Situation Awareness and Workload in Aviation

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Abstract

A pilot faces special challenges imposed by the need to control a multivariate lagged system in a heterogeneous multitask environment. The time lags between critical variables require prediction in an uncertain world. The interrelated concepts of situation awareness and workload are central to aviation psychology. Three components of situation awareness are spatial awareness, system awareness, and task awareness. Each of these components has real-world implications, spatial awareness for instrument displays, system awareness for keeping the operator informed about actions that have been taken by automated systems, and task awareness for attention and task management. Task management is directly related to mental workload, as the competing demands of tasks for attention exceed the operator's limited resources.

Keywords

mental workload; attention; situation awareness; displays; spatial cognition

The study of aviation psychology has borrowed from other domains to apply psychology to all aspects of aviation, including selection and training of pilots, performance of the aviation team (communications and interactions), and pilots' perception, decision making, and performance under stress. However, my focus in this review is on situation awareness and workload, concepts that although not unique to aviation are particularly relevant to aviation psychology and have presented important challenges to classic experimental and cognitive psychology. In this review, I describe how aviation

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psychologists have represented and studied these phenomena, and the particular research challenges they present.

To understand the intertwining of situation awareness and workload, consider a single pilot approaching for a landing in rapidly deteriorating weather. Already overloaded just in keeping the plane aloft and tracking the aircraft's instruments along the flight path, the pilot does not initially notice a failure of one of the navigational instruments. After noticing this failure, and while trying to diagnose the nature of the instrument problem, the pilot loses awareness of both the present off-course path and a large thunderstorm that appears on the radar display. Finally, after noticing the plane's path and taking steps to correct it, in this overloaded state, the pilot has forgotten to lower the landing gear. Thus, our pilot, because of the high mental workload, fails to maintain awareness of the surrounding environment and the state of the aircraft, and at various points "sheds" certain critically important tasks.

SITUATION AWARENESS

Endsley (2000) defined situation awareness as "the (1) perception [noticing] of the elements in the environment within a volume of time and space, the (2) comprehension of their meaning, and the (3) projection of their status in the near future" (p. 5). This three-stage construct can be further understood in terms of three important features. First, it involves cognition and working memory (the temporary store of information that is rapidly forgotten if not rehearsed), rather than action and response. Good situation awareness may support good choice of action, but is not inherently a part of that choice. Second, situation awareness is relevant to dynamic, evolving situations, and therefore is not the same as the more static knowledge of long-term memory (e.g., knowledge of how systems work or appropriate procedures to follow, mental models). Third, content or the product of situation awareness is distinct from the process of maintaining situation awareness (Adams, Tenney, & Pew, 1995). The pilot who is situationally aware has rapid access to an accurate mental representation of the changing environment that is broader and more enduring than that which can be held within the very restricted capacity of working memory, or "consciousness." The pilot with good situation awareness may not be consciously thinking about the fact that there is an aircraft close by to the side, but if called upon suddenly to respond appropriately to this situation, the pilot will do so rapidly and accurately because of the ability to rapidly access the information from memory (Kintsch & Ericsson, 1995). Thus, finally, good situation awareness supports the response to the unexpected (Wickens, 1999). Hence, aircraft design features that enhance routine performance may inhibit situation awareness, creating a "tunneling of attention" focusing primarily on expected events and tasks.

Three aspects of situation awareness that are most relevant for aviation are three-dimensional (3-D) spatial awareness, system (mode) awareness, and task awareness. I discuss each in turn, before showing how all three are directly linked to the issues of workload and task management.

Spatial Awareness

The concept of spatial awareness is inherent in the task of moving an aircraft through a 3-D space filled with hazards. The pilot in control confronts the following cognitive, or information processing, challenges: First, the system has six variables that have to be monitored and controlled as they change over time: three variables of orientation around the axis of the aircraft—pitch, roll, and yaw (heading)—and three position variables—altitude, lateral deviation from a flight path, and position along a flight path. Second, all of these six variables are linked, or "cross-coupled," in the flight dynamics; for example, pitch determines future altitude, and roll determines future heading, future lateral deviation, and future pitch. The skilled pilot represents these linkages and constraints in a mental model (Wickens, 1999). Third, these causal sequences produce time lags, lasting several seconds, between changes in the orientation variables, which can be directly controlled, and the positional changes that result. The cognitive challenges of anticipation when tracking systems with lags (Wickens & Hollands, 2000) impose an additional mental workload beyond that associated with the multivariable complexity of the system. (The perceived lags between an air-traffic controller's instructions to a pilot and the change in the aircraft visible on the controller's display are even greater than the lags for the pilot, and the cognitive challenges of anticipation are thus amplified for air-traffic control; Wickens, Mavor, & McGee, 1997). Fourth, the pilot must coordinate sometimes-conflicting goals of aviating (maintaining the proper orientation to preserve lift) and navigating (moving from point to point in 3-D space). Fifth, such coordination is carried out in a 3-D space that itself contains numerous dynamic hazards (weather, other traffic), whose 3-D trajectories cannot themselves be predicted with certainty.

To address these multiple challenges to spatial awareness, designers are endeavoring to create instrument displays with 3-D graphics. Such displays must be compatible with pilots' mental models, and with the limits of visual attention, which is required to process multiple sources of dynamic information (Wickens, in press). Three general themes capture the questions that arise in designing aircraft displays that promote spatial awareness.

- The *frame-of-reference* issue concerns whether information should be presented from the pilot's frame of reference, an egocentric ("inside out") view of the airspace corresponding to what the pilot sees, or from an exocentric ("outside in") view of the airspace, stabilized to a world-centered frame. Should the world rotate and translate around a fixed aircraft (egocentric), or should the aircraft rotate and translate on the display (exocentric)? Should the viewpoint show the pilot's forward view, or should it show the aircraft from above and behind? The answers to these questions depend on both the task and the user. For example, several studies have found that flight control (tracking accuracy) is much better with an egocentric view (Fig. 1, viewpoint A), but that noticing hazards in the airspace (referred to as Level 1 spatial awareness, or Level 1 SA) and understanding their general location (Level 2 SA) are better served by a more exocentric view (Fig. 1, viewpoint B; Wickens, in press). Other studies have compared two kinds of egocentric displays: moving-aircraft displays, which are consistent with a mental model that represents an aircraft moving in a fixed environment, and fixed-aircraft, moving-environment displays, which are more familiar to skilled pilots. These studies have revealed that novice pilots are better served by moving-aircraft displays, but that skilled pilots track equally well with the two kinds of displays (Previc & Ercoline, 1999).
- The *degree-of-integration* issue concerns whether it is better to use an integrated, ecological representation of the airspace, providing indications of 3-D motion flow (Fig. 1, viewpoints A and B; Gibson, 1979), or a more separated, analytical representation (Fig. 1, viewpoint C). Here again, there appears to be a trade-off that is task dependent (Wickens & Prevett, 1995): Because ambiguities result whenever a 3-D

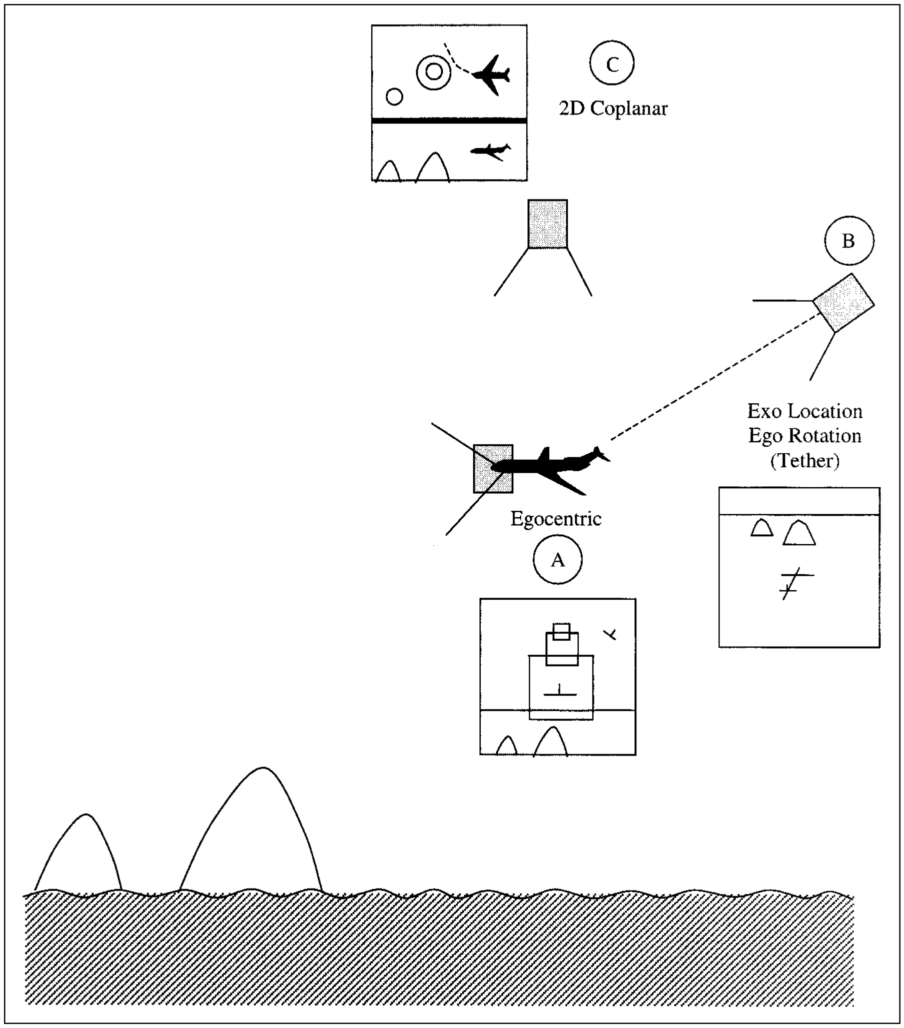

Fig. 1. Three representations of a pilot's airspace as the aircraft approaches two hills. The gray box near each display represents the "camera view" relative to the large black aircraft. The most egocentric representation (viewpoint A) is from the pilot's eye point. It depicts a three-dimensional (3-D), forward-looking command flight path "tunnel" (represented by the three squares, which are "windows," receding in depth, to be flown through) and the aircraft's current location (represented by the large inverted *T*); the small inverted *T* shows the predicted location of the aircraft a few seconds in the future. The 3-D exocentric viewpoint (viewpoint B) depicts the airplane (shown by the lines in the middle of the display) from behind and above; the view maintains a constant distance behind the plane, as if "tethered" to it by a rope (represented as the dashed line). The 2-D co-planar display (viewpoint C) depicts two separated views: a map view at the top and a vertical profile view below; the dashed path predicts the aircraft's movement in a turn. The changes from viewpoints A to B to C produce progressively less egocentric, integrated, and ecological representations.

volume is represented on a 2-D viewing surface, 3-D ecological views (e.g., viewpoint B in Fig. 1) create ambiguity in precisely locating entities in the airspace (Wickens, in press). In contrast, more analytical 2-D representations avoid those ambiguities, but impose greater attentional demands and cognitive load. For example, in the case of viewpoint C in Figure 1, the pilot must integrate the vertical and lateral displays in order to attain a mental "picture" of the 3-D airspace, which is needed to fly a 3-D trajectory (Wickens & Prevett, 1995), or mentally rotate the displays into a forward view, which is more characteristic of a 3-D view.

- The *prediction* issue concerns the degree of prediction, or "look ahead" capabilities, that should be built into a display. For both pilots and controllers, prediction capabilities support Level 3 SA—the ability to deal with lagged systems. Reliable predictive displays (e.g., seen in Fig. 1, viewpoints A and C) are always helpful for controlling the aircraft. However, the reliability of prediction in an airspace full of uncertainties regarding future wind, weather, and the pilot's own control actions will be less than perfect. An automated system can provide inferences about the future (e.g., viewpoint A in Fig. 1 shows where the aircraft is predicted to be a few seconds in the future), but may prove wrong, and incorrect predictions may destroy the human's trust in the system, thereby negating its benefits (Parasuraman & Riley, 1997). It is known that the reliability of prediction decreases as the predicted interval increases. But determining precisely how long this interval should be to support automation usage, without engendering mistrust, remains a major research challenge.

Designers need to understand these three general issues and integrate the principles of visual attention, spatial cognition, and manual control to craft the configuration of aircraft displays that will support all of the needed tasks, without overloading attentional capabilities.

System Awareness

Just as the aircraft and its airspace are complex and dynamic, so also are the systems within the aircraft. In modern aircraft, designers have provided a host of automated flight-control systems in an effort to relieve pilots' workload. Thus, increasing computer power has enabled aircraft to perform many actions—status monitoring, situation inference, and changing the mode of flight (e.g., climb, cruise, descent)—that pilots need not usually be aware of, unless the unexpected situation arises. The complexity of many of these automated systems, coupled with poorly designed symbolic displays, makes system awareness difficult to maintain (Sarter & Woods, 1995). Furthermore, the fact that people remember actions that they themselves have initiated better than those initiated by another agent (in this case, automation) poses an additional challenge to automation-system (or mode) awareness. Finally, the high workload imposed by other aspects of flying may further degrade the pilots' monitoring of automation-controlled devices (Parasuraman & Riley, 1997; Parasuraman, Sheridan, & Wickens, 2000). How to exploit the workload-reducing advantages of automation while still keeping the pilot adequately "in the loop," aware of actions taken by automated systems, provides a tremendous challenge for aviation psychology (Adams et al., 1995). Recent psychological research on change detection should provide important insights into how to keep pilots aware of the changes of their flight modes that are relevant to the safety of flight.

Task Awareness, Task Management, and Workload

The pilot actually has four different generic classes of tasks to perform. I have described the tasks of aviating and navigating already. The two additional tasks are communication (on the flight deck and with air-traffic control) and systems management (e.g., managing fuel, cabin pressure, electricity). These four tasks are arranged somewhat on a priority hierarchy in the order in which I have just referred to them (aviating, navigating, communications, and systems management, or "ANCS" for short), although the hierarchy has some flexibility. The busy pilot must always be aware of what tasks need to be performed, and in what order (Adams et al., 1995). The number of such tasks is so extensive and, in some cases, their performance is so vital that a host of checklists provide reminders of what to do and when to do it, thereby circumventing the frailties of human *prospective memory* (memory for things to be done in the future). Yet such proceduralized checklists, reinforcing the knowledge acquired from pilot training and experience, fall short in several respects (Wickens, 1999). First, in some situations, performing two or more tasks at once, or rapidly switching between them, is desired, if not required. Checklists provide no guidance on how to do this. Second, unexpected events can require actions that could never be fully laid out in written procedures. Third, many cognitive tasks, such as maintaining situation awareness, cannot easily be codified in checklists and procedures, yet performance of such ongoing tasks is vital in supporting the response to the unexpected.

One important domain of aviation research concerns the "rules" of task management and task switching. Research in this area has investigated both the tendencies that characterize pilots in general and those that discriminate better from more poorly performing pilots. In the former category are studies that have examined task interruptions—the extent to which the ANCS hierarchy is maintained when a task with a lower or higher priority arrives while another task is ongoing. Some evidence suggests that auditory tasks low on the ANCS hierarchy, and particularly auditory communication tasks, tend to be both more interrupting and less interruptible than tasks with a higher priority (e.g., navigation). Studies comparing better and more poorly performing pilots have indicated that better multitask performance results from rapid switching between tasks (Wickens, 1999).

Task-management research has a natural link to more traditional studies of attention as a perceptual phenomenon because highly salient perceptual events within a task can capture attention and thereby remind the pilot that the task needs to be performed. Without such events, a task might be neglected. One direct linkage of task management to situation awareness is inherent in the extent to which the pilot or air-traffic controller notices that a task should be attended to as a result of an automated alerting signal (Level 1 SA), and retains an understanding that the task should be done now (in the face of competing task demands, Level 2 SA), or in the future (Level 3 SA). Remembering to take care of future requirements (such as when an air-traffic controller remembers to take an arriving aircraft out of a "holding stack" around an airport) depends on prospective memory.

A second linkage between task management and situation awareness is inherent in the fact that maintaining situation awareness is itself a task, requiring the allocation of mental resources to the processes of selective attention (i.e., selectively attending to some events in the environment and ignoring others) and of working memory or short-term memory. In this regard it is important to realize that those attention-management strategies that support routine performance are likely to narrow the focus of attention on the parameters of flight control and potential hazards in the forward path, but this narrow focus does not necessarily support situation awareness. For example, a display (e.g., viewpoint A in Fig. 1) that channels attention to the forward flight path inhibits attention to surrounding hazards even when these are displayed elsewhere in the cockpit (Wickens, in press; Wickens & Prevett, 1995). Thus, a good pilot must allocate attention both to sources of information for routine performance and to information from the broader environment (in anticipation of unexpected events), and training in task-management skills can help to maintain situation awareness. A good display designer must create displays that can effectively integrate the representation of the two classes of information. Finally, effective models of mental workload should be able to predict the circumstances in which the workload of routine performance is raised to such a level that resources are not available to maintain situation awareness and the latter task is shed.

CONCLUSION

I have described an interlinking set of cognitive phenomena relating to awareness, aircraft control, attention, mental resources, and strategic task management. Much basic research in psychology has effectively addressed these issues in isolation. However, understanding and then modeling the complex interactions among these phenomena remains a critical challenge posed by aviation to psychological researchers who are interested in "scaling up" their theories to real-world problems. Overlaid upon this complexity are the fascinating challenges of understanding how powerful yet imperfect computer automation, in predictor displays, warnings, inference making, and flight management, affects pilots' situation awareness, mental workload, and task management (Parasuraman et al., 2000).

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Note

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