982).

Some designers have chosen to address issues of clutter by developing computer-based *decluttering* tools, in which a switch can turn off classes of information deemed temporarily irrelevant (Mykityshyn *et al.* 1994; Kroft & Wickens 2003). However, such devices invite the danger of "out of sight out of mind" (Wickens *et al.* 2003). That is, the pilot may erase information that, at the time, may appear irrelevant (in order to aid focused attention on the relevant), only to forget the existence of that erased information at a time when it suddenly becomes directly relevant to a navigational decision, perhaps because it has changed while hidden. Rensink (2002) refers to this as blindness for a "completed" change. For example, a pilot might declutter weather information, and hence fail to realize the approach of hazardous weather. Thus more effective solutions to clutter may involve low lighting or "layering" information at different intensities, rather than erasing it entirely (Kroft & Wickens 2003).

COMMUNICATIONS

Cockpit communications can be categorized into three sorts. First, the pilot and air traffic controller are both involved in an intricate network of ground-to-air voice communications which is particularly, although not exclusively, focused on the navigational subtask. Second, personnel within the flight deck (i.e., pilot and copilot) must often communicate among themselves. Third, pilots may communicate with an on-board "mission" crew, such 6 as flight attendants on a commercial flight (Chute & Wiener 1995). Flight deck communications, whether within the aircraft, or with the ground, is highly vulnerable to human error. Such breakdowns may occasionally result in tragedy, as when a communications error led the pilot of a 747 aircraft to mistakenly believe that he had been granted clearance for takeoff (Hawkins 1993). The takeoff proceeded while another 747 was still on the runway, and the resulting collision caused more than 500 deaths.

While the absolute frequency of incorrect air-to-ground communications is relatively small (estimated to be approximately 10 per cent; Morrow *et al.* 1993), this number is still large enough to warrant serious concern for its causes, many of which are based on cognitive factors. We focus our discussion here most directly on air-to-ground communications, rather than intra-cockpit communications, because the former have generally been better analyzed, studied, and proceduralized. Furthermore, the latter are more heavily influenced by characteristics of social and personality psychology, and hence beyond the scope of this chapter (Foushee 1984; Wiener *et al.* 1993).

Task analysis of the communications process reveals that a "unit" of communications generally includes (1) a *transmission* typically from controller to pilot relaying an instruction (e.g., "United 486, climb to flight level 210 and turn to heading 180; anticipate climb to 240"); (2) a subsequent *readback* or acknowledgment which contains the source, and repeats all the key features of the transmission ("Roger; United 486 flight level 210, heading 180 anticipate 240"); and (3) a *covert monitoring* of the readback by the message

E1

transmitter (in this example the air traffic controller), to ensure that the message sent was accurately read back by the recipient. Such an accurate readback is implicitly assumed by the controller to indicate that the pilot will comply with the instruction. One class of errors in the process are *procedural* errors in which, for example, a readback is incomplete or missing altogether, or in which a controller fails to deliver instructions in standard terminology. A second class of errors are *transmission* errors, in which a communication is heard incorrectly. In some cases this error may be detected (by the transmitter) in the readback; in other cases it may not be, particularly if the procedural error of a readback failure occurs. The vulnerabilities in the communications process can readily be linked to four well-known characteristics of human information-processing: procedural knowledge, cognitive workload, expectancies and working memory limitations, and we describe the interlocking influences of these factors as follows.

Under some circumstances, often resulting from lack of experience, standard communications procedures are violated, perhaps via an incomplete readback (Morrow *et al.* 1993) or an improper sequence as described above. Also controllers may sometimes deliver a single message that is considerably longer than that which is procedurally recommended (Morrow *et al.* 1993), because long messages impose on the pilots' limits of working memory.

The likelihood of both controller and pilot procedural errors may be amplified by the effects of high cognitive workload and time pressure. For example, higher cockpit workload may lead the pilot to truncate, and possibly eliminate, the appropriate readback, whereas high controller workload (coupled with the time cost required to initiate and complete each communications exchange) may lead the controller to deliver a long string of instructions in a single message, rather than dividing this message across two or more shorter communications. This choice is made for the sake of efficiency because the single message will shorten the total amount of time the controller must deal with each individual aircraft. For the pilot, and particularly, the controller, high workload can eliminate careful readback monitoring (Redding 1992).

The cognitive bias of expectancy-driven top-down processing, which causes us to hear what we expect to hear, can itself amplify the influence of the factors described above. Whenever the bottom-up signal quality of communications is made more difficult (e.g., by low acoustic quality, or by a rapidly spoken long message) the pilot's bias will be to hear the expected message. Thus, if an unexpected or unusual item is delivered in the communications, an error in understanding is invited. Furthermore, the controller expects the pilot to read back the transmission as it was delivered (as is typically the case, a typicality that is the very basis for the expectancy). Hence, in the covert monitoring component of the transmission sequence, the controller may *fail* to detect a pilot's incorrect readback; what Monan (1986) has described as the "hearback" problem (ATC: "reduce speed to 220." Pilot response: "Roger: speed 200").

Finally, the limited capacity of working memory is clearly evident in the communications transmission errors that are observed (Loftus *et al.* 1979; Morrow *et al.* 1993). The contents of any sequence of instructions must be maintained in working memory until it is fully read back, and beyond that, until it is written down, entered into a computer, or actually executed on the flight controls. The more chunks that a transmission contains, or the more rapidly it is delivered (hence, leading to less opportunity for rehearsal or deeper encoding of each chunk), the greater is the chance of forgetting. Such forgetting may often result from confusion, such as a pilot transposing digits (115 vs. 151), or even confusing the three critical message components – heading, airspeed, and flight level – all of which are generally expressed as three-digit numbers as in the example above.

Solutions to such communications problems can readily be found in the form of *data link* (Kerns 1999; Navarro & Sikorski 1999; Helleberg & Wickens 2003), a digitized communications system, beginning to be introduced in the next generation of aircraft, whereby instructions flow between ground and air over digital channels, rather than voice-based radio. Such a system has at least three cognitive advantages over the conventional radio channels. First, because communications data would be available (and therefore preservable) electronically in the cockpit, it can be visually displayed and maintained, hence offloading the limited capacity working memory system (Helleberg & Wickens 2003). Second, because of its availability in digital form, it may be displayed in a multimedia fashion, hence capitalizing on both human's facility with redundant information (Garner & Morton 1969) and certain principles of cognitive display compatibility (e.g., a spatial trajectory instruction can be represented spatially on an electronic navigation display, rather than, or in addition to, being presented in verbal form (Hahn and Hansman 1992). Third, visual display may be less interruptible of ongoing tasks, an issue we address below.

SYSTEMS MONITORING AND MANAGEMENT

The fourth major task domain within the cockpit is that associated with monitoring (and occasional control over) aircraft systems. As with many other process monitoring tasks (Moray 1986, 1997; Parasuraman 1987), the task of aircraft systems monitoring takes on tremendous importance on the rare occasions when systems do malfunction. In such cases the speed of detection becomes a critical factor, as does the speed and accuracy with which diagnosis and selection of remedial action are accomplished (Rasmussen & Rouse 1981).

In this domain, designers of automation have provided a valuable service by providing pictorially based, easy to interpret graphics of many aspects of systems monitoring tasks, the so-called Electronics Instrument Caution and Advisory System or EICAS. Furthermore, to attenuate the clutter associated with the massive number of systems to monitor on the modern transport aircraft, as well as to allow integrated depiction of textual and status information, designers have gone to menu-based *multifunction displays*, in which multiple pages of information can be examined (albeit sequentially) through a single viewport. While this centralized computer-based graphics image capability has many advantages, it also raises some important cognitive issues regarding the structure of the computer database (Seidler & Wickens 1992; Wickens & Seidler 1997), and the extent to which this organizational structure matches the pilot's cognitive model of systems relatedness (Roske-Hofstrand & Paap 1986). Where the design mismatches the pilot's mental model, added time costs in navigating through the data base are invited.

PILOT'S PROCEDURES AND ACTIONS

Much of task selection in aviation is *procedural*. Tasks are carried out at certain pre-designated times or sequences during a flight. For example, the landing gear must be lowered prior to landing and raised after takeoff; particular communications must be initiated when the aircraft transitions between ATC sectors in the airspace. With repeated practice, the pilot builds up what are called "schemata" of the appropriate procedures and actions to be performed at the appropriate times. The airlines put great emphasis on training pilots in what they call "standard operating procedures" (Degani & Wiener 1993; Hawkins 1993; Orlady & Orlady 2000), capturing many of these sequences of tasks or actions. Correspondingly, there is great emphasis on "proceduralizing" most aspects of air traffic control, through standard communications protocols, standardized aircraft departure and arrival routes and so forth (Wickens *et al.* 1997). Most of these procedures depend upon a vast array of declarative knowledge, nearly all of which is backed up by published federal air regulations (FARs), operating manuals, and checklists (Orlady & Orlady 2000). The various procedures, such as configuring the airplane for takeoff, dealing with a malfunctioning instrument, filing a flight plan, or checking the status of the aircraft prior to engine start, have two general attributes: *how* they should be carried out, and *when* they should be done.

While extensive training, practice, and rehearsal may be necessary to assure that procedures are carried out fluently, such training is never entirely sufficient to assure safe flight because the appropriate sequence of procedures will not have been learned well by the student pilot and may occasionally be forgotten or missed even by the skilled pilot. Hence procedures-following is always supported by the checklist.

Checklists

Because of human frailties in both declarative knowledge (*how*), and prospective memory (*when*; Harris & Wilkins 1982), an absolutely critical memory support for the pilot is the *checklist* (Degani & Wiener 1993). The pilot will have several checklists for both routine and emergency procedures, each listing the nature of the procedure (characterizing the "how"), in the sequential order in which it should be accomplished (characterizing the "when"), thus providing what Norman (1988) has characterized as "knowledge in the world."

Yet even such a valuable support as the checklist is vulnerable to certain cognitive frailties. Two in particular are related to *expectancy-driven processing* and *selective attention*. As an example of the former, it is possible that a checklist might ask the pilot to "check that switch X is on." If the normal state of switch X is in the "on" position, the pilot may "see" the switch in that state, based on expectancy alone, rather than making a careful evaluation based upon bottom-up visual inspection of the switch itself (Mosier *et al.* 1992). In this example the tendency for the top-down processing is reinforced by the greater ease with which people judge "true positive" responses in a word picture comparison task (Clark & Chase 1972), which characterizes the information-processing demands of the checklist item.

Selective attention also plays a role in checklist following, as the pilot's eyes must move down the list from item to item. Here the orderly sequence may be disrupted. While disruptions may sometimes only be minor, as when the eyes must move away to assure that the item is in the appropriate "checked" state, there is always a danger that such a diversion can disrupt the orderly sequential flow of attention down the list. When diversions of attention are large or long, they can be more likely to lead to a disruption of the flow, as occurred tragically in 1987 when pilots of a commercial airliner taxiing prior to takeoff at Detroit Metropolitan Airport had their attention disrupted from the checklist by a required take-off runway change directed from air traffic control (Wiener 1988). When the pilots' attention returned to the list, it apparently did so one item *beyond* the last item prior to the interruption. The missing item turned out to be the critical one of setting the flaps and slats for takeoff. This omission compromised the amount of lift generated by the plane, and left it with too little altitude to clear obstructions after it left the runway. Over 100 lives were lost in the resulting crash.

High levels of time pressure may amplify expectancy-driven top-down processing as above, and may also influence selective attention by causing a pilot to rush through and finish a checklist prematurely and turn attention toward another activity, hence leaving the final items uncompleted (Degani & Wiener 1993). Such instances may occur, for example, if ATC suddenly requests an expedited procedure (preparation for takeoff, or final approach to landing), in order to maximize traffic flow.

As with so many of the vulnerabilities that we have described above, good human factors, along with automation, are suggested as a remedy for some of the problems with checklists (Palmer & Degani 1991; Degani & Wiener 1993). For example, to avoid time-pressure problems, "killer items" (those with catastrophic consequences if undone) should never be placed toward the end of a checklist. Electronic checklists can require that each item be actively "checked" by the pilot providing a machine readable input (e. g., a touch screen overlaying the list), and hence offering a monitoring device that could prevent the error of omission described above (Palmer & Degani 1991; Bresley 1995). Checked items turn green, while unchecked items remain red, offering a salient, attention-capturing sign that a checklist has not been completed. While such an approach would not address the problems associated with expectancy-driven processing (Mosier *et al.* 1992), these could be addressed, in some circumstances, by sensors in the aircraft that could sense and self-report their state (e.g., the switch in the previous example could report that it is in the "off" position, and alert or suggest that the pilot should turn it "on" Bresley (1995).

Cockpit Task Management

While it might be ideal if all of a pilot's tasks could be proceduralized and therefore supported by checklists, in practice, this is not possible. There are simply too many unexpected events that can occur in the airspace, and in some emergencies checklists cannot predict (and therefore dictate) all the appropriate actions to be taken. Furthermore, numerous situations exist when two (or more) tasks compete for the pilot's attention, and he or she must then choose which to perform and which to defer, if they cannot be accomplished in parallel. The issues of *cockpit task management* (CTM; Funk 1991; Chou *et al.* 1996; Dismukes 2001), or *strategic workload management* (Hart & Wickens 1990), or interruption management (McFarlane & Latorella 2002) describe the characteristics of such strategies that are employed by the pilot choosing which tasks to perform, which to delay or "shed" and which tasks may interrupt or "preempt" other ongoing tasks (see also Adams *et al.* 1995). We identify below, three general characteristics that appear to underlie breakdowns in task management.

Preemption and the ANCS Hierarchy

In aviation, the ANCS hierarchy can often be used to define an “optimal” prioritization or importance ordering of tasks, and there is little doubt that air safety is compromised by poor cockpit task management when more important tasks are allowed to be preempted or superseded by those of lesser importance. Such a conclusion comes from several sources. For example, the crash of Eastern Airlines Flight 401 into the Florida Everglades in 1972 resulted because pilots became fixated on a landing gear problem (systems management), failing to heed a loss of altitude (aviate), which resulted from an accidentally disengaged autopilot (Wiener 1977). Indeed, Chou *et al.* (1996) have documented that 23 per cent of 324 NTSB reported accidents during the period 1960–89 had poor CTM as one underlying cause. Raby and Wickens (1994) found that, although pilots were generally fairly optimal in task management, they tended not to exhibit highly sophisticated rescheduling routines when workload was unexpectedly increased. Furthermore, the better performing pilots in a high workload simulation tended to switch attention between tasks more frequently than those pilots who performed less well. Raby and Wickens (1994) and Laudeman and Palmer (1995) both found that better performing pilots were more optimal in *when* they performed the higher priority activities, tending to accomplish these earlier.

Other investigators have studied interruptions, in which the performance of certain ongoing tasks is terminated by the arrival of a new task (Damos 1997; Dornheim 2000; Dismukes 2001; McFarlane & Latorella 2002). Analyzing a series of videotaped scenarios, in which professional pilot crews handled unexpected circumstances, Damos (1997) found that in ATC communications (the third task on the ANCS hierarchy) would often interrupt or preempt a pilot’s involvement with navigational planning tasks, which may be considered a second level task, a characteristic that can be described as non-optimal task management. In contrast, however, pilots were fairly effective at protecting the hand flying of the aircraft (Aviate: first priority) from being interrupted. Latorella (1996) and Dismukes (2001) have also noted the preemptive nature of ATC communications into a pilot’s ongoing task, an issue that will be addressed below. A general finding too is the extreme vulnerability of visual monitoring (necessary for maintaining stage 1 situation awareness) to interruptions.

Auditory Preemption

Noteworthy in the discussion above is the finding that the disruptive communications task (no. 3 on the hierarchy) often interferes with no. 2 navigation, which is primarily a visual task. This pattern seems to reflect a more general tendency for auditory preemption. At least two reasons for such preemption can be offered. First, auditory onsets are inherently
7 (and biologically) attention-grabbing, perhaps because they are omni-directional (Spence, 2000; Banbury *et al.* 2001). This would explain their near-universal preference for use in high-priority alarms (Stanton 1994). Second, because of working memory limitations, people want to keep attention directed to an auditory task until it is completed, so that material is not forgotten from working memory (Latorella 1996). Hence they will deal with an auditory communications immediately when it arrives.

If auditory events tend to preempt visual ones, then visual events by contrast do so to a much lesser extent. This has a positive facet of flexibility in that, when material is presented visually the pilot can divert attention from the task supported by that visual material, and return to it later knowing that it will still be perceptually available (unlike the decaying representation of auditory material in working memory). Thus the visually presented data link, described in section 5, enables that flexibility to operate with communications tasks (Helleberg & Wickens 2003). But the negative facet is that our visual 8 modality is relatively insensitive to noticing changes (Carpenter 2001; Rensink 2002), in elements like cockpit-displayed traffic and weather (Muthard & Wickens in press; Iani & 9 Wickens in press).

Cognitive Tunneling

A final problem in task management results when a pilot "tunnels," or focuses attention on a particular activity for a longer period than is optimal, and therefore fails to switch attention visually (via scanning) or cognitively (via thought) to tasks deserving of attention (Wickens 2005). Dismukes (2001) has noted the extent to which the task of failure management tends to induce such tunneling. Wickens (2005) has reviewed a number of studies that suggest that highly realistic immersed three-dimensional displays, as discussed above (see Figure 14.3), also induce attentional tunneling, and a resulting neglect of scanning to the outside world beyond the cockpit displays, thereby rendering the pilot vulnerable to events and hazards that may not be registered on those displays.

COGNITIVE FACTORS IN AEROSPACE AUTOMATION

The previous sections have identified several ways in which automation may be considered to remedy the cognitive challenges of aviation. Indeed automation, both in the cockpit and in the ATC control room, has both increased the efficiency of air transport, and saved lives. For example, each successive generation of more highly automated aircraft has a higher safety record (Sparaco 1998), and automated alerts and warning systems (discussed below) have prevented potential collisions with other aircraft and with the terrain.

Automation is sometimes represented in the framework of the stages of pilot information-processing activities that it replaces (or augments – see Figure 14.2; Parsuraman *et al.* 2000). For example automation may (1) direct selective attention via techniques such as cuing or filtering; (2) draw inferences or assessment about the current and future state of the airspace (e.g., conflict warnings), or aircraft (e.g., smart failure diagnostics, Hicks and DiBrito 1998); (3) select or recommend; or (4) execute actions. Across all these stages (see Wickens 2002), automation has a number of well-documented strengths, but weaknesses as well.

Problems with Automation

Much has been written about human factors problems with automation (e.g., Parasuraman E1 & Riley 1997; Parasuraman and Lorenz, Chapter 16, this volume), even when the automa-

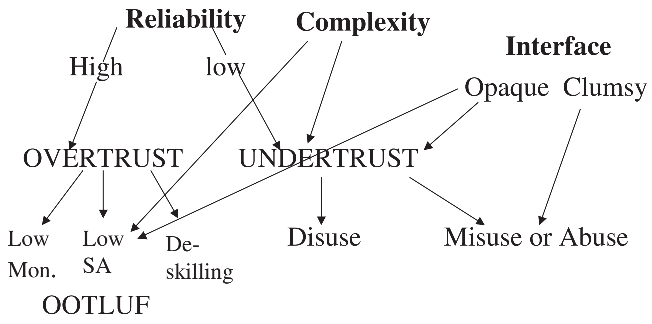

Figure 14.6 Some human cognitive factors underlying automation

tion functions better than the human capabilities that it replaced (or is relieving a great amount of mental workload). As applied particularly to automation of aerospace systems, we represent these problems in Figure 14.6. The figure identifies three important attributes of automation in **bold face** across the top (reliability, complexity and interface properties), two critical cognitive states in CAPITALS, related to human trust in and dependence upon the automation, and a set of behavioral consequences that flow from these properties, mediated by human the human's cognitive state. Starting at the left, if automation is extremely reliable, it breeds the danger of over-trust, sometimes described as "complacency" (Parasuraman *et al.* 1993). Three behavioral consequences of this are that the operator will:

1. no longer monitor (low mon) the processes controlled or supervised by the automation (trusting it to "do right");
2. lose situation awareness of the current state of what automation is doing, a joint consequence of not watching it, and of the fact that people are less proficient at remembering the consequence of an action when they have witnessed another agent doing it, than when they have done it themselves: this is the "generation effect" (Slamecka & Graf 1978; Hopkin 1995);
3. lose skill at performing the task manually if they need to do this once the automation has failed, since this task had been repeatedly done by automation in the past.

These three cognitive/behavioral changes present no problem *unless* automation fails, and the human must suddenly step "into the loop." Under such circumstances the human will be slower to detect the failure, slower to understand the current state and future implications and therefore choose the appropriate actions, and less skilled in executing those actions. These three symptoms of over-trust are often joined to define what is called the "out of the loop unfamiliarity" (OOTLUF) syndrome.

In contrast, automation whose reliability is low – for example, the alert system that gives too many false warnings – is one of three causes that breed *under-trust* in automation. This influence of low reliability is joined by the influence of a high degree of "opacity" of the automation – the inability of the user to see or learn what is going on within the "black box" (Sarter and Woods 1997); and of a high degree of complexity of the automation (its algorithms and functionality; Degani 2003), further hampering the user's ability to understand what the automation is doing. In isolation, or in combination, all three of these influences breeding under-trust may cause the user to stop using the automation (disuse, as when we no longer heed an alarm), or possibly even "misuse" or "abuse" the automation (Parasuraman & Riley 1997). In this representation it is worth noting the common influence of unreliability and opacity/complexity. While a complex/opaque automation system such as the flight management system we discuss below, may actually carry out its function reliably, it may do things that are surprising to the user, leading the user to assume that automation is actually unreliable, with the consequent distrust (Sarter & Woods 1997, 2000).

In discussing problems with automation, as depicted in Figure 14.6, it is important to include the clumsy nature that is often inherent in the interface with which the pilot must program (or reprogram) what the automation is doing. For example, while it is generally found that the flight management system (see below) reduces workload, in order to change a runway assignment while on an approach, 28 programming steps are required. Such clumsy features of the automation interface invite misuse.

While the number of automated systems on the flight deck and in Air Traffic Control is large, including such systems as datalink, and the automated checklist as we have discussed above, we single out two in particular for more extensive discussion: alerting systems, because of their ubiquity in the air and on the ground (ATC); and the flight management system (FMS), because it has often served as the prototype for both what is right and what is wrong with automation.

Imperfect Alerting Automation

Within the taxonomy of automation stages described above (information selection, integration, action choice, and execution), an important generic class are those automated systems that warn or alert operators to dangerous conditions (Pritchett 2001). In essence these functions may combine stage 1 and stage 2 automation. Simple alerts that replace human monitors (like the engine temperature alert) are stage 1 attention guiders that call the pilots' attention to the critical signal. More complex inference-makers, like those diagnostic systems that infer a particular root cause failure from a collection of symptoms (Hicks & DiBrito 1998), or an impending mid-air collision by integrating trajectory information are stage 2 automation examples. By diagnosing "what is" or predicting "what will be," they implicitly direct visual attention to the relevant displays of system state, as well as direct cognitive attention to the relevant hypotheses.

Both stages of automation have in common two key aspects. (1) Both can be represented within the framework of signal detection theory, with its two classes of errors – misses (a dangerous condition exists that automation fails to detect) and false alerts (an alert is raised when all is well). (2) Such automation is often asked to perform tasks where automation will be imperfect and hence these automation errors actually occur with some frequency (reliability is less than 1.0), often because of the probabilistic nature of the world that automation is trying to overcome (consider automated weather forecasts). This is particularly true when automation is designed to support the prediction of future states across long prediction intervals: the crystal ball becomes hazier the further into the future we look.

Referring to Figure 14.6, we find that the effectiveness of such diagnostic alerting systems is based on trust or dependence. Trust is a psychological state. Dependence describes the actual behavioral consequences of trust, the degree of use or disuse of the

E1

automation (Parasuraman & Riley 1997). With regard to the diagnostic automation typical of alerting systems, Meyer (2004) has distinguished between the dependence states of *reliance* and *compliance*. Reliance is fostered by miss-free automation; that is, an automation system that never (or rarely) fails to detect a critical condition when one occurs. The reliant pilot or controller will have plenty of spare capacity to carry out other concurrent tasks besides monitoring the process that automation is also monitoring. But, the (now very rare) automation miss that *does* occur might well be missed by the complacent, over-dependent, over-reliant human operator. In contrast, the skeptical operator, with lower reliance, will then allocate more attention to monitoring the "raw data" which the automation is also monitoring, but as a consequence will have fewer resources available for concurrent tasks.

Compliance describes the operator's tendency to respond in a timely fashion whenever the system diagnoses a dangerous or important situation (e.g., the alarm or alert sounds). High compliance is bred by a false alarm-free system. Conversely, a false alarm-prone system will degrade compliance, leading to the so-called "cry wolf" syndrome where all alerts may be dealt with on a non-urgent basis, or ignored altogether, including those that should be attended because they are true (Breznitz 1983; Sorkin 1989).

Naturally, the lower reliability confronting more challenging automation diagnosis (e.g., 10 a prediction of traffic collision with longer look-ahead time; Thomas & Rantanen in press), may decrease both reliance and compliance, as miss and false alert rates rise respectively. However, the designer of the alert system has a choice of where to place the "threshold" of the alert, corresponding to setting the response criterion (β) of signal detection theory, in order to achieve the optimal balance between the two types of errors. Dixon and 11 Wickens (in press), studying system failure alerts in unmanned air vehicles, found that a designer-adjusted threshold with higher misses indeed reduced reliance; concurrent tasks suffered but operators were quite proficient in detecting the events when the automation missed the system failure. However a false alert-prone system not only degraded compliance (delayed pilot response to all alerts), but also appeared to disrupt the symptoms of reliance as well, suggesting that false alerts may be overall more damaging to human performance with automation. This finding was reflected in the reports of pilots concerning alerting systems in real aircraft (Bliss 2003), where the false alert problem was viewed as more severe than the miss problem.

Whether the problem is misses or false alerts, if alerting systems are asked to carry out diagnostic tasks in which they may be forced to be imperfect (e.g., because of long look-ahead times), at least two solutions may be imposed. First, it is logical to provide the operator with some view of the "raw data" upon which the automation is making its diagnosis or prediction, so that the veracity of the alert can be checked if needed. Second, it is important to provide the operator with training and understanding of the inevitability that alerting system errors will occur in such circumstances; so that appropriate oversight of the raw data is maintained, and false alerts are not viewed as an indictment of the system leading to disuse.

The Flight Management System

The flight management system (FMS) is an example of a system that implements stages 3 and 4 automation, and is a fixture on all commercial air carriers. It decides how (where E1 and how fast) to fly the plane to implement pilot goals, and then executes those responses.

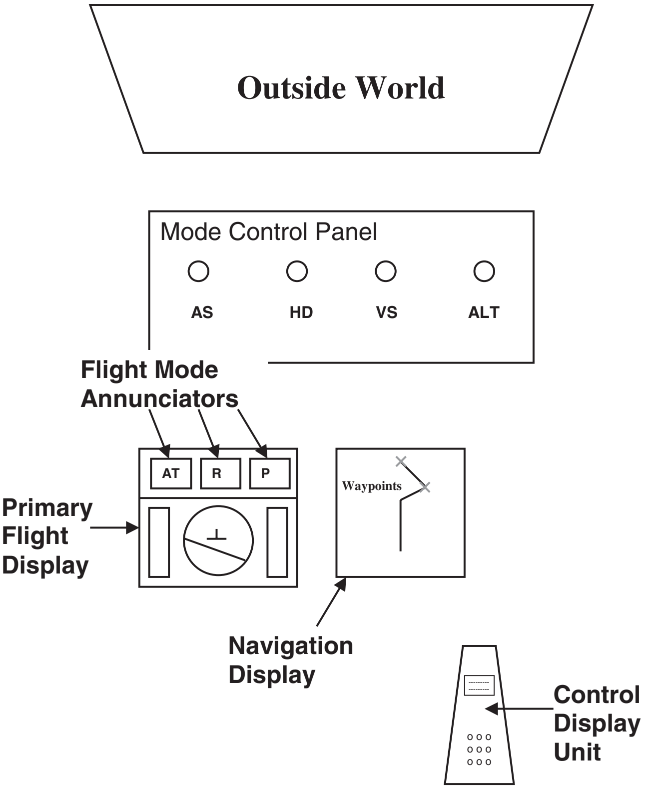

Figure 14.7 Components of the Flight Management System, as described in the text. The flight mode annunciator abbreviations are AT (auto throttle), R (roll: lateral control), and P (pitch: vertical control)

More specifically, the FMS is a collection of autopilots, combined with an intelligent logic, that can accomplish the goal of navigating the aircraft to varying points and along varying trajectories in three-dimensional space (Sarter & Woods 1994, 1995, 1997; Sherry & Polson 1999). The FMS actually consists of a number of components, distributed throughout the flight deck, as shown in Figure 14.7. The pilot can program the FMS through a flight management computer, housed in a control display unit (CDU) which is typically positioned between the seats. This programming may be accomplished before a route is flown (i.e., on the ground). Then the FMS will fly the aircraft along various three-dimensional trajectories by setting various *modes* of operation: for example, climbing at a particular rate (feet per minute) or angle with the ground, reaching particular waypoints over the ground at particular times, and adjusting particular speeds. Because the three-dimensional trajectories must be accomplished and coordinated in time, this is sometimes referred to as "four-dimensional navigation," with time as the fourth dimension.

The pilot may intervene with this automation at any time, either by reprogramming through the CDU, or by setting in particular target values to a device called a *mode control panel* mounted at the top of the instrument panel just below the windshield. The pilot may also view what the automation is doing, or is about to do, as this is represented spatially on a two-dimensional electronic map, the navigation display, and symbolically, through a set of three small windows, known as the *flight mode annunciators*, positioned at the top of the primary flight displays.

While the FMS can be programmed to fly extremely efficient routes, both selecting (stage 3 automation) and executing (stage 4), control of heading, location, and altitude, past experience has identified a number of human factors problems for the pilot (e.g., Sarter & Woods 1994, 1997, 2000), problems that have led to accidents (Dornheim 1995) as well as incidents where highly qualified pilots will ask what the FMS is doing and why, in response to its sometimes surprising actions (Funk & Lyall 1999).

Many of these problems can be well represented within the context of Figure 14.7. Thus while the reliability of the FMS is high, it is nevertheless sometimes subject to under-trust because of its overwhelming complexity and features of its interface. Regarding complexity, the FMS has many *modes* particularly in accomplishing vertical flight (five different ways of changing altitude, for example), and these modes can be combined in many different ways (Degani 2003). Furthermore, the logic within the FMS allows the plane to transition from one mode to another (a stage 3 decision) without any direct action from the pilot at the time of the transition. This transition may involve both activating certain modes (e.g., a speed control mode, once a certain target altitude is reached), or in some cases deactivating a mode. Thus, because of the generation effect described above, the pilot will lose situation awareness of the changing modes (and resulting state of the aircraft), compared to a situation in which she were directly controlling the aircraft with the yoke and throttle.

These problems of under-trust are exacerbated by three properties of the interface:

1. It is somewhat opaque, contributing to the loss of situation awareness. Many of the mode changes that go on within the FMS, particularly in the complex vertical flight, are represented to the pilot only by non-spatial changes in symbolic abbreviations posted on the flight mode annunciators. Not only are these not intuitive or easy to understand, but their actual occurrence often goes unnoticed by the pilot busy scanning the full cockpit (Wickens *et al.* 2003), a failure of bottom-up attention capture (Nikolic *et al.* 2004).
2. There is no spatial analog representation of the complex vertical navigation that would correspond to the spatial map (navigation display) for lateral navigation. Instead, symbolic representation of vertical behavior is found in text on the pages of the flight management computer, visible in the CDU, and in alphanumeric mode abbreviations visible within the FMA windows. Thus, there is a violation of display compatibility in representing symbolically, the inherently spatial information regarding vertical flight (Wickens & Hollands 2000).
3. The information concerning overall status of the FMS is, as shown in Figure 14.7, spatially distributed about the cockpit. Yet this information needs to be integrated in the mind (a violation of the proximity compatibility principle; Wickens and Carswell 1995; Wickens 2003).

It is at least evident that designers are aware of these issues, and some effort is being made to support better situation awareness, particularly by considering graphic analog vertical situation displays (Hughes 2004), and developing fewer and more intuitive symbolic labels for FMS-related flight modes (Sherry & Feary 2005).

CONCLUSIONS

This chapter has really only scratched the surface of the multitude of cognitive challenges confronting the pilot. Indeed because of space, we have neglected entirely discussing the important cognitive issues related to pilot judgment and problem-solving, as well as those related to pilot training and instruction (see Garland *et al.* 1999; Orlady and Orlady 2000; and Tsang and Vidulich 2003 for further information on these topics). Another area that 12 we believe will represent an important future in aviation psychology is computational models (Foyle & Hooey in press). Such models have the advantage of generating predictive data as to how pilots and controllers will respond to new technology and new procedures, without requiring time-consuming and expensive human-in-the-loop simulations. Thus they should become vital tools in ensuring the continued safety of the airspace and its human users.

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